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Differential effects of fresh and composted organic wastes on soil bacterial community and maize growth

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ABSTRACT

The use of organic waste in agriculture improves soil health although its interaction with mineral fertilizers is not fully understood. This study investigated the impact of combining mineral fertilizers with organic wastes, such as sugarcane filter cake, poultry litter, and chicken manure in both fresh and composted forms, on maize (*Zea mays*) growth, soil bacterial communities, and their potential metabolic functions. The assessment was conducted 90 days post-application on two different soil types (*i.e.*, clay and sandy clay loam) in a greenhouse setting. While fresh animal-derived organic wastes generally boost short-term plant growth and nutrient uptake, composted wastes can be more effective in reducing nitrogen losses and methane emissions over the long term. The impact of organic waste on soil microbial communities and functions varies, with fresh wastes increasing nitrification and methanogenesis, while composted wastes tend to stabilize carbon and reduce these processes. Evaluating different organic waste sources and forms, and considering their C:N ratios, is crucial for optimizing soil health and minimizing greenhouse gas emissions. They also boosted plant growth and nutrient uptake, whereas composted waste increased soil mineral-associated organic matter (a more stable carbon pool) and phosphorus availability. These findings are crucial for optimizing the synergy between organic wastes and mineral fertilizers to enhance soil productivity and agricultural sustainability.

1. Introduction

The growing global emphasis on sustainable agricultural production has stimulated a movement towards reducing reliance on external inputs and considering organic amendments as alternatives to synthetic agricultural fertilizers (Garbowski et al., 2023; Pittelkow et al., 2015). Brazil, a major contributor to global food, fiber, and energy production, leads in sugarcane cultivation with a production of over 598 million tons in 2022 (CONAB, 2022). The country also ranks second in broiler meat production (14.8 million tons in 2023) and fifth in chicken egg production (52.4 billion units in 2023) (ABPA, 2023). These activities generate tons of organic wastes annually that can be reused in agriculture as organic fertilizers. For example, approximately 30 kg of sugarcane filter cake is produced for each ton of processed sugarcane, resulting in approximately 19 million tons of waste annually (Lopes et al., 2021). Similarly, the broiler industry produced over 13.5 million tons of organic waste in 2023 (ABPA, 2023). The combined volume of organic wastes from these three sectors alone could have met 14 % of Brazil's demand for mineral fertilizers in 2015, potentially saving 1.1 billion dollars (Cruz et al., 2017). Therefore, utilizing these organic wastes for agriculture use is widely recommended due to their abundance and benefits to soils and plants, thereby mitigating the reliance on mineral fertilizers (Arif et al., 2021).

Unfortunately, little attention has been given to the quality of organic wastes used in agriculture, with the focus often restricted to macronutrient contents, mainly nitrogen, phosphorus, and potassium. However, other aspects should also be considered when selecting the most suitable organic wastes for agriculture, such as their potential to enhance microbial abundance and activity (Siles et al., 2024), nutrient cycling (Hoang et al., 2022), carbon sequestration in the soil (Lal, 2004),

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as well as to reduce greenhouse gases emissions (Lazcano et al., 2021). It is also crucial to recognize organic waste source and treatment can affect nutrient availability, which influences not only plant growth and yield but also impact soil health and microbial metabolism (Liu et al., 2023). Moreover, nutrient efficiency should be regarded towards a more sustainable agriculture instead an immediate growth, using a better cost-effectiveness and resource management to promote long-term agricultural productivity and environmental stewardship for specific soil types and agricultural needs.

For example, fresh organic wastes are more likely to have detrimental effects on soils, resulting in heavy metal and organic pollutant accumulations (Seleiman et al., 2020; Wajid et al., 2020), amplifying greenhouse gas emissions (Nigussie et al., 2017; Sadet-Bourgeteau et al., 2019), and disseminating pathogens, antibiotic residues, and resistance genes in soils (Deng et al., 2020; Urra et al., 2019). Nonetheless, composted organic wastes are more likely to enhance soil attributes and provide a more sustained nutrient supply since humified materials are more stable, thus providing slow-release nutrients while also reducing or eliminating pathogenic organisms (De Corato, 2020). These composted organic wastes seem to be more prone to benefit soil-plant-microorganism interactions, improving nutrient cycling and soil functionality (Grigatti et al., 2020; Liu et al., 2018). Consequently, comparing the use of fresh and composted organic waste in agriculture can help researchers and farmers make informed decisions to maximize benefits, such as nutrient management, soil health improvement, environmental protection, and sustainable crop production.

Nevertheless, studies comparing the impacts of fresh and composted organic wastes coupled with mineral fertilizers on plant growth and soil microbial communities are limited. To address this gap, our study was guided by the following hypotheses: (1) organic wastes derived from animal and vegetal sources, whether in fresh or composted form, exert distinct impacts on plant growth and soil attributes; (2) soil type may be a driver for enhancing or suppressing the microbial potential of organic wastes; (3) composted organic wastes could lead to a larger soil residual effect due to their higher bacterial diversity.

2. Material and methods

2.1. Soils and mesocosm experiment

Two contrasting agricultural soils were collected at Piracicaba, São Paulo State, Brazil: a clay soil (Oxisol; Soil Survey Staff, 2014) under sugarcane (*Saccharum officinarum*, 23°44′09″ S; 47°59′29″ W) and a sandy clay loam soil (Oxisol; Soil Survey Staff, 2014) under pasture cultivation (*Urochloa decumbens*, 23°11′46″ S; 48°02′18″ W), both sampled from the surface layer (0–20 cm) (Table 1). The area has a tropical altitude climate (Cwa, Köppen), with annual rainfall of 1273.3 mm and temperatures ranging from 9.6 (minimum) to 29.9 °C (maximum), on average (Alvares et al., 2013).

Table 1
Physical-chemical attributes of the soils.

Soil attributes	Soils	
	Clay	Sandy clay loam
Sand (g kg^{-1})	281	773
Silt (g kg^{-1})	154	25
Clay (g kg^{-1})	565	202
O.M. (g dm^{-3})	27	21
pH ($CaCl_2$)	4.2	4.8
P (mg dm^{-3})	5	6
K^+ (mmol$_c$ dm^{-3})	2.0	1.1
Ca^{2+} (mmol$_c$ dm^{-3})	6	10
Mg^{2+} (mmol$_c$ dm^{-3})	3	5
CEC (mmol$_c$ dm^{-3})	23	17
Al^{3+} (mmol$_c$ dm^{-3})	12.3	1.5
m (%)	53	9
V (%)	17	41

O.M = soil organic matter; CEC = cation exchange capacity; m = aluminum saturation; and V = base saturation.

The mesocosm experiment was conducted in a greenhouse for 90 days, using 11 L plastic pots (24 × 27 cm) arranged in a completely randomized factorial design. Each soil type had four replications with two factors: 3 organic waste types [sugarcane filter cake (FC); poultry litter (PL); and chicken manure (CM)] and 2 organic waste treatments (fresh or composted), plus a control (soil without or with mineral fertilizer applications), totaling 64 experimental units.

Initially, all experimental units were amended with limestone for 30 days to reduce aluminum toxicity and increase soil pH. Subsequently, the fertilized control treatment received 100 % of the recommended fertilization rate for maize (*Zea mays* L.) (Aguiar et al., 2014), while the unfertilized control received no amendments. Fertilization rate was calculated based on recommendations for maize crops (kg ha^{-1}) considering concentrations of N, P_2O_5, and K_2O in the mineral fertilizers (Table 2). Applications were made based on the pot area. The other treatments were amended with 7 Mg ha^{-1} (dry mass) of the respective wastes and 50 % of the mineral fertilization rates.

Hybrid maize (BM207 Biomatrix®) was adopted as the model plant. Their seeds were planted and cultivated for 90 days, and the pots (one plant/pot) were irrigated manually with deionized water according to plants' need up to harvesting (end of VT stage, when the lowest branch of the tassel was visible). Afterwards, it was assessed plant heights, stem diameters, and shoot dry masses.

2.2. Organic waste composting process and chemical attribute measurements

The organic wastes were composted outdoors for 90 days at the Center of Studies and Research for Reuse of Agro-industrial Wastes (CEPARA) at ESALQ/USP in Piracicaba, São Paulo State, Brazil, following the procedures described in our previous article (Martins et al., 2023). An extensive discussion about composting conditions as well as bacterial communities changes before and after composting process were presented. Briefly, all compost piles were maintained with a C/N ratio of 20:1 using wood chips, without exogenous inoculation. Temperature and humidity were controlled through manual irrigation and aeration, ensuring similar conditions for all piles. The labile macronutrient (N, P, K, Ca, Mg, and S) and micronutrient (Fe, Cu, Zn, and Mn) contents, as well as other attributes such as total carbon (TC), pH, and C/N ratio, were evaluated according to the Brazilian legislation for organic fertilizer's (Brazil, 2006) (Table 3).

2.3. Phytotechnical attributes, sample collection, and laboratory analysis

At the end of the 90-day experiment, plants were collected and evaluated for height, diameter, and dry mass (oven-dried at 65 °C for 48 h). Macronutrient (N, P, K, Ca, Mg, and S) and micronutrient (Fe, Cu, Zn,

Table 2
Details of the mineral fertilizers used on the experiment.

Organic waste	Type	Applied fertilizer (kg ha^{-1})			
		$CO(NH_2)_2$	P_2O_5	K_2O	
				Clay	Sandy clay loam
Control	Unfertilized	–	–	–	–
	Fertilized	140	120	90	110
Filter cake (FC)	Fresh	40	60	45	55
	Composted	40	60	45	55
Poultry litter (PL)	Fresh	40	60	45	55
	Composted	40	60	45	55
Chicken manure (CM)	Fresh	40	60	45	55
	Composted	40	60	45	55

$CO(NH_2)_2$ = urea fertilizer; P_2O_5 = triple super phosphate; K_2O = potassium chloride.

Table 3
Organic waste chemical attributes.

Attributes	Filter cake (FC)		Poultry litter (PL)		Chicken manure (CM)	
	Fresh	Composted	Fresh	Composted	Fresh	Composted
pH	6.7	7.0	8.2	6.9	9.7	8.0
TC (g kg^{-1})	162	100	413	113	210	112
TN (g kg^{-1})	18.0	8.6	20.0	5.9	18.0	7.0
C/N	9.0	11.6	20.7	19.2	11.7	16.0
NH_4^+ (mg kg^{-1})	22	64	73	38	227	178
NO_3^- (mg kg^{-1})	1059	1411	943	1600	141	1045
P (g kg^{-1})	10.2	7.0	12.1	10.0	38.9	10.3
K (g kg^{-1})	4.5	1.9	15.5	5.4	47.9	8.2
Ca (g kg^{-1})	29	20	26	24	172	71
Mg (g kg^{-1})	2.4	1.4	3.4	3.3	9.2	2.7
S (g kg^{-1})	4.9	2.9	4.5	1.9	9.0	1.7
Fe (mg kg^{-1})	16,043	24,171	649	19,656	972	28,164
Cu (mg kg^{-1})	34	37	56	51	766	215
Mn (mg kg^{-1})	487	476	398	503	534	495
Zn (mg kg^{-1})	100	101	382	327	753	246
B (mg kg^{-1})	nq	nq	40.4	nq	64.9	nq

TC = total carbon; nq = not quantified (below detection level).
Complete table presented at Martins et al. (2023).

and Mn) uptake by plants were evaluated according to Malavolta et al. (1989). Soil attributes (pH, organic matter, P, K, Ca, Mg, Fe, Cu, Mn, Zn, and B) were evaluated according to Van Raij and Cantarella (1996). Soil organic matter fractionation into particulate (POM) and mineral-associated (MAOM) organic matter was determined according to Cambardella and Elliott (1992). Total soil C and N contents in these fractions were quantified by dry combustion using a LECO TruSpec CN elemental analyzer (Leco Corp., St. Joseph, MI, USA).

2.4. DNA extraction, 16S rRNA sequencing, and bioinformatics analysis

After 90 days, the total DNA was extracted using the PowerSoil Pro Kit (Qiagen, Hilden, Germany), following the manufacturer's recommendations. DNA quantity and quality were evaluated using a Nanodrop 2000c spectrophotometer (Thermo Fisher, USA). DNA integrity was checked by electrophoresis in 1 % agarose gel at 90 V for 1 h. The amplification of the 16S rRNA gene V4 region was performed using the primers 515F and 806R (Caporaso et al., 2012), along with Illumina adapters on the MiSeq platform (Illumina, San Diego, USA). PCR products were purified with AMPure XP Beads (Beckman Coulter, Indianapolis, USA) and fragment sizes were confirmed by agarose gel electrophoresis. The second PCR was performed to attach the Nextera XT Kit barcodes (Illumina, San Diego, CA, USA), and the products were purified to confirm libraries, which were quantified in a Qubit 2.0 fluorimeter (Thermo Scientific, USA) to standardize equimolar amounts in a single pool. Sequences then underwent quality control to remove primers, barcodes, adapters, and chimeras, and only high-quality sequences ($Q > 30$) were retained for analyses using *DADA2* default parameters (Callahan et al., 2016) and *phyloseq* (McMurdie and Holmes, 2013) packages in the R environment (R Core Team, 2022)(v. 4.1.3.). Taxonomy of ASV sequences was assigned using the SILVA database (v. 138.1; Quast et al., 2012). The sequences are submitted to the NCBI Sequence Read Archive under the identification PRJNA1111064.

2.5. Data analysis

Data were submitted to a three-way ANOVA ($p \leq 0.05$) to contrast differences among soils (clay and sandy clay loam), organic waste types and controls (FC, PL, CM, and Control), and their respective treatments (fresh or composted for the organic wastes and unfertilized or fertilized for the controls). Errors' normality was assessed using the Shapiro-Wilk test, whereas asymmetry and kurtosis coefficients were evaluated according to linear predictors. Then, soils were analyzed individually by a two-way ANOVA ($p \leq 0.05$).

To reduce diversity index bias, DNA sequences were rarefied to 18,644 (the lowest found abundance). Microbial community alpha diversity indices were contrasted using the Tukey-HSD test (honestly significant difference) ($p \leq 0.05$). Beta diversity was used to assess bacterial community structure using principal coordinate analysis (PCoA), based on Bray-Curtis distance, and was compared by PERMANOVA ($p \leq 0.05$). Differential abundance was assessed using the "ALDEx2_t" function from the *microeco* package (Liu et al., 2021), which uses Welch's and Wilcoxon *t*-tests to compare groups. The algorithm used centered log-ratio (clr) transformation, and technical variation characteristics within each sample were evaluated using Monte-Carlo permutations of Dirichlet distribution.

Functional prediction for carbon fixation, methane metabolism, and nitrogen metabolism was conducted by unobserved state reconstruction using the PICRUSt2 pipeline (Douglas et al., 2020), with KEGG as a reference database. PICRUSt2 predicts the functional profile of 16S amplicons, based on fully annotated genomes of reference organisms. The gene abundance associated with biogeochemical functions was extracted and summarized from PICRUSt2 (details presented in Supplementary Material). KEGG Orthologs (KOs) were categorized into functional groups for carbon, methane, and nitrogen metabolism, according to the DiTing program (Xue et al., 2021). Total gene abundance was transformed into a z-score to improve results visualization.

3. Results

3.1. Effects of composting organic waste on soil attributes and plant growth

The three-way ANOVA revealed that soil texture, composting, and organic waste source significantly affected plant biomass, soil organic carbon (SOC) contents, and nutrient accumulation in plants (Fig. 1 and Table S1). Organic waste amendments increased soil organic carbon (SOC) contents compared to the controls after 90 days, although the differences were not significant. Particulate organic matter (C-POM) contents were higher, whereas mineral-associated organic matter (C-MAOM) contents were lower in the sandy clay loam soil. Application of fresh forms of PL and FC enhanced C-POM most significantly in the sandy clay loam soil, but no differences were observed in the clay soil. Application of CM, whether fresh or composted, significantly increased C-MAOM in sandier soil (Fig. 1C and D).

The residual effects of the organic wastes, evaluated through soil nutrient availability at the end of the experiment, showed higher effects for phosphorus, calcium and nitrogen (Table S4 and S5). The CM waste

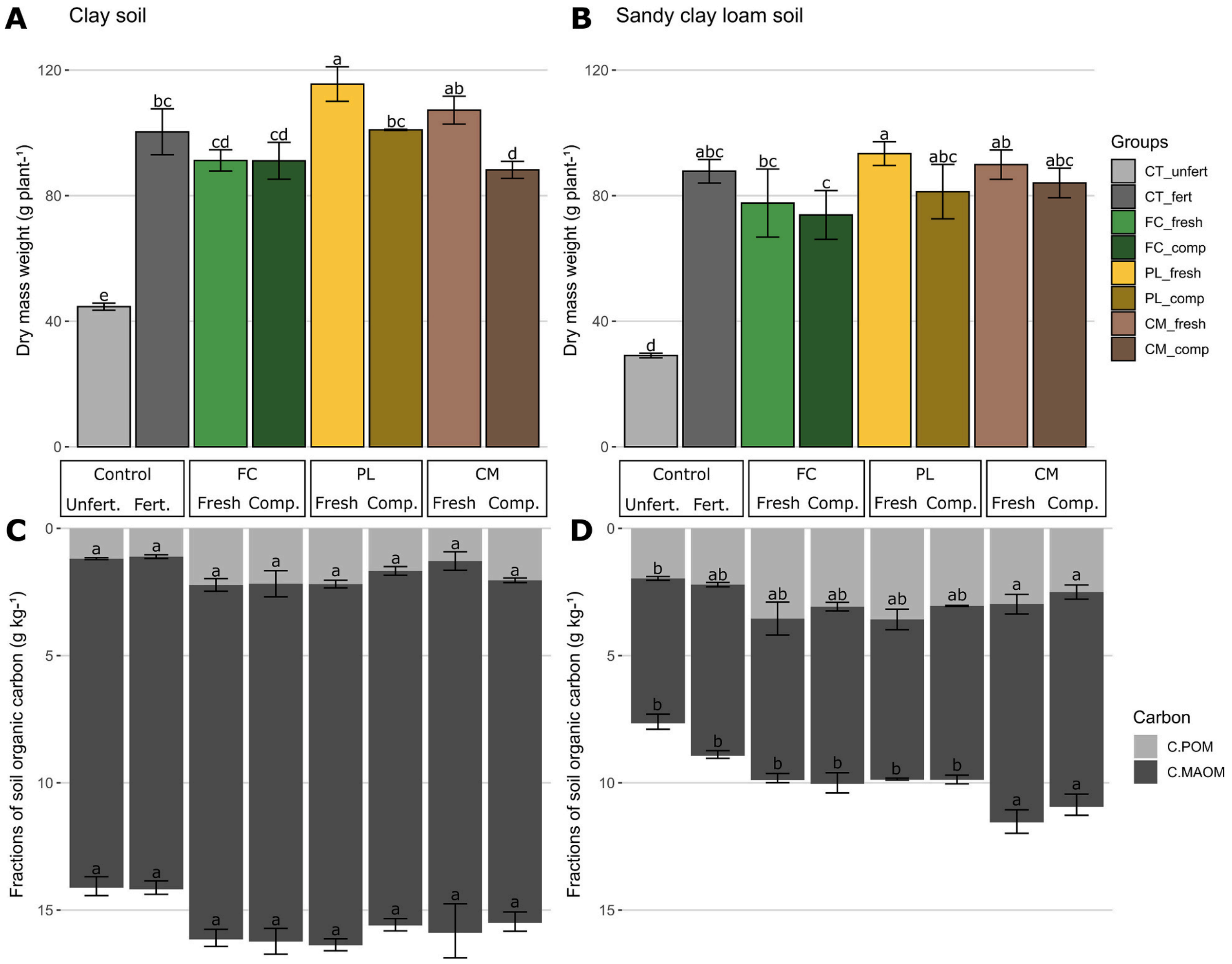

Fig. 1. Effects of fresh and composted organic wastes [sugarcane filter cake (FC), poultry litter (PL), and chicken manure (CM)] on plant dry masses (A and B) and soil organic carbon fractions [particulate organic matter (C-POM) and mineral-associated organic matter (C-MAOM)] (C and D) in clay and sandy clay loam soils. Two control treatments were adopted [no fertilization (Unfert, soil only) and full mineral fertilization (Fert)]. Data presented as mean ± standard deviation ($n = 4$). Different letters indicate significant differences by the Tukey-HSD test ($p \leq 0.05$).

showed the highest soil residual effect for phosphorus and nitrogen, while composted CM and PL wastes had greater residual phosphorus availability than fresh forms, and FC waste showed no significant differences. Mineral fertilizer alone had no residual effects on soil elements.

For both soil types, the highest plant biomass was observed with the application of fresh-PL, followed by treatments using fresh-CM waste and exclusively mineral fertilization (MF = 100 % of full dosage). Conversely, composted organic wastes yielded lower plant biomass compared to their fresh counterparts, while fresh forms of PL and CM exhibited a significantly higher plant uptake of all major macronutrients (Tables S2 and S3). However, fresh and composted FC did not show significant differences in nutrient uptake. Irrespective of their type or form, the application of organic wastes significantly enhanced phosphorus uptake, even when compared to fertilized control.

3.2. *Fresh and composted organic wastes affect soil bacterial diversity and composition*

DNA sequences yielded an average of 38,360 reads per sample (merged and non-chimera). In total, 1.84×10^6 sequences were clustered into 8128 amplicon sequence variants (ASVs), which were categorized into 42 phyla, 115 classes, 459 families, and 954 genera. Alterations in the alpha and beta diversity of the soil bacterial communities were observed 90 days after waste application in both soils (Fig. 2).

Alpha diversity indices differed significantly between soils, being much higher in the clay soil (Fig. 2A and B, Table S6). Applying composted-FC resulted in an increased alpha diversity compared to other treatments, especially in the clay soil ($P < 0.05$). However, applying animal-derived wastes, such as PL and CM, did not show any significant differences compared to controls, although fresh-CM impacted negatively in sandier soil. Interestingly, composted forms of FC and CM had higher diversity indices compared to their fresh counterparts ($p < 0.05$).

The bacterial community structure was significantly affected by soil type, organic waste source, and the composting process (Fig. 2C and D; Table S2). According to PCoA, the first two axes explained 36.3 % and 54.3 % of the observed variations in clay and sandy clay loam soils, respectively. Regardless of their sources, all composted wastes exhibited less variation and a more uniform structure of their bacterial communities compared to the controls (Fig. 2B). Conversely, fresh organic wastes had a greater potential to alter soil bacterial community structure than their composted counterparts, though this alteration also depends on the source of the waste. This suggests that while composting tends to stabilize the bacterial community, the introduction of fresh organic waste can lead to more pronounced changes, varying with the type of waste used.

The Venn diagram showed that FC shared 58.4 % and 63.5 % similarity in total abundance of bacterial communities for clay and sandy

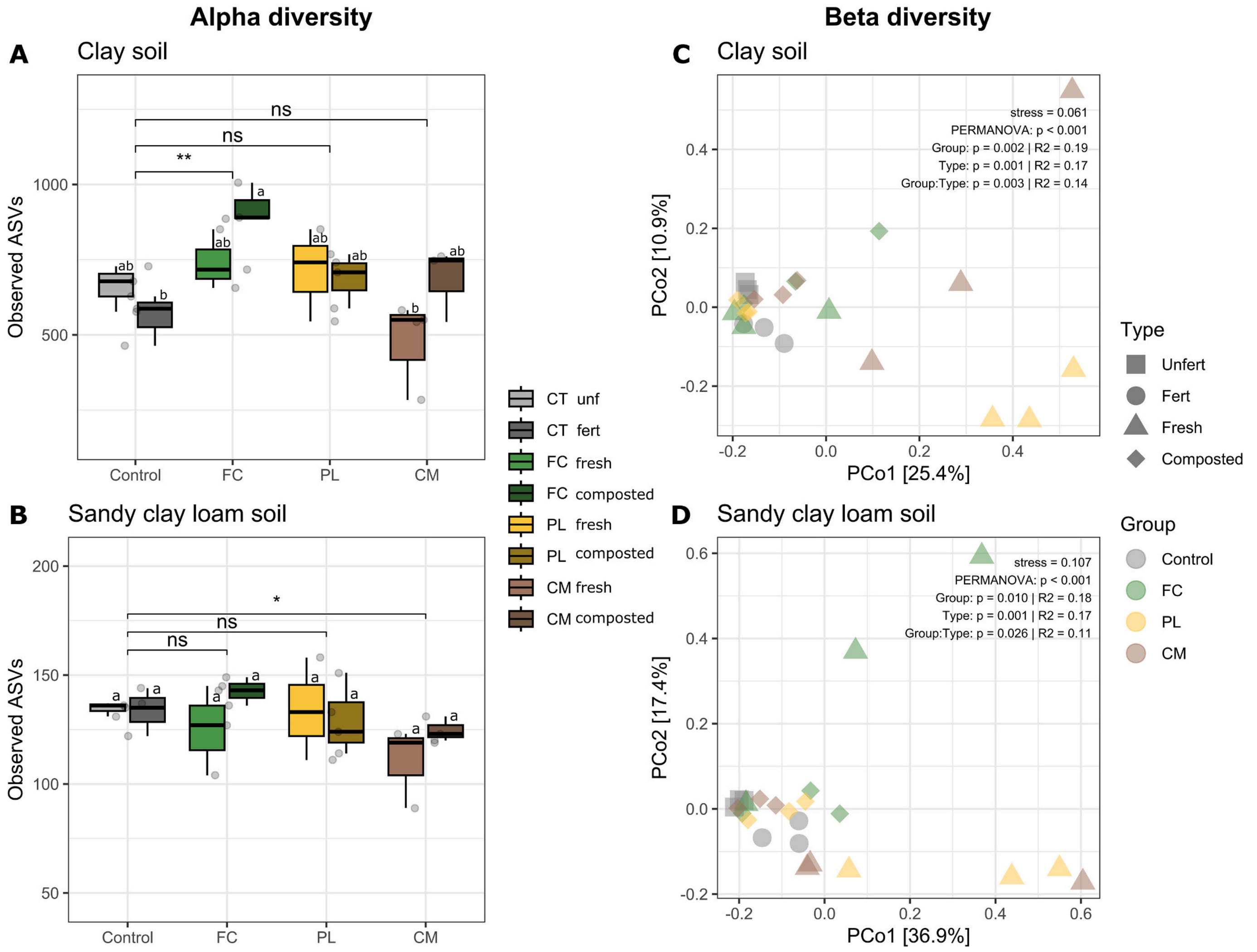

Fig. 2. Effects of fresh and composted organic waste [sugarcane filter cake (FC), poultry litter (PL), and chicken manure (CM)] on alpha (A and B) and beta (C and D) diversities of bacterial communities in clay and sandy clay loam soils. Two control treatments were adopted [no fertilization (Unfert, soil only) and full mineral fertilization (Fert)]. Boxplots stand for means, median, and confidence intervals at 95 % ($n = 3$). Asterisks show significant differences between groups by Welch's *t*-test ('**' = $p \leq 0.01$; '*' = $p \leq 0.05$; ns = not significant).

clay loam soils, respectively, whereas PL and CM displayed average similarities of 43 % and 63 %, respectively (Fig. 3). Fresh-PL waste led to the most significant alteration in the bacterial community, with unique relative abundances of 18 % and 10 % in clay and sandy clay loam soils, respectively. In contrast, composted PL showed unique relative abundances of 2 % and 1.3 % for the same soils. Fresh-CM induced unique relative abundances of 8.9 % and 5 % in clay and sandy clay loam soils, respectively, while the composted counterpart induced unique relative abundances of 5.3 % and 2.2 % for the same soils.

Relative abundance analysis revealed that genera composition differed between soils even when they were treated with the same organic waste (Fig. 3). Clay soil exhibited a higher number of differentially abundant genera. Moreover, composted FC significantly increased *Curvibacter* genus abundance in clay soil. Fresh PL and CM decreased *Microvirga* and *Clostridium* genera in both soils. Composted PL increased *Bradyrhizobium* and *Azospirillum*, while composted CM increased *Parasegetibacter* and *Burkholderia* abundances.

3.3. Compost effects on soil bacterial community metabolic potential

The soils did not show significant differences in the abundance of genes related to putative carbon fixation functions, regardless of whether organic waste or mineral fertilizer was added (Fig. 4 and Table S3). The genes associated with reductive citrate cycle were the most abundant, followed by 3-hydroxypropionate and then Calvin-Benson cycles. In both soils, composted PL presented a lower abundance of carbon fixation genes compared with its fresh counterpart. Conversely, FC and CM showed no significant differences between their fresh and composted forms. Interestingly, unfertilized soils had a higher abundance of carbon fixation genes than those under mineral fertilization.

The application of composted organic wastes and mineral fertilizers exhibited the potential to alter methane metabolism in both soils (Fig. 4 and Table S3). The methanogenesis function showed the highest gene abundance for acetate oxidation to methane, followed by CO_2 reduction to methane, and methanol reduction to methane. Overall, the clay soil showed a higher abundance of these genes. In the sandier soil, composted PL potentially reduced the abundance of genes related to methanogenesis compared to its fresh form, while CM showed fewer genes involved in methane formation.

The use of organic wastes has the potential to influence the abundance of genes associated with the nitrogen (N) cycle in both soils (Fig. 4 and Table S3). Functions with the highest gene abundance include assimilatory and dissimilatory nitrate reduction, followed by denitrification, nitrification, and nitrogen fixation. These patterns were consistent across all treatments in both soils. Compared to the control (soil

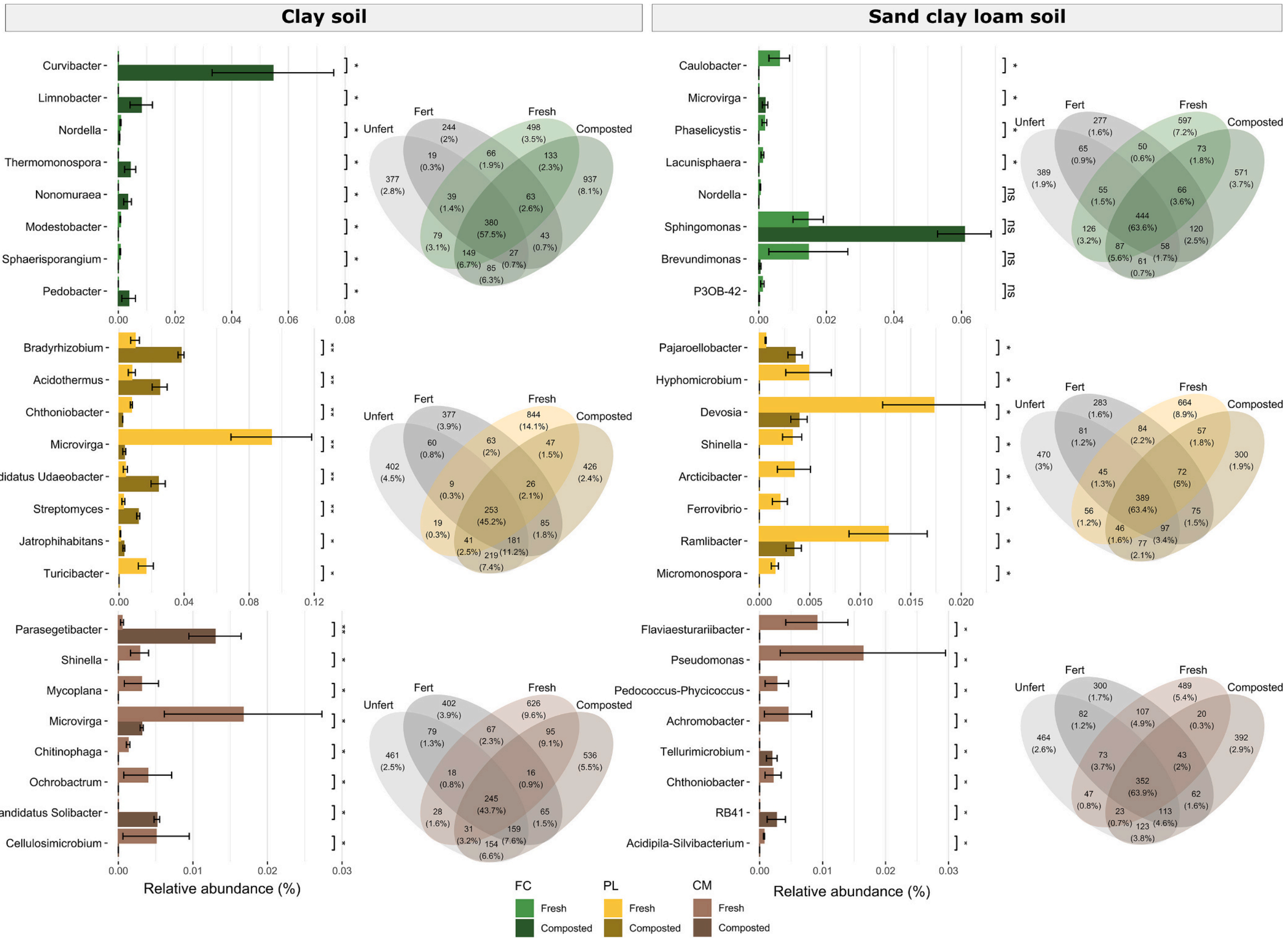

Fig. 3. Differential abundance of the most abundant genera as affected by organic waste [source sugarcane filter cake (FC), poultry litter (PL), and chicken manure (CM)], treatment (fresh or composting), and soil type (clay and sandy clay loam). Asterisks indicate significant differences by Welch's *t*-test calculated using the ALDEx2 algorithm ("**" = $p \leq 0.01$; "*" = $p \leq 0.05$; ns = not significant). Venn diagram shows the number and percentage of unique ASVs found in each treatment.

only), mineral fertilization exhibited a greater potential to increase the abundance of nitrification genes. However, composted PL and CM displayed a lower abundance of denitrification and nitrate reduction genes compared to their fresh counterparts, whereas fresh PL increased the abundance of N-fixation genes in both soils.

4. Discussion

4.1. *Organic wastes modulate soil carbon accumulation and plant development*

Agricultural use of organic wastes often enriches soil with organic carbon, enhancing microbial activity and biomass regardless of their sources (Han et al., 2021; Rui et al., 2009). Our short-term study revealed an overall non-significant augmentation of both recalcitrant and labile soil carbon contents upon waste application. This effect was more pronounced and had statistical significance for chicken manure in sandier soil, echoing previous research that reported substantial increases in soil organic matter content following prolonged animal manure application (de la Fuente et al., 2011; Lin et al., 2019). Intriguingly, fresh chicken manure also showed an increase in mineral-associated carbon in both soils, likely due to higher rates of labile carbon mineralization in animal-derived wastes (Bian et al., 2022; Li et al., 2019). However, we should keep in mind that amending fresh organic wastes often leads to greater nitrogen immobilization and volatilization than their composted counterparts, which is driven by high contents of labile carbon compounds (Bernal et al., 2009; Paul, 2016).

Contrary to our expectations, the inclusion of composted wastes did not result in higher soil organic carbon contents compared to their fresh counterparts, likely due to the relatively short duration of our experiment. However, composted wastes tend to have more persistent effects since their carbon compounds are more stable, thus favoring long-term outcomes as well as soil quality and soil health (Bastida et al., 2008). In other words, composted wastes provide larger quantities of humified carbon that ensures hydrophobic protection to soil organic matter against degradation (Spaccini and Piccolo, 2020, 2007). Both fresh and composted organic wastes have a limited capacity to augment carbon stocks; however, their primary efficacy lies in stabilizing soil organic matter (Chaker et al., 2019; Jeong et al., 2019). In the long-term, composted wastes combined with mineral fertilizers should enhance soil carbon sequestration (Li et al., 2023), nitrogen retention (Chen et al., 2024), and soil aggregation (Nath et al., 2023), thus promoting higher multifunctionality and soil health compared to conventional management (Walder et al., 2023).

Organic wastes, especially those from animals, showed greater nutrient absorption and plant development than the plant-derived one, aligning with findings from previous research (de la Fuente et al., 2011; Jeong et al., 2019). This effect was mainly caused due to differences in macronutrient levels, as poultry litter and chicken manure showed significantly higher contents of labile nitrogen and phosphorus than sugarcane filter cake (Martins et al., 2023). In addition, fresh animal wastes exhibited higher nutrient contents compared to their composted

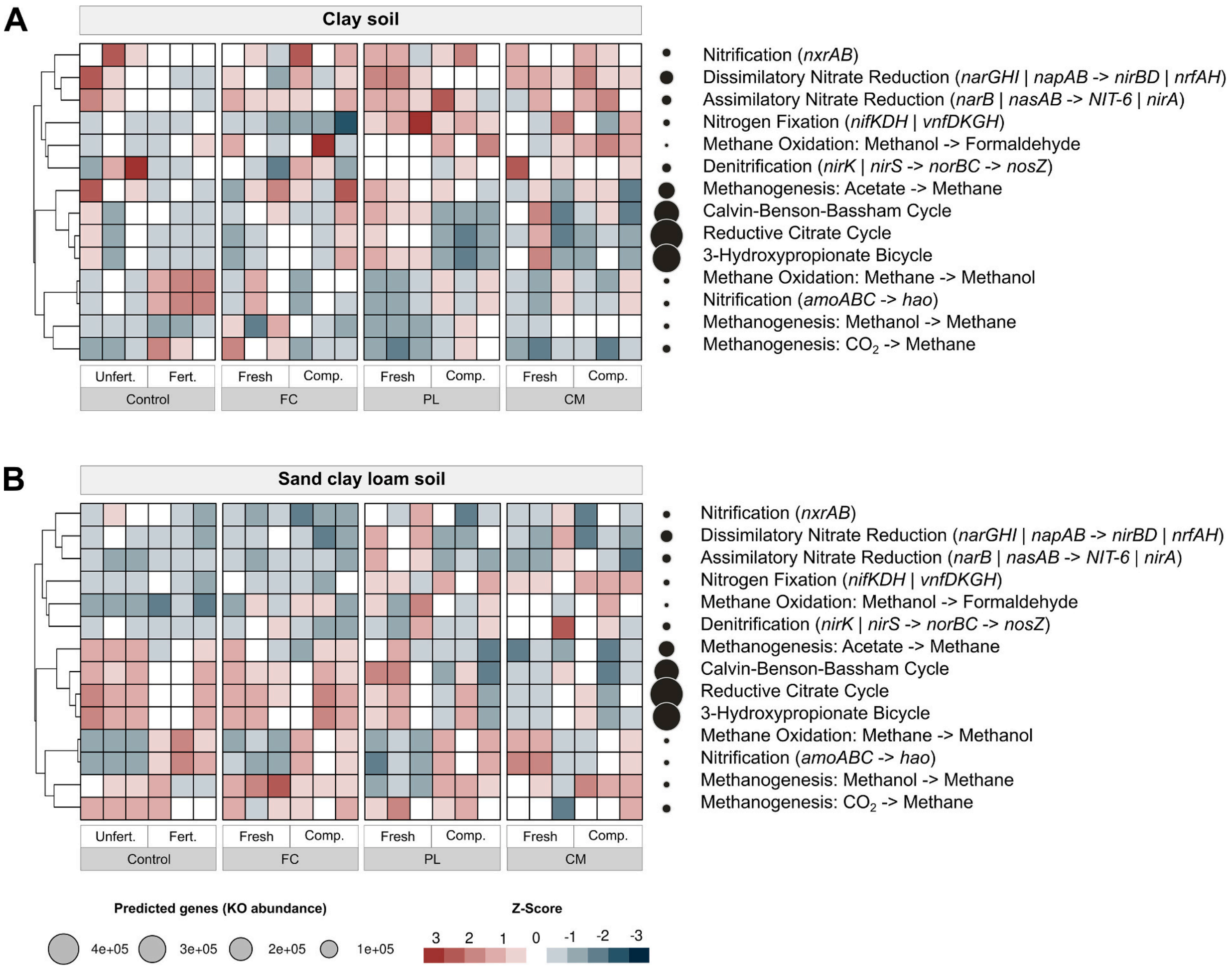

Fig. 4. Functions related to carbon fixation, nitrogen and methane metabolism as predicted by the reconstruction of unobserved states using PICRUSt2. Predicted genes based on KEGG orthologs (KOs) abundance. The analysis was performed 90 days after application of fresh and composted organic wastes [sugarcane filter cake (FC), poultry litter (PL), and chicken manure (CM)] on clay soil (A) and sand clay loam soil (B).

forms. Li et al. (2021) also noted differences between vegetal and animal-derived wastes, attributing the lower nutrient availability in plant-derived wastes to their low C/N ratio and high recalcitrance, which seems to be the case for the sugarcane filter cake whether composted or not. This is further supported by the fact that both fresh and composted filter cake exhibited lower but similar levels of nitrate, phosphorus, and potassium (Martins et al., 2023). Our findings indicate that short-term performance of plants is primarily driven by the levels of labile nutrients in organic wastes. However, the differences between soils may be attributed to clay's higher nutrient content and cation exchange capacity (Rosolem et al., 2010).

Organic waste effectiveness will depend on its source and composting, as well as on soil type (Han et al., 2021). These findings underscore the importance of selecting the appropriate type and form of organic waste for optimal nutrient management. While fresh animal-derived wastes tend to enhance nutrient availability and plant growth, composted wastes might be more suitable in systems where long-term soil health is prioritized. The choice between fresh and composted waste should therefore be guided by specific crop needs and soil conditions to achieve the best outcomes (Imran, 2024; Morash et al., 2024).

Overall, the combined use of organic wastes with reduced rates of mineral fertilizers proved more effective than mineral fertilization alone, making this practice a valuable strategy for enhancing nutrient use efficiency and crop productivity (Chen et al., 2021), while reducing management costs in agricultural practices (Du et al., 2022). Nevertheless, further research is required to refine their application in agriculture for the long-term enhancement of soil health attributes (Brichi et al., 2023). Organic wastes may also have a role in soil recovery from fire damage (Hueso-González et al., 2018), regulation of N_2O emissions (Zhu et al., 2014), and soil aggregation (Bipfubusa et al., 2008). This study highlights the multifaceted influence of organic waste on soil quality, nutrient dynamics, and agricultural productivity.

4.2. *Organic wastes use modulates soil bacterial community*

Organic wastes typically enhance soil prokaryotic alpha diversity, in contrast to mineral fertilizers (Bebber and Richards, 2022). This augmentation depends on various factors, including waste sources and treatments, as well as soil attributes (Lin et al., 2019; Sun et al., 2016). Organic wastes proliferate new microorganisms by introducing energy-rich organic carbon and substrates rich in macro- and micronutrients (Calleja-Cervantes et al., 2015; Dumontet et al., 2017). This, in turn, stimulates microbial activity and multifunctionality, promoting a more diverse and abundant microbial population (Martínez-García et al., 2018; Shu et al., 2022). In the long term, such practices increase soil heath through organic carbon accumulation, especially in carbon-poor croplands (Bai et al., 2023). Moreover, both animal and plant fertilizers improve soil health and plant health by establishing communities with higher diversity, complexity and stability (Yang et al., 2023; Yu et al., 2024).

Higher bacterial diversity has been shown to enhance maize yield (Liu et al., 2022a). Our findings suggest a less pronounced effect, except for composted filter cake in the clay soil. One explanation is that animal-derived organic wastes can cause more substantial changes in soil microbial community structure than plant-derived wastes, primarily due to their influence on resource availability through macroaggregate formation (Li et al., 2021; Liao et al., 2020). Conversely, fresh chicken manure even reduced alpha diversity in the sandier soil, which was much lower than in the clay soil. This reduction in soil bacterial diversity and the changes in bacterial community structure may be associated with the greater sensitivity of sandy soils due to their lower organic matter and nutrient contents (Yao et al., 2024). Due to their higher bacterial diversities (Martins et al., 2023), plant-derived wastes seem to introduce a broader spectrum of bacterial groups to soils, especially in composted form. Conversely, fresh animal-derived wastes present higher abundance of antibiotic resistance genes and pathogenic organisms (Kubasova et al., 2022; Urra et al., 2019), thus contributing more to the changes in soil bacterial structure.

Organic wastes composting can reduce the risks associated with dissemination of pathogens and antibiotic-resistant genes in soils (Deng et al., 2020; Soobhany et al., 2017). Apart from its source, composted wastes resulted in minimal changes in soil bacterial community structure compared to their fresh counterparts. Therefore, fresh organic wastes tend to have stronger short-term effects on bacterial communities of the soil, which may potentially introduce exogenous harmful microorganisms at long-term (Sardar et al., 2023). On the other side, the use of composted wastes may increase the abundance of beneficial bacterial genera, such as *Curvibacter*, which aids in organic matter biodegradation (Hui et al., 2019); *Limnobacter*, which contributes to thiosulfate oxidation and maize growth (Nguyen and Kim, 2017); and *Parasegetibacter*, which shows potential for promoting plant growth and cadmium biotoxicity tolerance (Yuan et al., 2022). For instance, the abundances of Proteobacteria, Acidobacteria, and Actinobacteria increased after composted sugarcane filter cake application (Estrada-Bonilla et al., 2021), whereas those of Acidobacteria, Sphingobacteria, and Alphaproteobacteria increased after composted poultry litter and chicken manure application (Ashworth et al., 2017; Subirats et al., 2021).

The influence of distinct organic wastes and composting on soil bacterial communities was highlighted in this research, which emphasized that their effects go much beyond nutrient and carbon accumulation. The synergistic use of organic waste alongside mineral fertilizers combines the benefits of both methods, enhancing soil microbial diversity, improving nutrient availability to plants, and optimizing nutrient utilization efficiency. While the short-term effects of organic wastes on soil microbial communities may be less pronounced than those of mineral fertilization, they still enrich beneficial taxa that contribute to various soil ecological services (Zhang et al., 2021).

4.3. Organic wastes and potential effects on soil metabolic functions

Organic waste materials, including plant residues and animal-derived byproducts, interact differently with soil microorganisms due to their distinct microbial communities, chemical compositions, and nutrient profiles, thereby affecting their metabolic activity (Bebber and Richards, 2022). Recognizing these differences is crucial for maximizing the effectiveness of organic waste utilization in agriculture and land management.

In our investigation, we used functional prediction to infer soil metabolism from the bacterial community taxonomic compositions, *i.e.*, predictions were based on unobserved functions. Yet, this method exhibits qualitative results similar to more established methodologies, such as metagenomics and enzymatic analyses (Breitkreuz et al., 2021). Certain authors even state that results from this approach might be more conservative and underestimate actual functional outcomes (Toole et al., 2021). The literature has already shown that organic wastes can enhance soil microbial communities' metabolic and functional capacity (He et al., 2022; Zhaoxiang et al., 2020). We also observed that organic waste sources and composting impacted potential metabolic functions.

Generally, organic waste application enhanced specific soil microbial functions, particularly those related to methane and nitrogen cycles but did not affect those related to carbon fixation, regardless of its source or form. Microbial activity and soil respiration are often performed by a wide variety of microorganisms and, most likely, are not affected by soil texture and nutrient status (Lauber et al., 2008). However, specific functions related to biogeochemical cycles, such as those for phosphorus, nitrogen, and methane, are often influenced by soil type and the use of organic amendments (Du et al., 2021; Yu et al., 2019). For example, composted wastes, particularly those derived from animals, can reduce soil denitrification compared to fresh wastes, suggesting that, in the long term, their amendment may lower nitrogen losses and N_2O emissions more effectively than mineral fertilization (Govednik et al., 2024; Liu et al., 2024). Additionally, compost application combined with fertilizers can reduce methane (CH_4) emissions and promote soil health by altering microbial composition and encouraging plant-growth-promoting bacteria (Brenzinger et al., 2021; Iqbal et al., 2023).

A dominance of genes related to reductive citrate and 3-hydroxypropionate was observed within the carbon fixation cycle. They were likely potentially amplified by soil microbial biomass, facilitating carbon substrate utilization even in the short term (Fanin et al., 2015; Shrestha et al., 2019; Sradnick et al., 2013). Although short-term effects were significant, long-term use of organic waste shows better results for microbial diversity (Daquiado et al., 2016; Su et al., 2015). Both composted and fresh chicken manure reduced carbon fixation pathways compared to control soils, likely due to increased soil carbon stabilization and microbial preference for recalcitrant carbon forms (Liang et al., 2012; Liu et al., 2022b). In parallel, fresh poultry litter increased genes related to methanogenesis likely due to the prevalence of methanogenic microorganisms, such as Thermoplasmata class members and the *Methanosaeta* genus (Ahn et al., 2012; Conrad et al., 2006).

These results underline the need to evaluate different compost sources and treatments to optimize organic waste effects on soil metabolism and health over both short and long terms. Studies show that a higher abundance of genes related to nitrification can boost plant yields in the short term (Zhong et al., 2020), but long-term use of organic waste can suppress nitrification and reduce nitrogen losses (Li et al., 2019). Lower C:N ratios, below 12, may enhance nitrogen mineralization and reduce nitrous oxide emissions (Zhu et al., 2014), highlighting the importance of considering C:N ratios in fresh organic waste to minimize gas emissions. Overall, different organic waste sources and forms affect soil metabolic functions, with fresh wastes generally increasing nitrification and nitrate reduction, while composted wastes decrease these functions. More advanced methods, like RNA-seq and shotgun metagenomics, are needed for a comprehensive comparison.

5. Conclusions

Our study highlights the effectiveness of integrating organic waste with reduced mineral fertilizer use in enhancing maize growth, soil microbial diversity, and its metabolic functions. Animal-derived wastes enrich soil organic carbon and increase mineral-associated organic matter, contributing to soil fertility. Fresh organic wastes, with their higher soluble nutrient content, boost plant growth, while composted wastes induce fewer changes in microbial community structure. Both types of organic waste improve soil metabolic potential, particularly in genes related to the nitrogen cycle following the use of fresh poultry litter. Different residues offer specific benefits: chicken manure enhances soil organic carbon, sugarcane filter cake promotes bacterial diversity, and composted wastes help reduce denitrification. These findings emphasize the need for further research into the impacts of fresh *versus* composted organic waste on greenhouse gas emissions, such as nitrous oxide and methane, to develop a more sustainable agricultural approach with reduced reliance on mineral fertilizers. Future studies should focus on understanding the differences between fresh and composted organic waste using more accurate methods like RNA-seq and shotgun metagenomics for a deeper understanding of these effects.

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CRediT authorship contribution statement

Guilherme Lucio Martins: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Thierry Alexandre Pellegrinetti:** Writing – review & editing, Validation, Formal analysis. **Anderson Santos de Freitas:** Writing – review & editing, Validation. **Gabriel Silvestre Rocha:** Writing – review & editing, Validation. **Gabriel Gustavo Tavares Nunes Monteiro:** Writing – review & editing, Validation. **Lucas William Mendes:** Writing – review & editing, Validation, Conceptualization. **Siu Mui Tsai:** Writing – review & editing, Validation. **Fernando Carvalho Oliveira:** Writing – review & editing, Resources, Funding acquisition, Conceptualization. **Jussara Borges Regitano:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apsoil.2024.105715.

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