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The pH and Phosphorus Availability as Primary Drivers of Compost-Induced CO_2 Emissions from Malaysian Tropical Soil: Mechanistic Evidence

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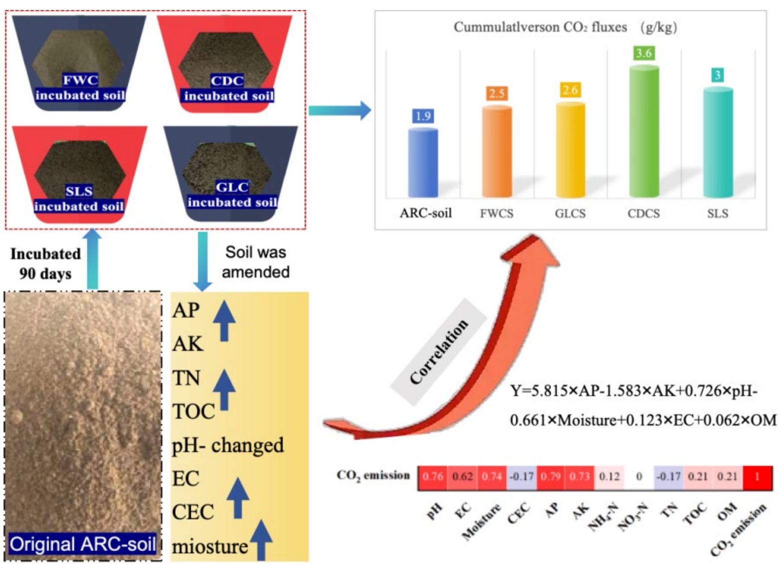
Abstract. Confronting the global need for climate-smart agriculture, this study investigated the mechanisms controlling CO_2 emissions from a Malaysian tropical soil amended with four composts. Multiple regression analyses identified soil available phosphorus (AP) and pH as the key interactive drivers of CO_2 emissions, 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



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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 evaluated the weighting of each factor's impact.

Keywords: Soil; Compost; CO_2 emission; Available phosphorus

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; 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; Luo et al., 2022), with its persistence now understood to be driven by functional complexity beyond mere input quantity (Lehmann et al., 2021). Consequently, strategies that can concurrently enhance soil carbon sequestration (SOC) 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., 2023). 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 (He et al., 2023; Li et al., 2022; Shi et al., 2022). However, the integration of this practice into climate-smart frameworks requires a nuanced understanding of its 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; Gao et al., 2023; Kuzyakov et al., 2000; Wang et al., 2023). Therefore, precisely quantifying the dynamics of soil CO2 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).

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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., 2023). Consequently, a large body of research has focused on monitoring the dynamics of CO_2 flux following compost application and 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 mechanisms 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., 2022; Zhang et al., 2023), nitrogen availability (Feng et al., 2024; Li et al., 2022), pH (Guo et al., 2022; Zhang et al., 2024), and microbial biomass with its stoichiometry (Rosinger et al., 2023; Liu 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 (Singh et al., 2023; Chen et al., 2024). This gap in mechanistic understanding hinders our ability to accurately predict the net carbon balance of different compost management practices (Du et al., 2023; Wang et al., 2024; Sun et al., 2024), as the ultimate outcome depends on complex interactions among these multiple factors (Cavalli et al., 2023; Fang et al., 2023; Ma et al., 2023) and is highly influenced by initial soil conditions (Ding et al., 2022; Oldfield et al., 2022). This limitation, in turn, constrains the development of optimized strategies to maximize soil carbon sequestration potential (Huang et al., 2023).

To address the current gaps in mechanistic understanding and quantitative prediction, this study focuses on a Malaysian typical soil, aiming to precisely quantify the soil carbon release process following compost input and to decipher its key driving mechanisms. 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.

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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.

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. Each of the four composts was tested at both ratios, creating eight distinct amended mixtures. These, alongside a pure soil control (200 g), constituted the nine core treatments, each replicated three times for a total of 33 units.

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 M NaOH in an open container) inside 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 NaOH and subsequently quantified via back-titration. This established method involved precipitating the trapped CO_2 as barium carbonate prior to titration with standardized acid, enabling the calculation of CO_2-C evolution, and was performed according to Cheng et al. (2025).

2.3 Statistical Analysis

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:

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

In this formulation, Y corresponds to the response or outcome variable. Each K_i symbolizes 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.

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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 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 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.

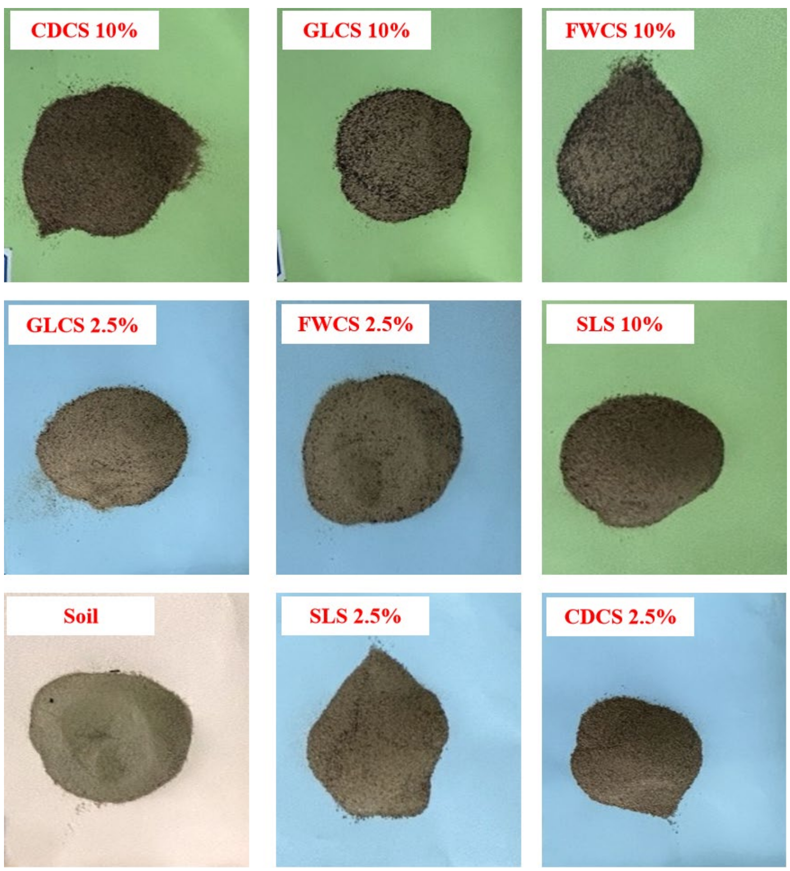

Figure 1: Images illustrating soil appearance after incubation under different compost treatments (types: FWC, GLC, CDC, SL; application rates: 2.5% and 10% by mass).

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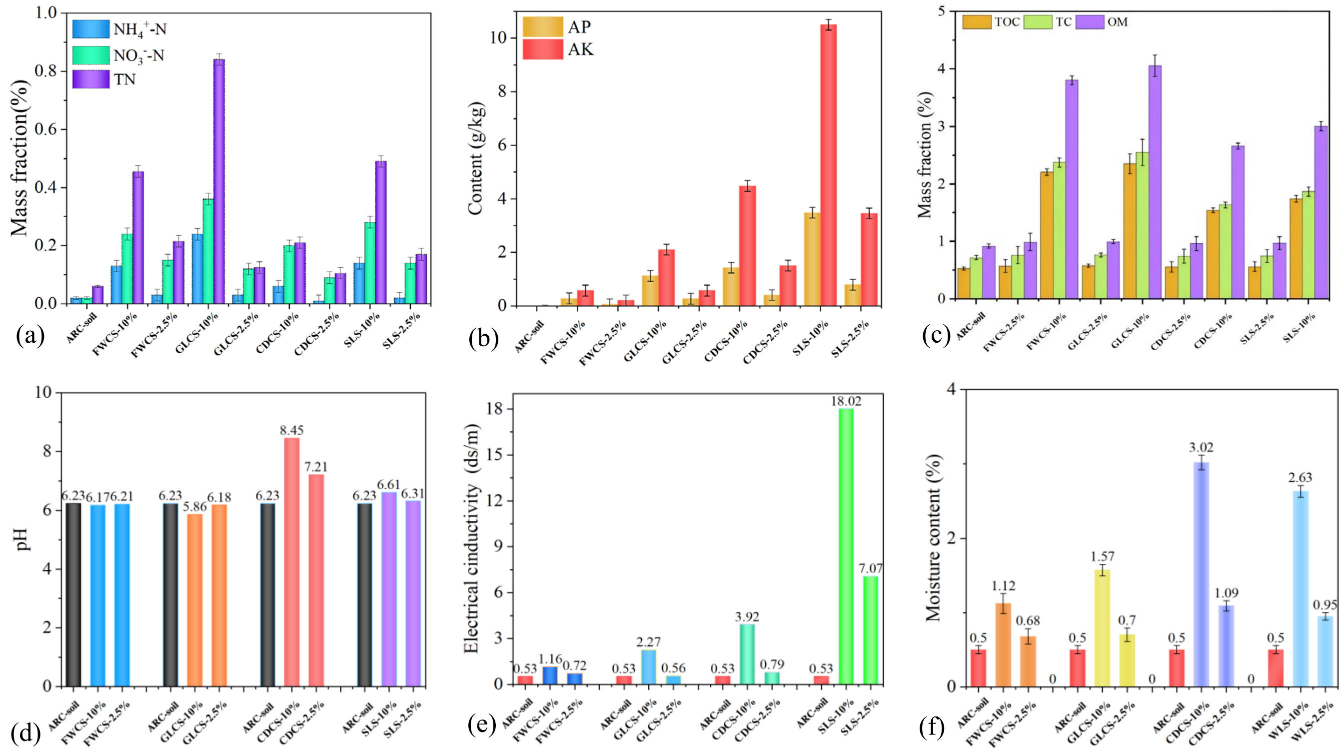
Concentrations of key nitrogen forms (NH_4^+-N, NO_3^--N, and TN) in both untreated ARC-soil and compost-amended soils following the 90-day incubation are presented in Figure 2(a). Compared to the unamended control, compost application significantly elevated soil TN content by 1.5- to 16- fold. Both NH_4^+-N and NO_3^--N levels were also markedly higher in amended soils. Furthermore, increasing the compost addition rate from 2.5% to 10% consistently enhanced the concentrations of all three nitrogen forms. Notably, while the original soil showed no significant difference between NH_4^+-N and NO_3^--N, compost-treated soils exhibited lower NH_4^+-N and NO_3^--N across all application rates, indicating that compost addition promoted nitrification process in the MT-soil system. As shown in Figure 2(b), the ART-soil had an AP content lower than the detection limit of the instrument. However, as the amount of compost added increased from 2.5% to 10%, both AP and AK contents significantly increased. Notably, the high AP and AK contents in CDCS and SLS were the result of additional external additions during the composting process, while FWCS and GLCS did not have external additions of AP and AK. Generally, without considering external additions, the composting process involves the conversion between inorganic and organic phosphorus. Figure 2(c) demonstrates that incubation with compost generally increased soil total organic carbon (TOC) relative to the non-incubated control. 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.



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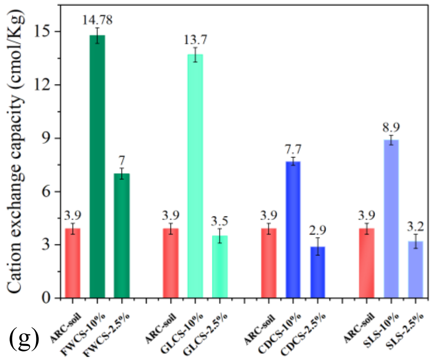

Figure 2: A comparison between the original ARC-soil and compost-incubated soils is shown for: (a) nitrogen species (NH_4^+-N, NO_3^--N,, TN); (b) available phosphorus (AP) and potassium (AK); (c) carbon and organic matter (TOC, TC, OM); (d) pH; (e) electrical conductivity (EC); (f) moisture content; and (g) cation exchange capacity (CEC).

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. 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. 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%). 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. 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 Fig 2(g), after adding 10% compost, the CEC of the soil increased 3-5 times overall. 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 higher soil fertility compared to FWCS and GLCS. Additionally, CDCS and SLS had better regulation of soil pH and EC fluctuations.

3.2 The dynamics of CO2 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 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 exhibited a brief decline from days 52 to 60, before stabilizing thereafter. As shown in Figure 3(b), with the addition of 10%, 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

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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 after day 50. CO_2 emission trends for CDCS and SLS showed consistency between the 2.5% and 10% application rates.

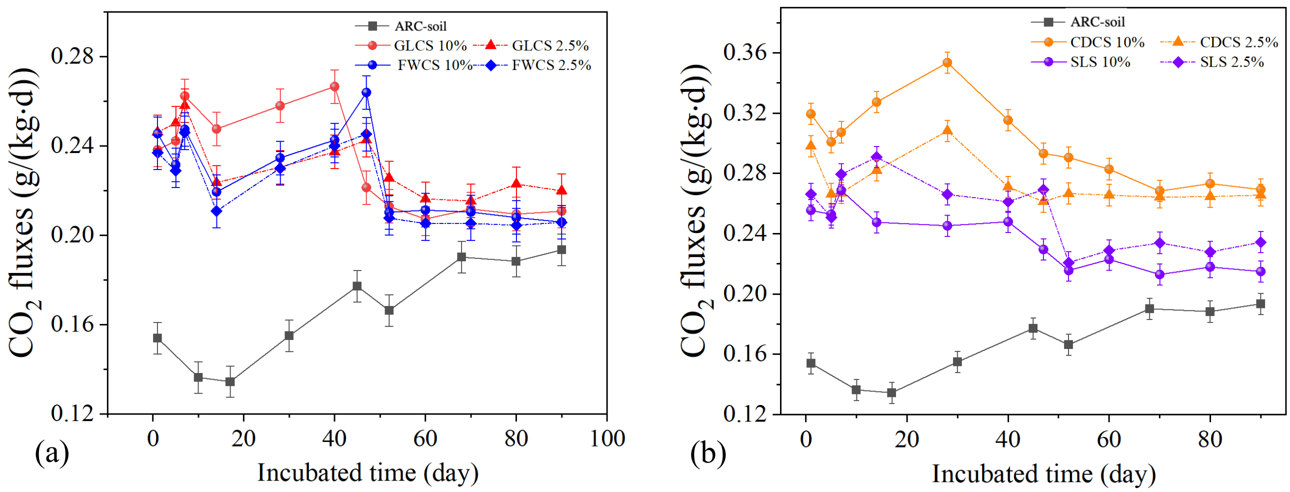

Figure 3: (a) Comparative CO_2 efflux in ARC-soil and FWCS (10%), FWCS 2.5% GLCS 10% and GLCS 2.5%; and (b) for ARC-soil, CDCS 10%, CDCS 2.5%; SLS 10% and SLS 2.5% during the 90-day.

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 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-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.

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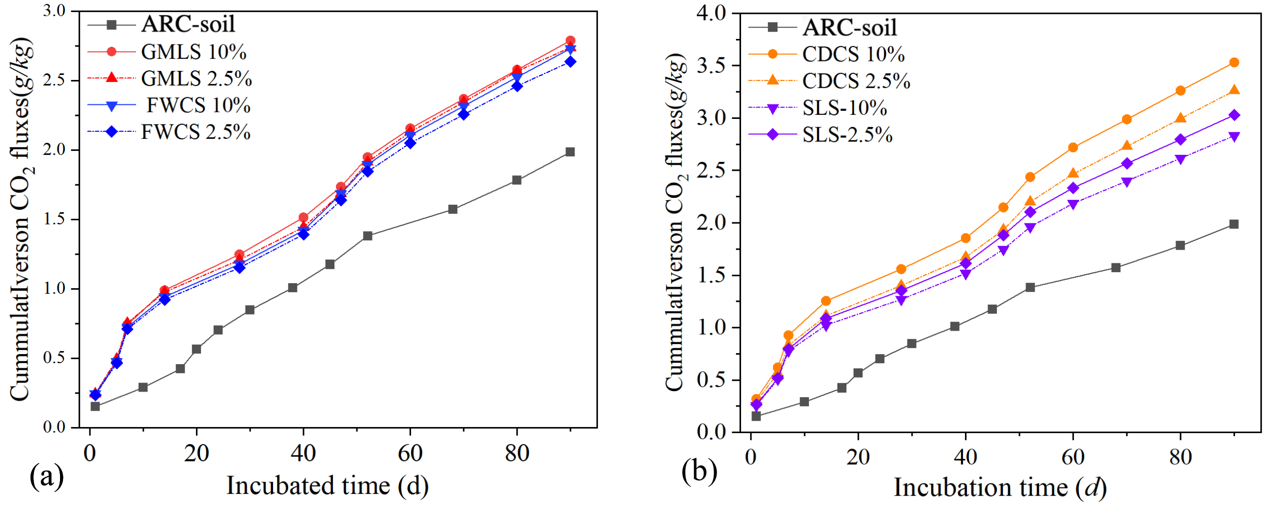

Figure 4: (a) Cumulative CO_2 emission of ARC-soil, FWCS 10%, FWCS 2.5%, GLCS 10% and GLCS 2.5%; (b) for ARC-soil, CDCS 10%, CDCS 2.5%; SLS 10% and SLS 2.5% throughout the 90-d incubation period.

3.3 Multiple Linear Regression Analysis (MLRA)

Figure 5a and b present the correlation and significance matrices for twelve soil physicochemical 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.

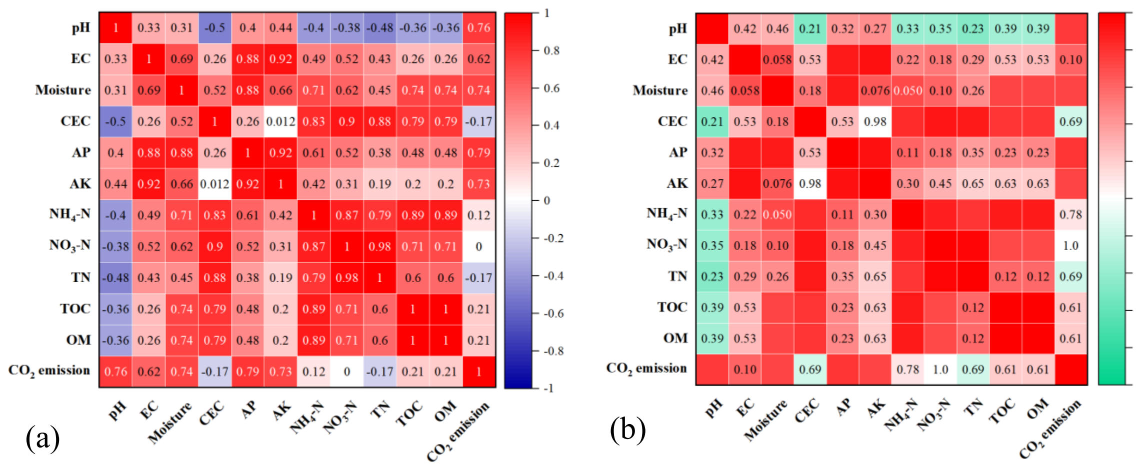

Figure 5: Analysis of key drivers of CO_2 emission: (a) inter-variable correlations and (b) their statistical significance ($P < 0.05$) for compost incubated soil.

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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, The 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.

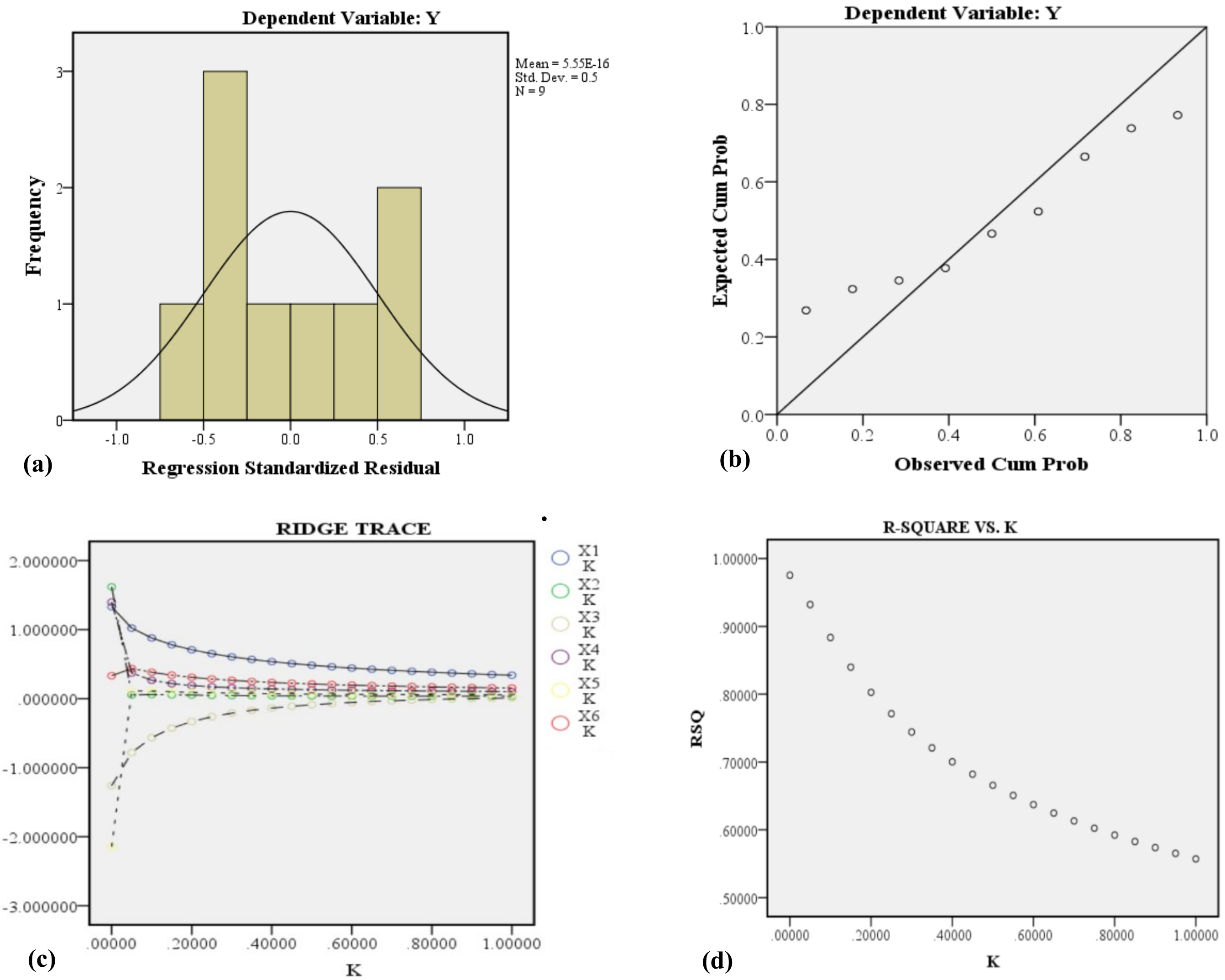

Figure 6: (a) Distribution Histogram; (b) P-P Plot for Normality Check; (c) Ridge Regression Trace; (d) Trade-off Curve: k vs. R².

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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 to this problem, the study implemented 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, with all curves converging 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

Therefore, the established regression equation is:

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

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, as evidenced by an adjusted R² value of 0.902, implying that approximately 90.2% of the variance in the response variable can be accounted for by the selected

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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 Zhan et al. (2015), the addition of compost to lateritic soils 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, 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 $H_2PO_4^-$ and HPO_4^{2-} (Lanno et al., 2021). Potassium in compost remains relatively stable and bioavailable as it 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 any losses during the composting process.

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.

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 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

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peak activity between pH 6 and 8. Crucially, pH influences soil organic matter (SOM) stability. Lower pH increases the positive surface charge on iron and aluminum oxides, enhancing their capacity to adsorb negatively charged organic molecules and thus promoting SOM stabilization (Wang et al., 2024; 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, 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.

(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.

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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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