The pH and available phosphorus as primary drivers of compost-induced CO_2 emissions from malaysian tropical soil: empirical relationships

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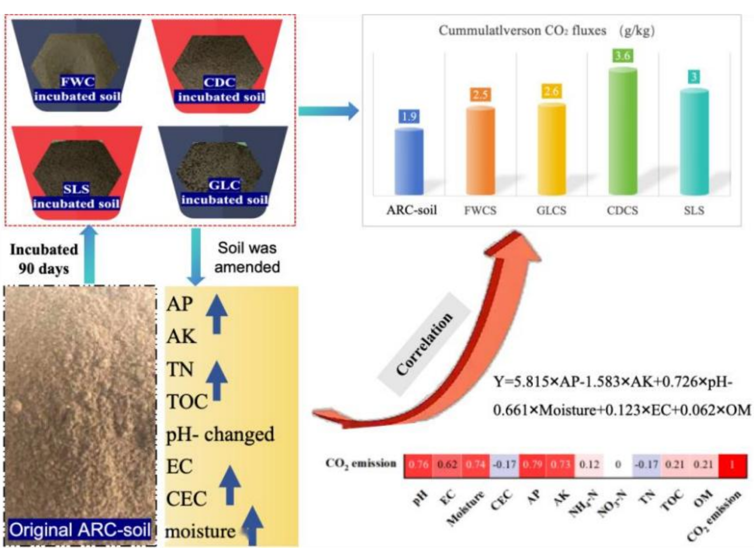
Abstract. Confronting the global need for climate-smart agriculture, this study investigated the major factors controlling CO_2 emissions from a Malaysian tropical soil amended with four composts. The cumulative CO_2 emissions followed the descending order: chicken dung compost (CDCS) > sludge compost (SLS) > goat manure-leaf compost (GLCS) > food waste compost (FWCS). Multiple regression analyses identified soil available phosphorus (AP) and pH as the key interactive drivers of CO_2 emissions.The significantly higher emissions from CDCS were primarily due to its pronounced elevation of soil pH, likely stimulating microbial activity. The positive correlation with AP indicated that enhanced phosphorus availability further promoted microbial carbon mineralization. The findings demonstrate that compost is not a carbon-neutral amendment; its net climate impact depends on the specific physico-chemical changes it induces in the soil. This provides a scientific basis for optimizing compost selection to reconcile soil fertility improvement with greenhouse gas mitigation in tropical agroecosystems.

Graphical abstract



In this experiment, four composts (FWC, GLC, CDC, SL) were applied at 2.5% and 10% rates to typical Malaysian tropical soils and incubated for 90 days. The CO_2 emission characteristics were measured in different soil types. To determine key drivers, the study examined correlations between soil physico-chemical properties and CO_2 emissions and selected the relative important factor.

Keywords: Soil incubation; Carbon dioxide emission; Regression analysis; Nutrient availability; Organic amendment

1 Introduction

Confronting global climate change and the strategic goals of "carbon peak and carbon neutrality" (IPCC, 2022), agricultural soils play a pivotal dual role in the global carbon cycle due to their vast carbon storage capacity and active biogeochemical processes serving as both a crucial organic carbon sink (Bolinder et al., 2020; Shu et al., 2022; Rumpel et al., 2022; Gu et al., 2024) and a potential significant source of CO_2 emissions (Lal, 2004; Paustian et al., 2016). The stability of this massive carbon pool, estimated to exceed the carbon in vegetation and the atmosphere combined, is highly sensitive to land management practices (Amelung et al., 2020; Sanchez-Moreno et al., 2025), with its persistence now understood to be driven by functional complexity beyond mere input quantity (Lehmann et al., 2020). Consequently, strategies that can concurrently enhance soil carbon sequestration and support agricultural productivity are critical for climate-resilient food systems.

In pursuit of sustainable agriculture, organic amendment practices, particularly compost application, have emerged as a cornerstone strategy. Composting transforms organic waste into a stable soil conditioner, closing nutrient loops and reducing reliance on synthetic fertilizers (Bong et al., 2018). Beyond waste management benefits, compost application is widely regarded as a core pathway for enhancing soil fertility by improving nutrient supply, water retention, and aggregate stability, and for actively promoting long-term carbon sequestration (Cotrufo et al., 2013; Oldfield et al., 2019). Recent meta-analyses confirm that organic amendments can significantly increase soil organic carbon (SOC) stocks, with the magnitude of increase dependent on climate, soil type, and application duration (Bai et al., 2023; Huang et al., 2022; Mao et al., 2024). However, integrating this practice into climate-smart frameworks requires a nuanced understanding of its full carbon budget, accounting not only for gains in stable carbon but also for potential losses.

However, this practice entails a fundamental scientific dilemma: while the input of exogenous organic matter enhances the soil's carbon sequestration potential, it may also lead to substantial initial carbon loss by priming microbial metabolism (Bai et al., 2018; Li et al., 2023; Kuzyakov et al., 2000; Bernard et al., 2022). Therefore, precisely quantifying the dynamics of soil CO_2 emissions following compost application and deeply deciphering the underlying biogeochemical drivers have become indispensable scientific foundations for accurately assessing the net climate impact of agricultural management practices (Smith et al., 2020) and formulating truly "climate-smart" land management strategies (Lipper et al., 2014).

It is well established that adding compost to soil typically causes a short-term increase in CO_2 emissions. This occurs because compost introduces readily decomposable organic carbon, which rapidly stimulates microbial metabolism and accelerates carbon turnover (Sarker et al., 2017). Consequently, a large body of research has focused on monitoring CO_2 flux dynamics following compost application and on establishing its empirical relationships with environmental factors such as temperature and moisture. However, a critical limitation persists in the current understanding. There is a lack of systematic investigation into the key factors through which compost alters the soil's internal state to drive these emissions (Bardgett et al., 2021). Specifically, compost input triggers a cascade of changes in key soil properties, including the dynamics of labile carbon pools (Chen et al., 2019; Laffely et al., 2020), nitrogen availability (Liu et al., 2019; Li et al., 2021), pH (Aye et al., 2017; Xiao et al., 2021), and microbial biomass with its stoichiometry (Rosinger et al., 2022; Gurmessa et al., 2024; Razavi et al., 2016). Yet, studies that systematically and quantitatively link these specific physico-chemical changes to CO_2 emission dynamics remain insufficient (Sarkar et al., 2018; Chen et al., 2018). This gap in process-based understanding hinders our ability to accurately predict the net carbon balance of different compost management practices (Niu et al., 2024; Wang et al., 2024a; Tang et al., 2023), as the ultimate outcome depends on complex interactions among these multiple factors (Cho et al., 2023; Yang et al., 2023) and is highly influenced by initial soil conditions (McFarlane et al., 2024; Oldfield et al., 2024). This limitation, in turn, constrains the development of optimized strategies to maximize soil carbon sequestration potential (Xiao et al., 2021).

To address the research gaps identified above, we propose the following hypotheses. First, compost application is known to induce a short term pulse of soil CO_2 emissions. We therefore hypothesize that the magnitude and duration of these emissions will vary significantly among different compost types due to their distinct physico-chemical properties. Second, compost simultaneously alters multiple soil properties, including labile carbon pools, nitrogen availability, pH, etc. We hypothesize that changes in these physico-chemical parameters will collectively drive the dynamics of post compost CO_2 emissions. Third, many tropical soils are acidic and limited in phosphorus. We therefore hypothesize that compost induced increases in pH and available phosphorus may exert particularly strong influences on CO_2 emissions. Multiple regression analysis will be used to quantitatively assess the relative contribution of each factor and to identify the dominant drivers governing variations in CO_2 emissions.

To address the current gaps in process-based understanding and quantitative prediction, this study focuses on a Malaysian typical soil and aims to precisely quantify the soil carbon release process following compost input and to decipher its key driving factors. Through a controlled incubation experiment, this research will systematically achieve the following objectives: (1) to monitor the continuous dynamics of soil CO_2 emissions under different compost treatments; (2) to simultaneously determine changes in key soil physico-chemical parameters (including water-soluble organic carbon, microbial biomass carbon, mineral nitrogen, and pH, among others) post-incubation; and (3) to employ correlation analysis and multiple regression modeling to quantitatively assess the independent influence of each physico-chemical parameter on CO_2 flux and to calculate their relative contribution weights, thereby identifying the core driving factors governing emission variations.

Consequently, by quantifying the relationships between CO_2 emissions and multiple intrinsic soil properties (e.g., labile carbon pools, nitrogen availability) following compost addition and identifying the dominant driving factors, this study provides concrete mechanistic evidence for understanding the carbon cycle response of tropical soils at a regional scale. The research findings can directly inform localized practices for agricultural soil carbon management in Malaysia, offering direct data support and decision-making references for assessing the short-term carbon loss risk associated with compost application and for optimizing application strategies to reconcile the conflict between soil improvement and carbon emissions.

2 Materials and methods

2.1 Soil and compost materials

Using a five-point random sampling strategy, a composite soil sample was collected exclusively from the 10-20 cm subsurface layer (excluding the 0-10 cm topsoil) at the Agricultural Research Center of the Universiti Malaya and named ARC-soil. The 0-10 cm topsoil was intentionally omitted to minimize spatial heterogeneity caused by surface litter, rhizosphere activity, and frequent anthropogenic disturbances (e.g., tillage, weeding), which could otherwise mask the specific effects of compost incorporation. The 10-20 cm layer represents a more homogenized baseline for evaluating the soil physicochemical changes and CO_2 emission patterns investigated in this study. The soil is a highly weathered, acidic ultisol typical of the humid tropics, with low natural fertility, a clayey texture, and a mineralogy dominated by kaolinite and oxides. The sample was air-dried, disaggregated, sieved (< 2 mm), and stored airtight at 3°C until use. The methods for testing soil physico-chemical properties are described in Sect 2.3.

Four types of compost were obtained from the composting facility at the Faculty of Science, Universiti Malaya. They were produced from distinct feedstocks and designated as: FWC, primarily derived from food waste; GLC, produced from a mixture of goat manure and shredded leaves; CDC, originating from chicken dung and amended with sawdust and rice bran as bulking agents; and SL, generated from dewatered food and beverage wastewater sludge. The four composts (FWC, GLC, CDC, and SL) used in this study were purchased from the Faculty of Science, Universiti Malaya. Detailed information on their production processes is not disclosed by the supplier. However, it is known that CDC and SL are commercially available products, and additional phosphorus and potassium were supplemented during their production. The physico-chemical properties of the composts, characterizing their quality and maturity, are summarized in Table 1. These parameters indicate that all four composts were well-stabilized and suitable for the subsequent experiments.

Table 1: Physico-chemical properties of the four composts used in the incubation experiment.

Compost Type	Abbr.	TP (%)	TK (%)	TOC (%)	pH
Food Waste Compost	FWC	0.22	0.076	18.5	6.63
Goat manure-Leaf Compost	GLC	0.42	0.33	24.9	6.12
Chicken Dung Compost	CDC	0.68	0.76	14.5	7.9
Sludge Compost	SLC	1.94	4.43	15.8	6

Note: Abbr., Abbreviation; TP, Total Phosphorus; TK, Total Potassium; TOC, Total Organic Carbon.

2.2 Soil incubation experiment for CO_2 emission monitoring

The experiment involved preparing soil-compost mixtures at two amendment ratios (2.5 % and 10 %, w/w), both adjusted to a total weight of 200 g per incubation unit. The two amendment ratios (2.5 % and 10 %, w/w) were selected based on the following: (1) the 2.5 % ratio corresponds to a typical field application rate of approximately 50 $t \cdot ha^{-1}$, which is commonly used in local agricultural practice; (2) the 10 % ratio was chosen to amplify the treatment effects, allowing for clearer mechanistic observation of compost-induced changes in soil properties and CO_2 emissions under controlled incubation conditions. Each of the four composts was tested at both ratios, creating eight distinct amended mixtures. These, along with a pure soil control (200 g), constituted the nine core treatments, each replicated three times for a total of 27 units. The soils were incubated at a constant temperature of 28 ± 2 °C. The CO_2 efflux was measured on 12 occasions over the 90 d incubation period, specifically on days 1, 5, 7, 14, 28, 40, 47, 52, 60, 70, 80, and 90.

The CO_2 emitted from the soil was trapped in 20 mL of 1 $mol \cdot L^{-1}$ NaOH. After a 24 h accumulation period, $BaCl_2$ was added to precipitate the trapped carbonate as $BaCO_3$. The residual NaOH was then titrated with standardized HCl to quantify the CO_2 evolved. These procedures were performed as described by Cheng et al. (2025).

2.3 Characterization of soil and compost incubated soil

Soil pH and electrical conductivity (EC) were measured in a 1:2.5 soil-water suspension. TOC was determined by wet oxidation. AP was extracted with 0.5 M $NaHCO_3$ and measured spectrophotometrically. Ammonium (NH_4^+-N) and nitrate (NO_3^--N) were extracted with 2 $mol \cdot L^{-1}$ KCl and analyzed by a continuous flow analyzer. Available potassium (AK) was extracted with 1 $mol \cdot L^{-1}$ NH_4OAc and quantified via flame atomic absorption spectroscopy (AAS). Cation exchange capacity (CEC) was determined by the ammonium acetate (NH_4OAc) saturation method at pH 7.0. Quantitative measurements of bulk density were not performed because the visual difference was so pronounced that sample processing for other analyses was prioritized. Nevertheless, the visual observation suggests a qualitative improvement in soil structure following compost addition.

2.4 Statistical analysis

One way analysis of variance (ANOVA) was performed to compare all soil physico-chemical parameters (pH, Moisture, EC, CEC, TOC, TC, OM, NH_4^+-N, NO_3^--N, AP, and AK) among the nine treatments (ARC-soil control, FWCS 2.5 %, FWCS 10 %, GLCS 2.5 %, GLCS 10 %, CDCS 2.5 %, CDCS 10 %, SLS 2.5 %, and SLS 10 %). Prior to ANOVA, the assumptions of normality and homogeneity of variances were verified. Normality was checked using the Shapiro-Wilk test ($p > 0.05$ for all variables), and homogeneity of variances was assessed using Levene's test ($p > 0.05$ for all variables). Tukey's honestly significant difference (HSD) post hoc test was used for multiple comparisons among treatment means. A significance level of $p < 0.05$ was considered statistically significant. All statistical analyses were conducted using SPSS version 26.0 (IBM Corp., Armonk, NY, USA).

A standard multiple linear regression model (Montgomery et al., 2021) was employed to evaluate the effects of soil properties on the response variable, following the general form:

$$Y = \xi_0 + \sum \xi_i K_i + \varepsilon \quad (1)$$

In this formulation, Y is the response variable (cumulative CO_2 emission). Each K_i corresponds to an explanatory or predictor variable included in the model. The parameters ξ_i quantify the partial effect of their respective K_i and Y, holding other variables constant. Finally, ε captures all unexplained variation, commonly known as the model residual.

Prior to model interpretation, the following assumptions were verified: (1) significant correlations between predictors and the response; (2) independent, normally distributed, and homoscedastic residuals. Normality was supported by the histogram and normal P-P plot of standardized residuals (Supplementary Figures S1a and S1b), residual independence was confirmed by the Durbin-Watson statistic (value of 2.597, close to 2; Supplementary Table S1), and homoscedasticity was examined using scatter plots of standardized residuals versus predicted values; and (3) absence of severe multicollinearity among predictors, diagnosed using tolerance and variance inflation factor (VIF), with tolerance < 0.2 or VIF > 10 indicating potential multicollinearity (Supplementary Table S2). To address multicollinearity, ridge regression was performed, and the optimal penalty parameter k was selected based on the ridge trace and the trade-off curve of k versus R^2 (Supplementary Figures S1(c) and S1(d)). Only after satisfying these criteria were the regression outputs deemed reliable.

3 Results

3.1 Changes in soil physico-chemical properties following incubation

The ARC-soil appeared visually compacted, whereas the compost-amended soils exhibited a more aggregated and porous structure (Figure 1).

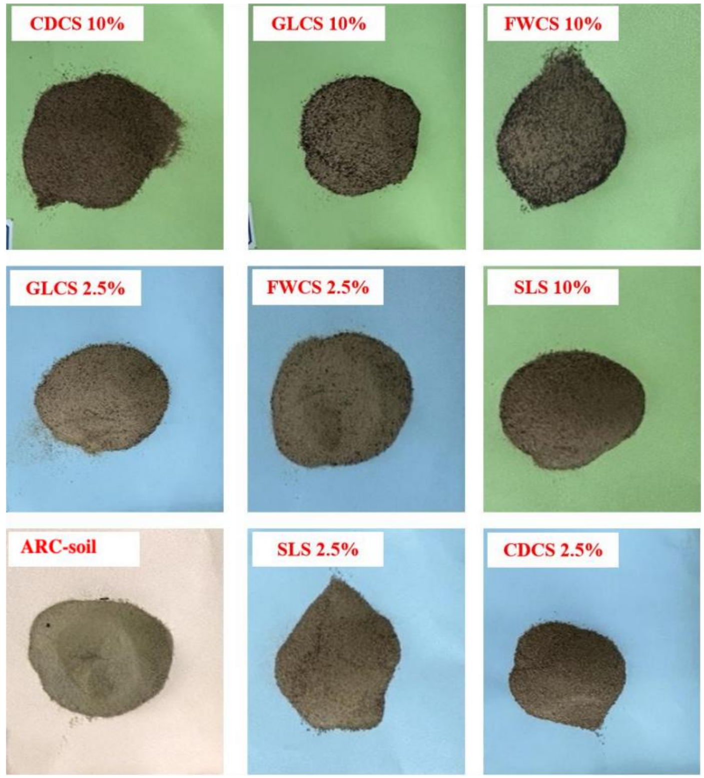


Figure 1: Images illustrating soil appearance after incubation under different compost treatments: food waste compost (FWC), goat manure-leaf compost (GLC), chicken dung compost (CDC), and sewage sludge compost (SL), at application rates of 2.5 % and 10 % by mass.

The detailed ANOVA results and Tukey HSD grouping letters are provided in Table 2. Prior to ANOVA, normality and homogeneity of variances were verified using the Shapiro-Wilk and Levene's tests, respectively (Supplementary Table S4). Most parameters satisfied both assumptions ($p > 0.05$); for the few cases with minor violations. To further ensure reliability, this study additionally performed the non-parametric Kruskal-Wallis H test for AK, EC, and AP, which confirmed the ANOVA results (Supplementary Table S5). One-way ANOVA followed by Tukey's HSD post hoc test ($p < 0.05$) was used to compare treatments. Compared to the unamended control, compost application significantly elevated soil TN content by 1.5 to 16 fold, and all compost-amended soils showed significantly higher TN than the control ($p < 0.05$). Both NH_4^+-N and NO_3^--N levels were also markedly higher in amended soils, with GLCS 10 % exhibiting the highest values among all treatments ($p < 0.05$). Furthermore, increasing the compost addition rate from 2.5 % to 10 % consistently enhanced the concentrations of all three nitrogen forms ($p < 0.05$). Notably, while the levels of NH_4^+-N and NO_3^--N in the original soil were similar (Figure 2a), compost-treated soils exhibited consistently lower NH_4^+-N than NO_3^--N across all application rates, indicating that compost addition promoted the nitrification process in the ARC-soil system.

Table 2: Physico-chemical parameters of soils treated with different compost types and rates, along with ANOVA F-values and post hoc groupings.

Treatment	Moisture	CEC	pH	EC	AP	AK	TOC	TC	OM	NH_4^+-N	NO_3^--N	TN
ARC-soil	f	d	d	g	h	h	e	f	f	d	h	f
FWCS-10%	d	a	d	e	f	f	a	b	b	b	c	b
FWCS-2.5%	ef	c	c	f	g	g	d	e	e	d	e	c
GLCS-10%	c	a	e	d	c	d	a	a	a	a	a	a
GLCS-2.5%	ef	d	c	g	f	f	d	e	e	d	f	e
CDCS-10%	a	c	a	c	b	b	c	d	d	c	d	c
CDCS-2.5%	d	e	b	f	e	e	d	e	e	d	g	e
SLS-10%	b	b	c	a	a	a	b	c	c	b	b	b
SLS-2.5%	de	de	cd	b	d	c	d	e	e	d	e	d
F-value	228.64	438.27	171.52	596.41	792.35	1246.88	356.94	401.22	487.53	132.76	364.19	911.47
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Significance	***	***	***	***	***	***	***	***	***	***	***	***

Table footnote: Table footnote: Different lowercase letters within the same column indicate significant differences among treatments according to one-way ANOVA followed by Tukey's HSD post hoc test ($p < 0.05$). Treatments sharing the same letter are not significantly different. df = degrees of freedom,*df (between groups) = 8, df (within groups) = 18 for all parameters. *** indicates $p < 0.001$.

As shown in Figure 2(b), the ARC-soil had a negligible AP content, while all compost-amended soils exhibited significantly elevated AP levels. However, as the compost addition increased from 2.5 % to 10 %, both AP and AK contents increased significantly. According to Tukey's HSD test, SLS 10 % and SLS 2.5 % showed the highest AP levels with no significant difference between them, while SLS 10 % had the highest AK among all treatments ($p < 0.05$). Notably, the high AP and AK contents in CDCS and SLS were due to additional external additions during composting, whereas FWCS and GLCS did not receive external additions of AP and AK. Figure 2(c) demonstrates that incubation with compost generally increased soil TOC relative to the non-incubated control. Tukey HSD comparisons revealed that FWCS 10 % and GLCS 10% gave significantly higher TOC than the control and all 2.5 % treatments ($p < 0.05$). Among the amendments, soils receiving FWC and GLC exhibited higher TOC levels than those treated with CDC or SL. It should be noted that lower TOC in a given amendment does not directly translate to reduced CO_2 emissions, as the stability of the carbon present also plays a determining role.

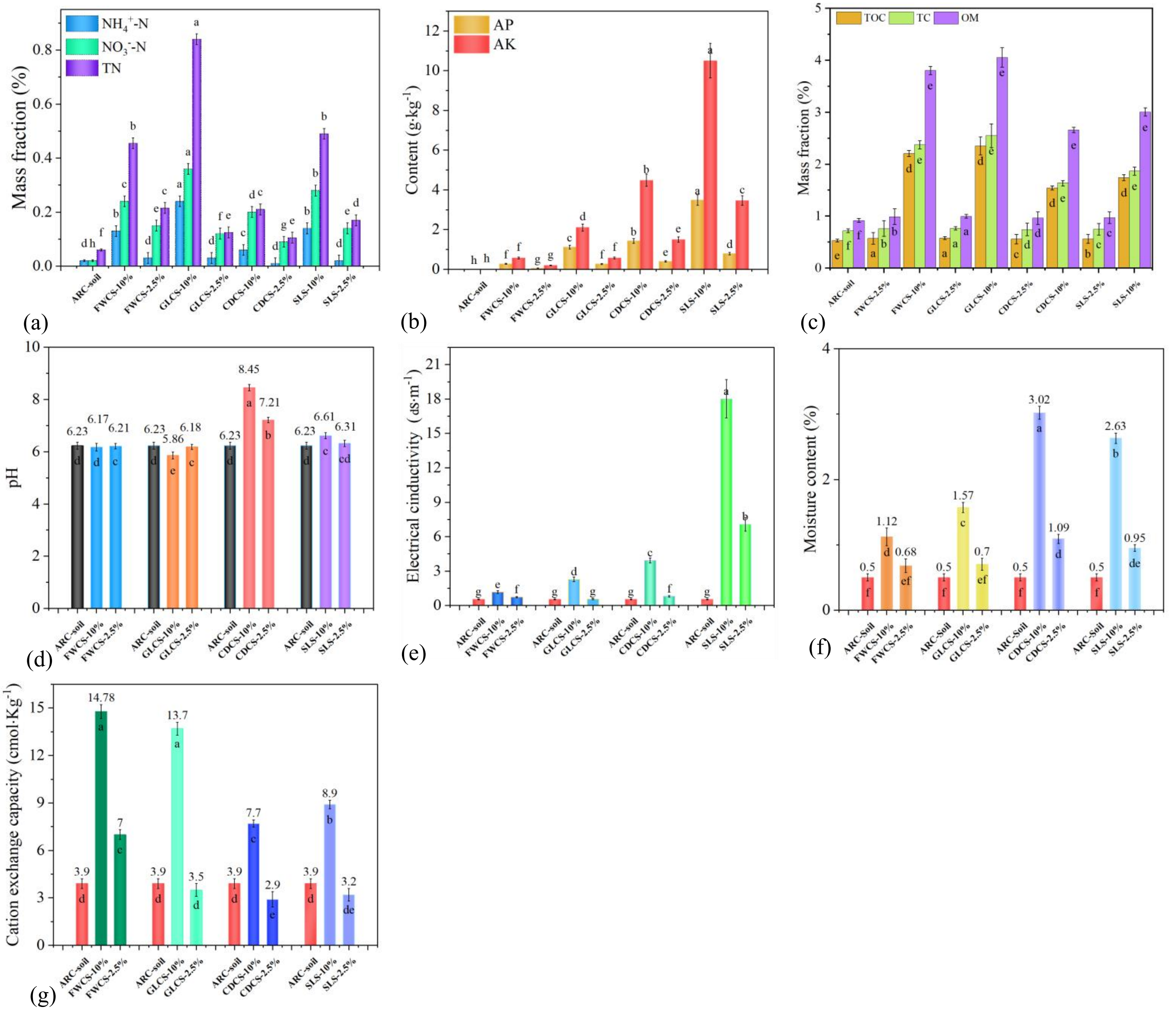


Figure 2: A comparison between the original ARC-soil and compost-incubated soils is shown for: (a) nitrogen species (NH_4^+-N, NO_3^--N, TN); (b) available phosphorus (AP) and available potassium (AK); (c) total organic carbon (TOC); total carbon (TC); organic matter (OM); (d) pH; (e) electrical conductivity (EC); (f) moisture content; and (g) cation exchange capacity (CEC). (Values are means (n = 3); error bars indicate SD. Different lowercase letters above the bars indicate significant differences among treatments according to one-way ANOVA followed by Tukey's HSD post hoc test ($p < 0.05$). Bars sharing the same letter are not significantly different.)

As shown in Figure 2(d), after adding 10 % compost, the pH values of FWCS and GLCS were slightly lower than that of the original ARC-soil, with values of 6.17 and 5.86 (the ARC-soil pH was 6.23), while the pH values of CDCS and SLS significantly increased. As shown in Figure 2(e), after adding 10 % compost, the EC values of FWCS, GLCS, and SLS were approximately 2 to 8 times higher than that of the original soil, while the EC values of SLS 10 % and SLS 2.5 % increased to

18.02 and 7.07 $dS \cdot m^{-1}$, which were approximately 13 to 34 times higher than that of the original ARC-soil, and SLS 10 % was significantly higher than all other treatments ($p < 0.05$). This indicates that the sludge composting from food and beverage wastewater contains a high level of soluble salts.

As shown in Figure 2(f), after adding 10 % compost, the moisture contents of FWCS, GLCS, CDCS, and SLS after 90 d were 1.12 %, 1.57 %, 3.03 %, and 2.63 %, respectively, all of which were higher than that of the original ARC-soil (0.5 %). Moreover, as the compost addition increased from 2.5 % to 10 %, the moisture content of FWCS, GLCS, CDCS, and SLS all increased to varying degrees, with CDCS 10 % being significantly higher than other treatments ($p < 0.05$). During the incubation experiment, the irrigation time and water volume were kept consistent for all samples, indicating that CDCS and SLS exhibited higher water retention compared to FWCS and GLCS.

As shown in Figure 2(g), after adding 10 % compost, the CEC of the soil increased 3-5 times overall, with SLS 10% and CDCS 10% showing significantly higher CEC than FWCS 10% and GLCS 10% ($p < 0.05$). A higher CEC value indicates a stronger ability of the soil to retain fertilizer components, better soil fertility, and the potential to mitigate fluctuations in soil pH and EC. Therefore, the results of this study show that CDCS and SLS had higher soil fertility than FWCS and GLCS. Additionally, CDCS and SLS had better regulation of soil pH and EC fluctuations.

3.2 The dynamics of CO_2 flux from the soil were monitored throughout the incubation period

Throughout the 90 d incubation period, CO_2 emissions from FWCS, GLCS, CDCS, and SLS remained consistently higher than those from ARC-soil, despite some temporal fluctuations during this period (Figure 3(a)). Over time, the CO_2 emissions from FWCS 10% / FWCS 2.5% and GLCS 10% / GLCS 2.5% significantly increased, reaching peak values around day 52 (0.264 / 0.245 and 0.266 / 0.242 $g \cdot (kg\text{-}soil \cdot d)^{-1}$, respectively). The CO_2 emissions declined briefly from day 52 to 60, then stabilized thereafter. As shown in Figure 3(b), with the addition of 10 %, CO_2 emissions from CDCS and SLS also exhibited instability, but remained higher than those of the original ARC-soil. After two weeks, CDCS emissions gradually increased, peaking around day 30, then decreasing over the next 20 days before stabilizing. In contrast, the CO_2 emissions from SLS showed a downward trend after 10 days and stabilized only after day 50. The CO_2 emission trends for CDCS and SLS were consistent across the 2.5 % and 10 % application rates.

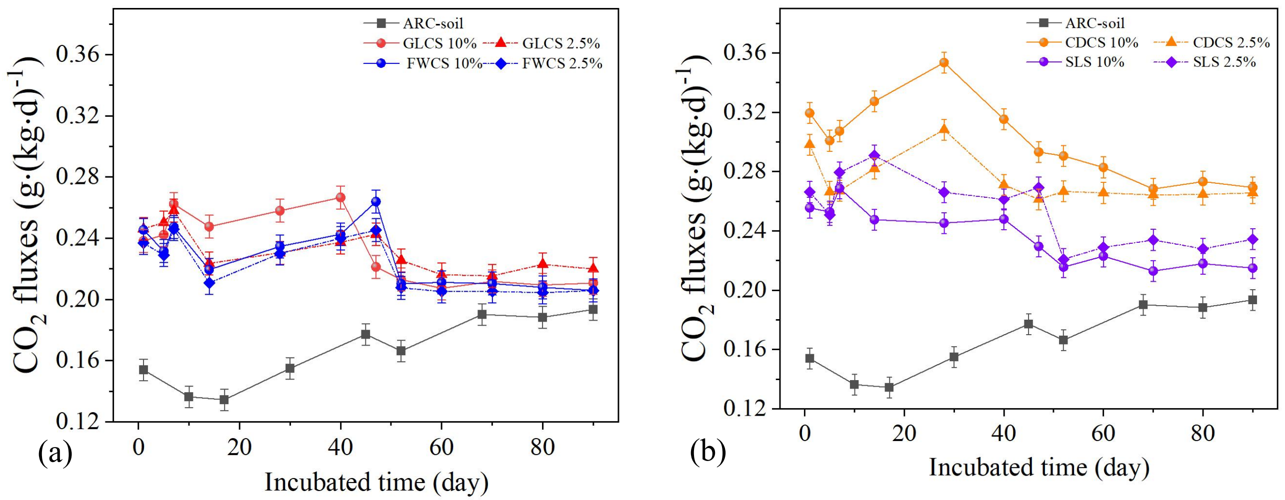


Figure 3: (a) Comparative CO_2 efflux in ARC-soil and food waste compost-amended soil (FWCS) at 10 % and 2.5 %, and goat manure-leaf compost-amended soil (GLCS) at 10 % and 2.5 %; and (b) comparative CO_2 efflux in ARC-soil and chicken dung compost-amended soil (CDCS) at 10 % and 2.5 %, and sewage sludge compost-amended soil (SLS) at 10 % and 2.5 % during the 90 d period.

Figure 4 presents the cumulative CO_2 emissions from soils amended with four distinct compost types (FWC, GLC, CDC, SL) at two application rates for a total of nine treatments. The emission patterns varied considerably depending on the compost type. As illustrated in Figure 4(a), soils treated with GLCS consistently exhibited slightly higher cumulative emissions than those receiving FWCS. Figure 4(b) further demonstrates that CDC produced the highest cumulative emissions throughout the experiment, significantly surpassing the levels observed in soils treated with SL, GLC, and FWC. Overall, the compost types can be ranked in descending order of their effect on cumulative soil CO_2 emissions as follows: CDCS > SLS > GLCS > FWCS.

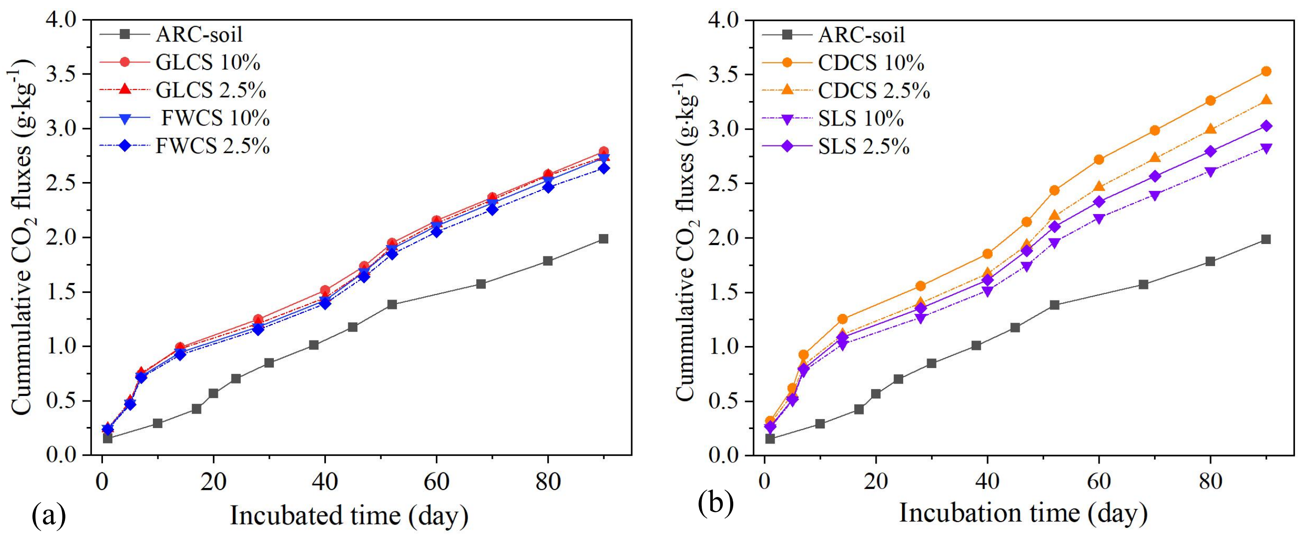


Figure 4: Cumulative CO_2 emission over the 90 d incubation period for: (a) ARC-soil and food waste compost-amended soil (FWCS) at 10 % and 2.5 %, and goat manure-leaf compost-amended soil (GLCS) at 10 % and 2.5 %; (b) ARC-soil and chicken dung compost-amended soil (CDCS) at 10 % and 2.5 %, and sewage sludge compost-amended soil (SLS) at 10 % and 2.5 %.

3.3 Multiple linear regression analysis (MLRA)

Figure 5(a) and (b) present the correlation and significance matrices for twelve soil physico-chemical properties and CO_2 emissions. The analysis reveals that CO_2 efflux is closely linked to several factors, showing strong positive correlations with available phosphorus (0.79), pH (0.76), moisture content (0.74), available potassium (0.73), and electrical conductivity (0.62). Based on the correlation coefficients, the relative influence of these key drivers on CO_2 emissions decreased in the order: AP > pH > moisture content > AK > EC.

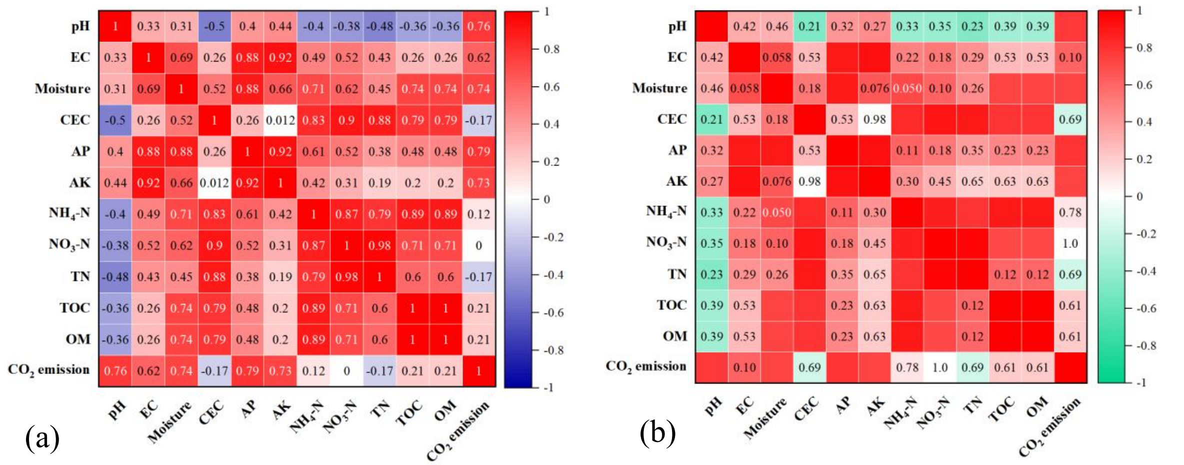


Figure 5: Pearson's correlation matrix of soil physico-chemical properties and their relationships with cumulative CO_2 emission. (a) Correlation coefficients (*R* values), with colors indicating the direction and strength of correlations (blue: positive; red: negative). (b) Statistical significance levels, with darker colors indicating significant correlations at the $p < 0.05$ level and lighter colors indicating non-significant correlations.

Validating the absence of residual autocorrelation is critical for confirming that regression model assumptions hold. The Durbin-Watson statistic, which ranges from 0 to 4, reflects residual independence when near 2. Values deviating toward 0 or 4 imply possible autocorrelation. In this analysis, the obtained statistic of 2.597 (Supplementary Table S1) closely approaches 2, indicating no substantial autocorrelation and thus satisfying the independence assumption.

The histogram of standardized residuals (Supplementary Figure S1(a)) displays a shape consistent with normality, centered near zero with a standard deviation of about 0.5. Correspondingly, the close alignment of points along the reference line in the first quadrant of the normal probability plot (Supplementary Figure S1(b)) also supports the normality of the residual distribution.

Collinearity diagnostics based on tolerance and variance inflation factor (VIF) are summarized in Supplementary Table S2. Conventionally, tolerance < 0.2 or VIF > 10 indicates potential multicollinearity. In this dataset, total carbon (TC), moisture content, available phosphorus (AP), and available potassium (AK) all exhibited tolerance values below 0.2 and VIF values exceeding 10, confirming multicollinearity among these predictors.

Table 3. Coefficients

Model		Variables in the Equation				P	R^2	Adj-R^2
		B	SE (B)	Beta	B/SE (B)			
1	(Constant)	-1.561	0.677	0.000	-2.303			
	pH	0.726	0.115	1.331	0.651			
	EC	0.123	0.189	1.620	0.154			
	Moisture	-0.661	0.140	-1.261	-4.711	0.072	0.975	0.902
	AP	5.815	3.927	1.399	1.481			
	AK	-1.583	2.25	-2.144	-0.702			
	OM	0.0619	0.047	0.332	1.301			
Y=5.815×AP-1.583×AK+0.726×pH-0.661×Moisture+0.123×EC+0.062×OM								

To address this problem, the study used ridge regression analysis. As depicted in Figure S1c, the trajectories of standardized coefficients across increasing values of the ridge parameter (k) show that each coefficient curve descends rapidly before stabilizing, and all curves converge to a common range.. Based on the stabilization patterns in Supplementary Figure S1(c) and the corresponding MSE profile in Supplementary Figure S1(d), a ridge parameter of k = 0.05 was selected. The resulting ridge-regression coefficients are reported in Table 3. The established regression equation is:

$$Y = 5.815 \times AP - 1.583 \times AK + 0.726 \times pH - 0.661 \times Moisture + 0.123 \times EC + 0.062 \times OM$$

In the regression equation, Y represents cumulative CO_2 emission. The regression model's overall validity was confirmed by analysis of variance (ANOVA), which yielded a statistically significant result (*p* < 0.1). The model demonstrated strong explanatory power, as evidenced by an adjusted R^2 value of 0.902, indicating that approximately 90.2% of the variance in the response variable is accounted for by the selected predictors. Within the fitted equation, the estimated coefficient for each independent variable quantifies its individual effect size and direction on the dependent variable.

4 Discussion

4.1 Mechanisms of compost in improving soil properties

The application of compost significantly enhances key soil physico-chemical properties. Firstly, the visual observations of soil structure (Figure 1) indicate that compost amendment alleviated soil compaction in a dose-dependent manner. This effect is likely attributable to the humic substances in the compost, which promote the formation of soil aggregates through adhesion, thereby improving soil porosity and structural stability. Secondly, compost application significantly altered soil nitrogen dynamics, as reflected by the decreased NH_4^+-N and increased NO_3^--N levels in all compost-treated soils (Figure 2(a)), suggesting enhanced nitrification. This is consistent with the findings of Zhang et al. (2015), who reported that the addition of compost to lateritic soils increased the abundance of ammonia-oxidizing bacteria, thereby promoting nitrification.

In this study, the CDCS treatment exhibited the strongest nitrification activity, likely due to its highest pH among the treatments. This aligns with the finding that low pH is detrimental to NH_3 retention in soil, as it promotes the ionization of NH_3 to NH_4^+, potentially creating a substrate shortage for nitrification and thus inhibiting the process (Ying et al., 2010). Furthermore, compost amendment markedly improves the bioavailability of phosphorus and potassium. Phosphorus in compost primarily exists in the form of mineral phosphates, such as calcium phosphate ($Ca_3(PO_4)_2$) and iron phosphate ($FePO_4$). Microbial activity during and after incorporation can solubilize these compounds, converting them into plant-available forms such as $H_2PO_4^-$ and HPO_4^{2-} (Lanno et al., 2021). Potassium in compost remains relatively stable and bioavailable as it exists mainly in ionic form (K^+). During the composting process and subsequent soil incubation, these potassium ions are released into the soil solution, directly increasing the soil's readily AK content. The final levels of AP and AK contributed by compost depend on the initial nutrient content of the raw materials or any losses during the composting process.

4.2 Key drivers of CO_2 emissions: pH and phosphorus as primary controls

The cumulative CO_2 emissions from the four compost-incubated soils followed a distinct descending order: CDCS > SLS > GLCS > FWCS. This pattern demonstrates that the specific type of compost significantly influences the magnitude of soil heterotrophic respiration. Notably, the CDCS treatment, characterized by the highest pH and substantial nutrient availability, also exhibited the greatest CO_2 efflux. This correlation suggests a strong link between compost-induced soil conditions and carbon mineralization rates.

Statistical analysis of influencing factors revealed that soil AP and pH were the primary drivers of CO_2 emissions in this compost-amended system, followed by moisture content and OM. The high adjusted R^2 (0.902) demonstrates that the selected physico-chemical properties are strong predictors of cumulative CO_2 emission, collectively accounting for the vast majority of the observed variance. This confirms that compost-induced changes in these soil properties are closely linked to enhanced microbial activity. This hierarchy underscores the complex interplay between compost-derived nutrients, soil abiotic conditions, and microbial activity in controlling carbon dynamics.

The dominant role of pH stems from its comprehensive control over soil biogeochemistry. It is a master variable regulating microbial community composition and metabolic activity. For instance, bacterial growth rates are typically optimized in neutral to slightly alkaline conditions, and specific microbial taxa dominate at pH extremes (e.g., Actinobacteria in alkaline soils) (Rousk et al., 2009; Fierer and Jackson, 2006). Most extracellular enzymes involved in decomposition also exhibit peak activity between pH 6 and 8. Crucially, pH influences the stability of SOM. Lower pH increases the positive surface charge on iron and aluminium oxides, enhancing their capacity to adsorb negatively charged organic molecules and thereby promoting SOM stabilization (Wang et al., 2024b; Oliver et al., 2019). Conversely, a rise in pH, as seen in CDCS, can accelerate the decomposition of particulate organic matter (Hayashi et al., 2024), explaining the higher CO_2 emissions from this treatment.

Phosphorus availability emerged as another critical factor. In many ecosystems, especially tropical ones, phosphorus is a key limiting nutrient for biological activity (Yang et al., 2014). The addition of compost, which increased soil AP, likely alleviated this limitation. As suggested by Sanchez-Rodríguez et al. (2024), phosphorus addition can indirectly stimulate CO_2 emissions by promoting the desorption of organic carbon compounds from mineral surfaces, thereby increasing substrate availability for microbes. This mechanism may explain the positive correlation between AP and CO_2 flux observed here. Soil moisture content, a secondary yet significant driver, primarily regulates the diffusion of oxygen within soil pores. This, in turn, governs the dominant mode of microbial respiration (aerobic vs. anaerobic) and overall microbial activity, making it a fundamental regulator for the soil biota responsible for decomposition (Lacroix et al., 2021).

In summary, our results supported all three hypotheses proposed in the Introduction. Hypothesis 1 was confirmed by the significant differences in cumulative CO_2 emissions among compost types, with CDCS > SLS > GLCS > FWCS. Hypothesis 2 was validated by the multiple regression analysis, which identified soil pH and available phosphorus as the primary interactive drivers of emissions. Hypothesis 3 was substantiated by the fact that CDCS induced the highest pH elevation and AP increase, leading to the greatest CO_2 flux, whereas FWCS showed the opposite effect.

5 Conclusion

This study examined the effects of adding four types of compost (FWCS, GLCS, CDCS, SLS) at two rates (2.5 % and 10 %) on ARC-soil properties and CO_2 emissions. The main findings are:

(1) Compost addition improved soil physical properties (e.g., reduced compaction, increased moisture retention) and significantly enhanced soil fertility. TN, NH_4^+-N, AP, and AK all increased markedly. Organic carbon increased significantly only under FWCS 10 % and GLCS 10 %. Notably, CDCS and SLS treatments resulted in higher pH, EC, and nutrient availability compared to FWCS and GLCS.

(2) The CO_2 emissions from amended soils were consistently higher than from the control, with distinct temporal patterns. Cumulative emissions over the 90-day incubation followed the order: CDCS > SLS > GLCS > FWCS, indicating that compost type strongly influenced heterotrophic respiration.

(3) Statistical analysis identified AP and soil pH as the primary drivers of CO_2 emissions, followed by moisture content and AK.

(4) The observed CO_2 emission patterns are linked to compost-induced changes in soil conditions. Higher pH likely stimulated microbial activity and organic matter decomposition, while increased AP alleviated phosphorus limitation. Moisture content further modulated microbial respiration dynamics.

These findings advocate for precision compost management. The core strategy is to select or formulate mature composts with near-neutral pH and controlled phosphorus release, guided by soil testing. This approach mitigates carbon loss risks while delivering agronomic benefits, advancing climate-smart agriculture.

We acknowledge that this study was conducted under controlled laboratory incubation conditions, which may not fully capture the complexity of field environments (e.g., temperature fluctuations, plant root activity, and longer-term carbon dynamics). Future field-scale studies with multi-year monitoring are needed to validate these findings under real agricultural conditions.

Code and data availability

The datasets and analysis code supporting this study are publicly available in the Zenodo repository: https://zenodo.org/record/20454193 (DOI: 10.5281/zenodo.20454193)

Author contributions

XC conceived and designed the study, developed the methodology, performed the formal analysis and data curation, conducted the validation, and wrote the original draft. OF and AR contributed to the investigation and reviewed and edited the manuscript. OCC acquired funding, supervised the project, contributed to the methodology and formal analysis, and reviewed and edited the manuscript. The final manuscript was prepared with contributions from all co-authors.

Competing interests

The authors declare the following financial interests/personal relationships, which may be considered as potential competing interests: Chiu Chuen, Onn reports financial support was provided by Malaysia Ministry of Higher Education. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Review statement

The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees according to their status anonymous or identified.

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