# The pH and ~~Phosphorus~~ Available~~Availability~~ Phosphorus as Primary Drivers of Compost-Induced $CO_2$ Emissions from Malaysian Tropical Soil: Empirical Relationships~~Mechanistic Evidence~~

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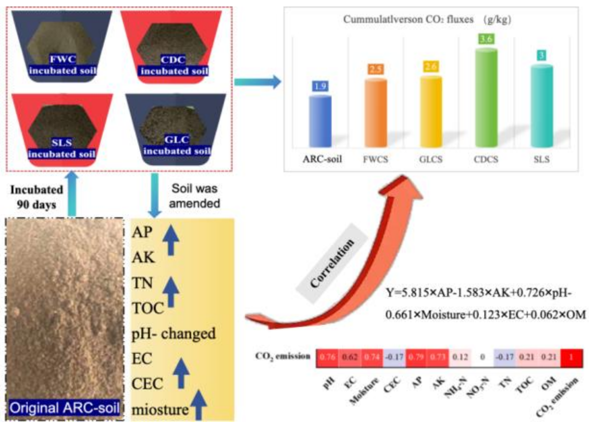
**Abstract.** Confronting the global need for climate-smart agriculture, this study investigated the major factors~~mechanisms~~ controlling $CO_2$ emissions from a Malaysian tropical soil amended with four composts. Multiple regression analyses identified soil available phosphorus (AP) and pH as the key interactive drivers of $CO_2$ emissions, in the following order:~~which followed the order~~: chicken dung compost (CDCS) > sludge compost (SLS) > goat manure-leaf compost (GLCS) > food waste compost (FWCS).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 physic-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 rainforest 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 physic-chemical properties and $CO_2$ emissions and evaluatedselected the relative importantimpact of weighting of each factor's impact.

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**Keywords:** Soil; Compost; $CO_2$ emission; Available phosphoru; pHs

## 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., 2024Bolinder et al., 2020; Chen et al., 2023; Fuchs et al., 2022; Jiang 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; Sánchez-Moreno et al., 2025Luo et al., 2022), with its persistence now understood to be driven by functional complexity beyond mere input quantity (Lehmann et al., 20210). Consequently, strategies that can concurrently enhance soil carbon sequestration (SOC) and support agricultural productivity are critical for climate-resilientclimate 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., 202318). 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 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., 2024He et al., 2023; Li et al., 2022; Shi et al., 2022). However, integratingthe integration of this practice into climate-smart frameworks requires a nuanced understanding of its  full complete 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., 2022Gao et al., 2023; Kuzyakov et al., 2000; Wang et al., 2023). 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., 2024).

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., 20172017). Consequently, a large body of research has focused on monitoring $CO_2$ flux dynamics the dynamics of $CO_2$ flux following compost application and on establishing 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 factorsmechanisms 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., 202219; Laffely et al., 2020Zhang et al., 2023), nitrogen availability (Liu et al., 2019; Li et al., 2021Feng et al., 2024; Li et al., 2022), pH (Aye et al., 2017; Xiao et al., 2021Guo et al., 2022; Zhang et al., 2024), and microbial biomass with its stoichiometry (Rosinger et al., 20232; Gurmessa et al., 2024; Razavi et al., 2016Liu et al., 2024; Razavi et al., 2021). Yet, studies that systematically and quantitatively link these specific physic-chemical changes to $CO_2$ emission dynamics remain insufficient (Sarkar et al., 2018; Chen et al., 2018Singh et al., 2023; Chen et al., 2024). This gap in process-basedmechanistic 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., 2023Du et al., 2023; Wang et al., 2024; Sun et al., 2024), as the ultimate outcome depends on complex interactions among these multiple factors (Cho et al., 2024; Yang et al., 2023; Ma et al., 2023Cavalli et al., 2023; Fang et al., 2023; Ma et al., 2023) and is highly influenced by initial soil conditions (McFarlane et al., 2024; Oldfield et al., 2024Ding et al., 2022; Oldfield et al., 2022). This limitation, in turn, constrains the development of optimized strategies to maximize soil carbon sequestration potential (Xiao et al., 2021Huang et al., 2023).

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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 physicochemical properties. Second, compost simultaneously alters multiple soil properties, including labile carbon pools, nitrogen availability, pH, etc. We hypothesize that changes in these physicochemical 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.

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To address the current gaps in process-based~~mechanistic~~ understanding and quantitative prediction, this study focuses on a Malaysian typical soil and aims~~,~~ ~~aiming~~ to precisely quantify the soil carbon release process following compost input and to decipher its key driving ~~mechanisms~~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 physic-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 physic-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 (10-20 cm depth) was collected from an Agricultural Research Center of the University of Malaya and named ARC-soil. 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 physic-chemical properties are described in Supporting Information **Text 1.**

Four types of compost were obtained from the composting facility at the Faculty of Science, University of 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, University of 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. To characterize the compost quality and maturity, the following physicochemical properties were determined: Total phosphorus (TP) (0.22%, 0.42%, 0.68%, and 1.94%, respectively), total potassium (TK) (0.076%, 0.33%, 0.76%, and 4.43%), TOC (18.5%, 24.9%, 14.5%, and 15.8%), and pH (6.63, 6.12, 7.90, and 6.0). These parameters indicate that all four composts were well-stabilized and suitable for the subsequent experiments.

### 2.2 Soil Incubation Experiment for $CO_2$ Emission Monitoring

The experiment involved preparing soil-compost mixtures at two amendment ratios (1:9 and 1:39, compost-to-soil 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/ha, 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 ~~side~~with a pure soil control (200 g), constituted the nine core treatments, each replicated three times for a total of 33 units. The soils were incubated at a constant temperature of 28 ± 2 °C. $CO_2$ efflux was measured on 14 occasions over the 90 day incubation period, specifically on days 1, 5, 7, 14, 28, 40, 47, 52, 60, 70, 80, and 90.

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$CO_2$ efflux monitoring followed a pre-determined schedule of 14 samplings spanning 90 days. The measurement protocol required the temporary placement of a $CO_2$ trap (20 mL of 1 mol/L~~M~~ NaOH in an open container) ~~inside~~in each vessel one day before a scheduled sampling. Following a 24-h accumulation period, the trap solution was removed, and its carbonate content was determined via back-titration to quantify the $CO_2$-C produced during that interval. The $CO_2$ emissions from soil were captured ~~using~~with NaOH and subsequently quantified ~~via~~by back-titration. This established method involved precipitating the trapped $CO_2$ as barium carbonate ~~prior to~~before titration with standardized acid, enabling the calculation of $CO_2$-C evolution, and was performed as described by~~according to~~ Cheng et al. (2025).

## 2.3 Characterization of Soil and Compost Incubated Soil

~~Baseline soil properties were analyzed.~~ Soil pH and electrical conductivity (EC) were measured in a 1:2.5 soil-to-water suspension. Total organic carbon (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 2mol/L KCl and analyzed by a continuous flow analyzer. Available potassium (AK) was extracted with 1 M $NH_4OAc$ 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.

## 2.~~3~~4 Statistical Analysis

One way analysis of variance (ANOVA) was performed to compare all soil physicochemical parameters (pH, Moisture, EC, CEC, TOC, TC, OM, $NH_4^+$-N, $NO_3^-$-N, TN, 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%). Tukey's honestly significant difference (HSD) post hoc test was used for multiple comparisons. Homogeneity of variances was assessed using Levene"s test. A significance level of $p < 0.05$ was considered statistically significant. All statistical analyses were conducted using SPSS version 26.0 .

~~Statistical analyses were conducted using SPSS 18.0.~~ 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:

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

In this formulation, Y corresponds to the response or outcome variable. Each $K_i$ corresponds to~~symbolizes~~ an explanatory or predictor variable included in the model. The parameters $\xi_i$ 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.

Coefficients were estimated via ordinary least squares, which minimizes the sum of squared residuals. Model diagnostics ensured: (1) significant correlations between predictors and the response, (2) independent, normally distributed and

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homoscedastic residuals, and (3) absence of severe multicollinearity among predictors. Only after satisfying these criteria were the regression outputs deemed reliable.

## 3 Results

### 3.1 Changes in Soil Physic-chemical Properties Following Incubation

Figure 1 presents physical photographs of soils incubated for 90 days with different compost types and application rates. The original ARC-soil ~~exhibited markedly~~ appeared visually more aggregated than the compost-treated soils (Figure 1). ~~more severe compaction compared to all compost-treated soils~~. This observation clearly indicates that compost amendment alleviates soil compaction, with the mitigation effect becoming more pronounced as the compost application rate increases.

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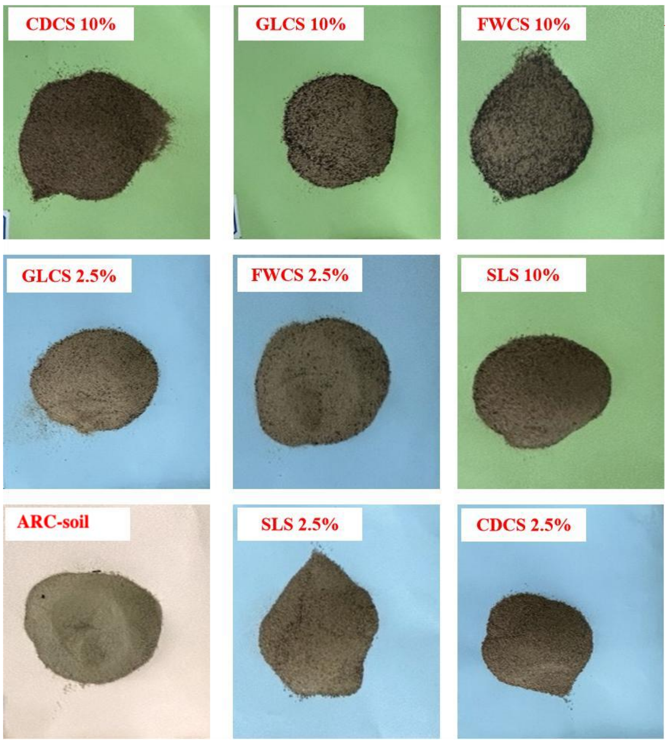
CDCS 10%
GLCS 10%
FWCS 10%
GLCS 2.5%
FWCS 2.5%
SLS 10%
ARC-soil
SLS 2.5%
CDCS 2.5%

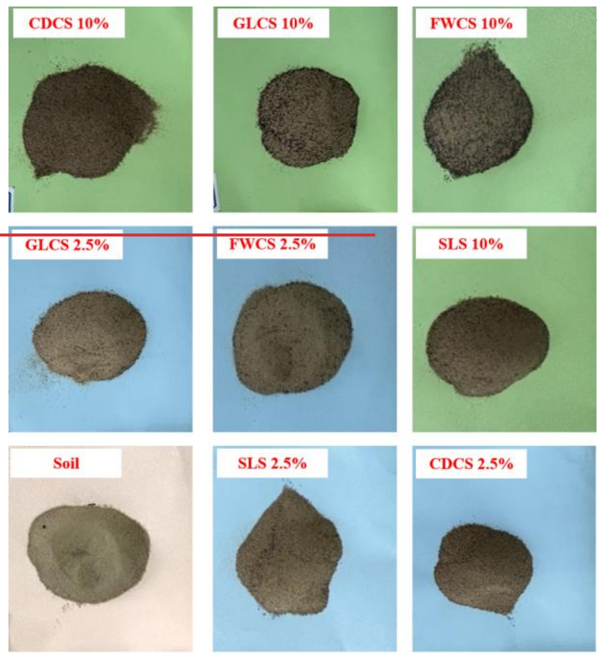


**Figure 1: Images illustrating soil appearance after incubation under different compost treatments (types: FWC, GLC, CDC, SL; application rates: 2.5% and 10% by mass).** (Quantitative measurements of bulk density were not performed because the visual difference was so pronounced that sample processing for other analyses was prioritized. Nevertheless, the visual observation suggests a qualitative improvement in soil structure following compost addition)

The detailed ANOVA results and Tukey HSD grouping letters are provided in Supporting Information Tables S~~1~~4 and S~~2~~5. 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, and for each compost type, the 10% addition gave significantly higher values than the 2.5% addition ($p < 0.05$). Notably, while the original soil showed no significant difference between $NH_4^+$-N and $NO_3^-$-N, 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. As shown in Figure 2(b), the ARC-soil had an AP content below the instrument's detection limit. 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,

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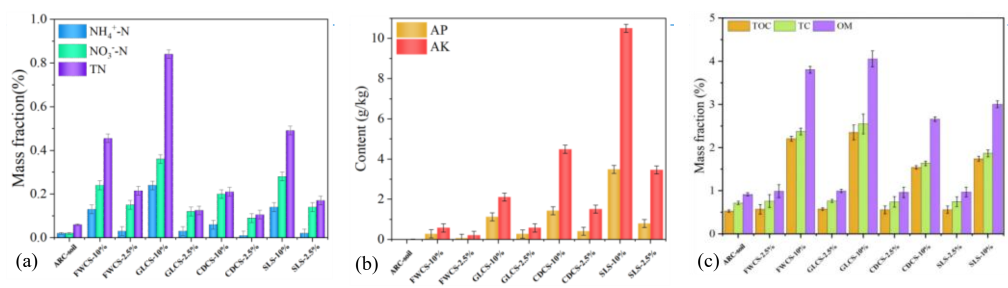

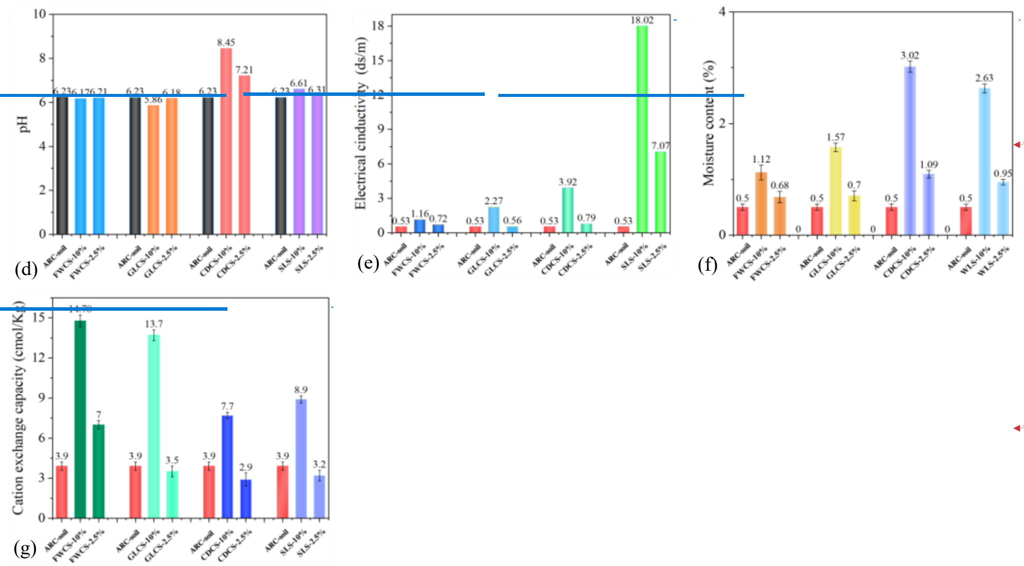


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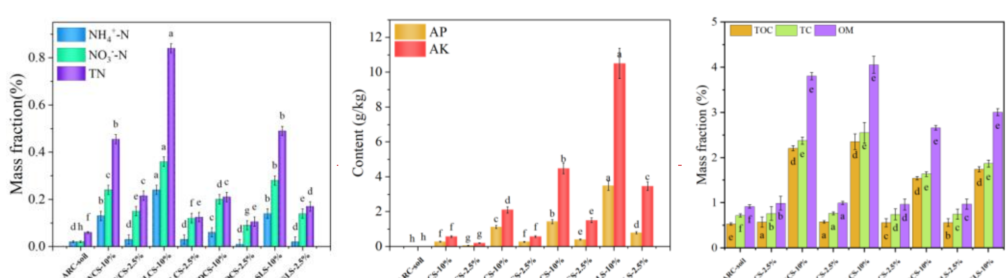


(a) (b) (c)

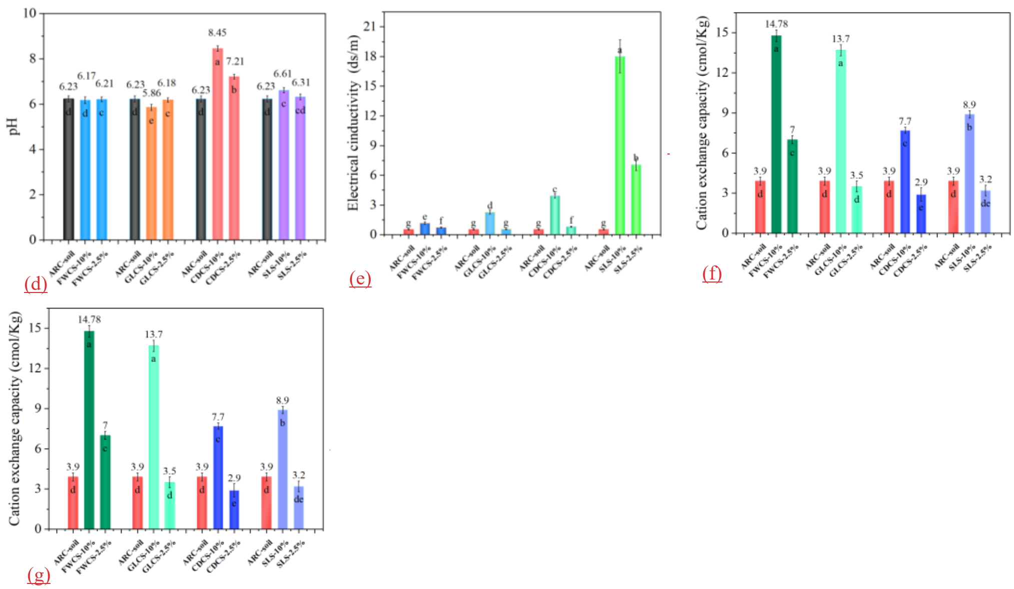


**Figure 2: A comparison between the original ARC-soil and compost-incubated soils is shown for: (a) nitrogen species ($NH_4^+$-N, $NO_3^-$-N,, TN); (b) ~~available phosphorus (~~AP~~)~~ and ~~potassium (~~AK~~)~~; (c) carbon and organic matter (TOC, TC, OM); (d) pH; (e) electrical conductivity (EC); (f) moisture content; and (g) cation exchange capacity (CEC).** Data are presented as mean ± SD (n = 3). 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~~01), while the pH values of CDCS and SLS significantly increased. ~~In particular, the pH values of CDCS-10% and CDCS-2.5% increased to 8.45 and 7.21, respectively.~~ As shown in Figure 2(e), after adding 10% compost, the EC values of FWCS, GLCS, and SLS were approximately 2-8 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, which were approximately 34-13 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.

~~ARC-Soil. 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 days 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%).

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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, irrigation time and water volume were kept constant with all samples, indicating that CDCS and SLS exhibited higher water retention than FWCS and GLCS. ~~–~~ 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 ~~electrical~~ EC. Therefore, the results of this study show that CDCS and SLS ~~exhibited~~had higher soil fertility ~~compared to~~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 first two weeks of incubation, $CO_2$ emissions from FWCS, GLCS, CDCS, and SLS remained consistently higher than -those from ~~the~~ ARC-soil, despite ~~showing~~ some instability during this period (Figure 3a). 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/(kg-soil·d), respectively). $CO_2$ emissions declined briefly from days 52 to 60, then stabilised thereafter.~~exhibited a brief decline from days 52 to 60, before stabilizing 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 soil. ~~the $CO_2$ emissions from CDCS and SLS also exhibited instability, but were always higher than that of the original 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 ~~only~~ stabilized only after day 50. $CO_2$ emission trends for CDCS and SLS were consistent across the ~~showed consistency between the~~ 2.5% and 10% application rates.

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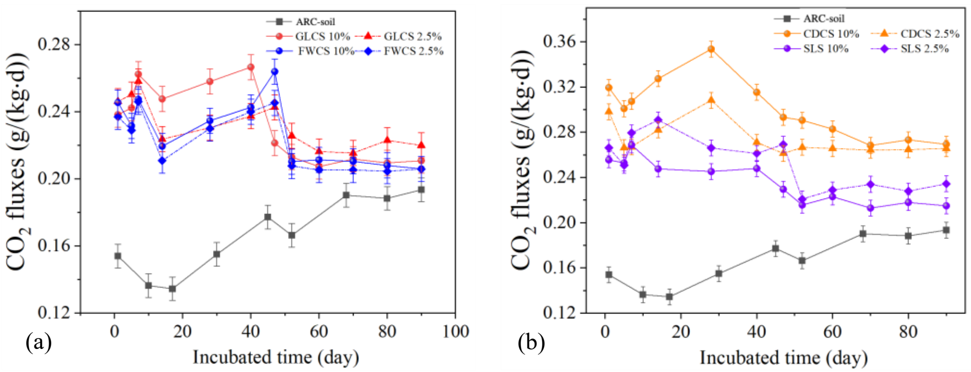
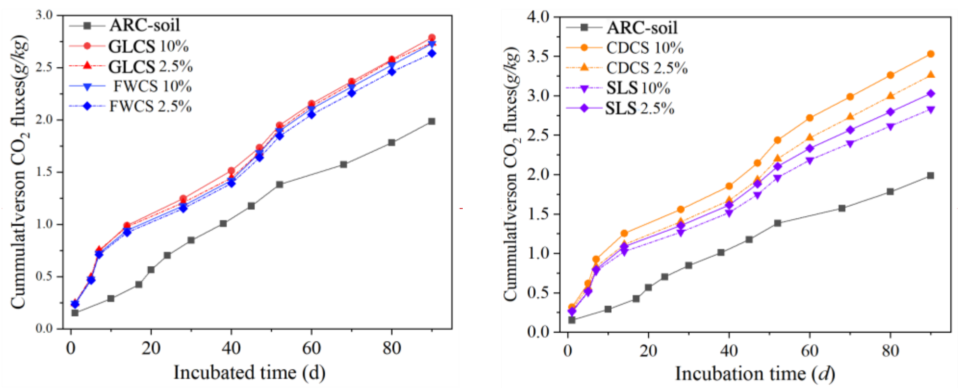



**Figure 3: (a) Comparative $CO_2$ efflux in ARC-soil and FWCS (10%), FWCS 2.5% GLCS 10% and GLCS 2.5%; and (b) for ARC-soil, CDCS 10%, CDCS 2.5%; SLS 10% and SLS 2.5% during the 90-day period.**

Figure 4 presents the cumulative $CO_2$ emissions from soils amended with four distinct compost types (FWCS, GLCS, CDCS, SLS) at two application rates, encompassing a totaltotalling 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-amended soils 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.



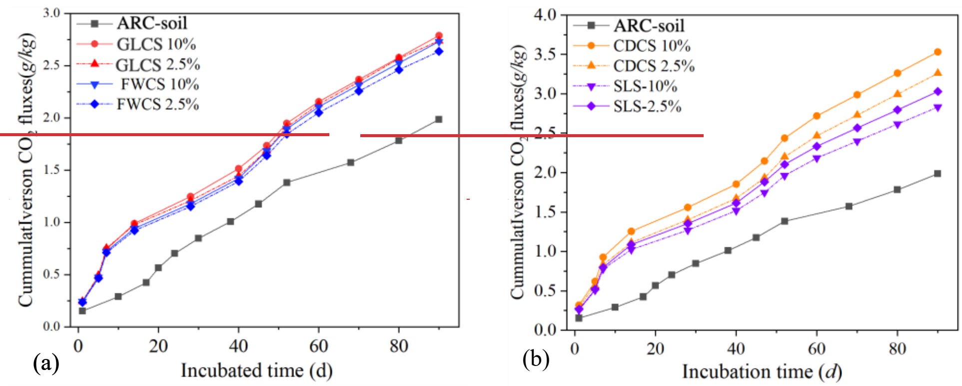



**Figure 4: (a) Cumulative $CO_2$ emission of ARC-soil, FWCS 10%, FWCS 2.5%, GLCS 10% and GLCS 2.5%; (b) for ARC-soil, CDCS 10%, CDCS 2.5%; SLS 10% and SLS 2.5% throughout the 90-d incubation period.**

### 3.3 Multiple Linear Regression Analysis (MLRA)

Figure 5a 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 was 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 magnitude of correlation coefficients, the relative influence of these key drivers on $CO_2$ emissions decreased in the order: AP > pH > moisture content > AK > EC.

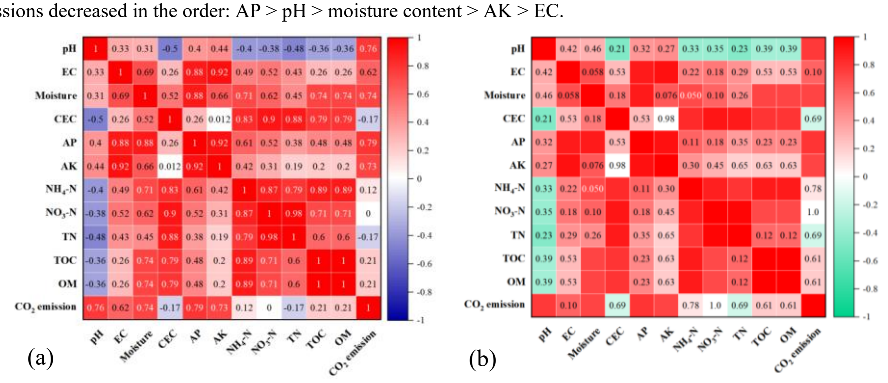



**Figure 5: Analysis of key drivers of $CO_2$ emission: (a) inter-variable correlations and (b) their statistical significance ($P < 0.05$) for compost-incubated soil.**

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 1.851 (Table S1) closely approaches 2, indicating no substantial autocorrelation and thus satisfying the independence assumption.

The histogram of standardized residuals (Figure 6a) displays a shape consistent with normality, centered near zero with a standard deviation of about 0.5. Correspondingly, Tthe close alignment of points along the reference line in the first quadrant of the normal probability plot (Figure 6b) also supports the normality of the residual distribution.

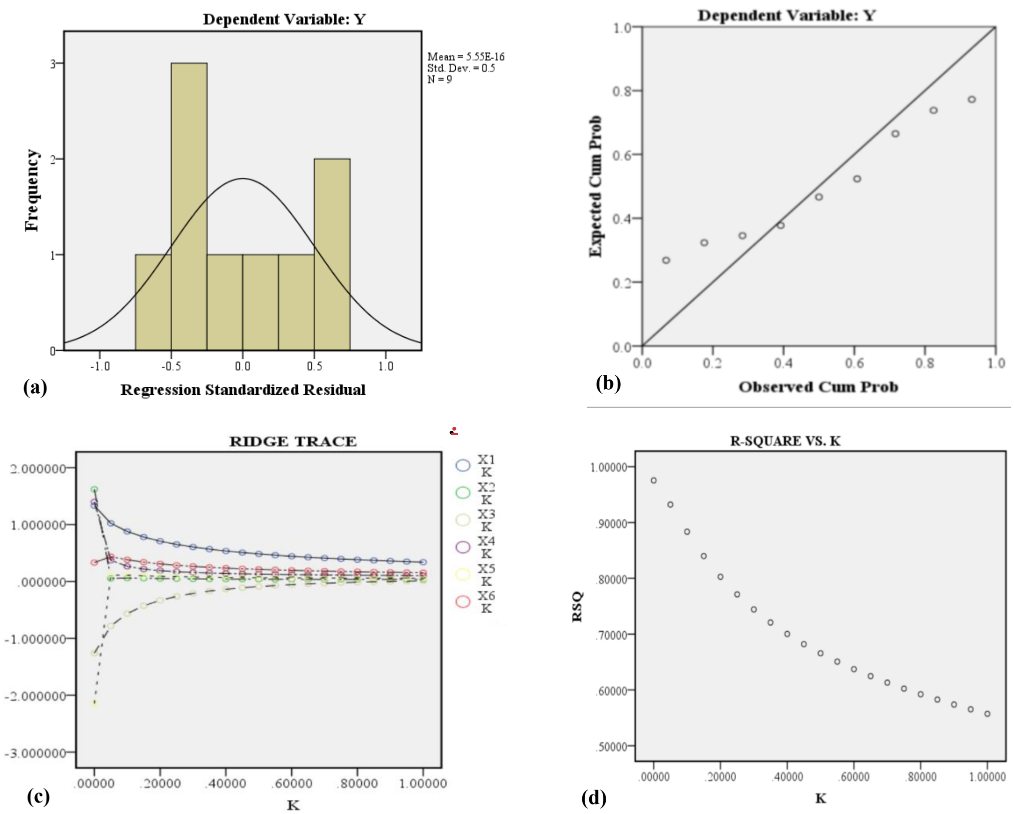



**Figure 6: (a) Distribution Histogram; (b) P-P Plot for Normality Check; (c) Ridge Regression Trace; (d) Trade-off Curve: k vs. R².**

Collinearity diagnostics based on tolerance and variance inflation factor (VIF) are summarized in Table S3. 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.

In response toTo addressed this problem, the study implementedused ridge regression analysis. As depicted in Figure 6c, which illustrates the trajectories of standardized coefficients across increasing values of the ridge parameter (k). Each coefficient curve descends rapidly before stabilizing, withand all curves converge toconverging toward a common range. Based on the stabilization patterns in Figure 6c and the corresponding MSE profile in Figure 6c, a ridge parameter of k = 0.05 was selected. The resulting ridge-regression coefficients are reported in Table 1.

**Table 1.** 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 addressed this problem, the study used ridge regression analysis. As depicted in Figure 6c, which illustrates the trajectories of standardized coefficients across increasing values of the ridge parameter (k). Each coefficient curve descends rapidly before stabilizing, and all curves converge to a common range. Based on the stabilization patterns in Figure 6c and the corresponding MSE profile in Figure 6c, a ridge parameter of k = 0.05 was selected. The resulting ridge-regression coefficients are reported in Table 1. Therefore, tThe established regression equation is:

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

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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 ~~capacity~~power, as evidenced by an adjusted $R^2$ value of 0.902, ~~implying~~indicating that approximately 90.2% of the variance in the response variable ~~can be~~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 physic-chemical properties. Firstly, it stimulates microbial processes related to nitrogen cycling. As reported by Zhang et al. (2015), the addition of compost to lateritic soils increased the abundance of ammonia-oxidising bacteria, thereby promoting nitrification.~~led to a significant increase in the abundance of ammonia-oxidising bacteria, thereby promoting the nitrification process.~~ In this study, the CDCS treatment exhibited the strongest nitrification activity, likely due~~which can be attributed~~ 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 ~~like~~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~~mainly exists~~ 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 ~~and~~ on any losses during the composting process.

### 4.2 Key Drivers of $CO_2$ Emissions: pH and Phosphorus as Primary Controls

### ~~4.2 Mechanistic Drivers of $CO_2$ emissions: pH and Phosphorus as Key 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.

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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 organic matter (OM). 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~~can be attributed to~~ 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 et al., 2006). Most extracellular enzymes involved in decomposition also exhibit peak activity between pH 6 and 8. Crucially, pH influences the stability of soil organic matter (SOM).~~Crucially, pH influences soil organic matter (SOM) stability~~. Lower pH increases the positive surface charge on iron and aluminium~~aluminum~~ oxides, enhancing their capacity to adsorb negatively charged organic molecules and ~~thus~~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 Antonio 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).

## 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. Total nitrogen, ammonium, nitrate, available phosphorus, and available potassium all increased markedly. Organic carbon increased significantly only under FWCS-10% and GLCS-10%. Notably, CDCS and SLS treatments resulted in higher pH, electrical conductivity (EC), and nutrient availability compared to FWCS and GLCS.

~~(2) Compost addition improved soil physical properties (e.g., reduced compaction, increased moisture retention) and significantly enhanced soil fertility. Total nitrogen, ammonium, nitrate, available phosphorus, available potassium, and organic carbon all increased markedly. Notably, CDCS and SLS treatments resulted in higher pH, electrical conductivity (EC), and nutrient availability compared to FWCS and GLCS.~~

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(2) $CO_2$ 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 available phosphorus (AP) and soil pH as the primary drivers of $CO_2$ emissions, followed by moisture content and available potassium (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.

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**Code and data availability**

The code and data are available from the corresponding author upon reasonable request.

**Author contributions**

Xingxing Cheng conceived and designed the study, developed the methodology, performed the formal analysis and data curation, conducted the validation, and wrote the original draft. Faridah Othman and Rosazlin Abdullah contributed to the investigation and reviewed and edited the manuscript. Chiu Chuen Onn 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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