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Influence of biochar, compost, and their combination on carbon mineralisation and the priming effect in low-carbon soil: an incubation experiment

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Abstract

Integrating biochar and compost into soils can enhance both carbon (C) sequestration and soil fertility. However, their combined effects on C mineralisation and priming in C-poor soils are not well understood. To address this gap, we conducted a 120-day laboratory incubation study. We applied biochar (2%) and compost (2%) individually and in combination (1% each) to a soil with low organic C content (0.12%). The biochars included poultry biochar, rice husk biochar, and Eucalyptus biochar, all produced at a temperature of 550 °C. Our findings indicate that co-application of compost and biochar resulted in non-additive effects on decomposition. Co-application increased decomposition (by 18%, poultry biochar), decreased decomposition (by 10%, rice husk biochar), or was similar (Eucalyptus biochar) compared to decomposition predicted from their separate applications. The difference between actual and predicted decomposition (i.e., priming effect) was positively related to microbial biomass C and pH, indicating that biochar properties can modulate the priming effect by changing microbial activity and pH, but possibly also by affecting C adsorption. Future research should also consider their combined effects on C stabilisation in different soils. Overall, our study underscores that co-application of compost and biochar can have non-additive effects on overall decomposition and that biochar properties such as pH should be considered when applied with compost for their C sequestration potential in soil.

Keywords Co-application, Decomposition, Priming effect, Microbial biomass carbon, Carbon stabilisation

1 Introduction

Modern agricultural activities, including soil manipulation by tillage and fertiliser application, significantly contribute to global warming [21, 29, 35]. Their contribution is estimated at ~10% of the total emissions of greenhouse gases (GHG) [16]. To address climate change challenges, it is necessary to explore innovative strategies, such as integrating sustainable soil management practices, e.g., application of biochar, compost, and



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other regenerative practices. However, the adoption of sustainable agricultural practices, including biochar and compost amendments, can have varying effects on overall GHG emissions, ranging from positive to neutral or even negative, depending on the specific soil amendment, its biochemical properties, soil properties, and environmental conditions. For instance, biochar amendments can reduce GHG emissions by sequestering carbon (C) into soil, reducing emissions of nitrous oxide (N₂O), and methane (CH₄) [25, 27, 34]. In contrast, compost has shown to increase GHG emissions, particularly as CO₂ and N₂O [7, 18]. Soils are frequently amended with both biochar and compost [44], but their combined effect on soil C dynamics remains unclear.

Biochar is defined as aromatic C-rich material, produced through pyrolysis of diverse feedstocks [23]. However, it also carries a small fraction of labile C, particularly when produced at relatively low temperatures. While biochar is widely considered as C neutral or C negative, when applied to soil, it can also reduce the soil native C stock by increasing microbial mineralisation, a phenomenon known as positive priming [26, 33, 45]. Biochar has a large surface area that can host soil microorganisms van Zwieten et al. [36] and nutritional value [12] while its liming effect can potentially promote microbial activity in acidic soils [24, 30, 32, 41]. Since biochar properties vary widely depending on production conditions, and the feedstock used for its production, the interactions between biochar and soil C can be different. Therefore, it is important to examine effects of biochar with diverse properties on C dynamics in soils, particularly soils with a low C content.

Application of compost to soil may affect the native C stock. It can increase the mineralisation of soil C through providing labile C (*i.e.*, energy source) as well as nutrients, particularly nitrogen (N) and phosphorus (P) [13, 15]. For similar reasons, the loss of native soil C from compost application might be more pronounced than for biochar since compost contains more labile C and available nutrients compared to biochar. However, the native C loss might be minimal or even negative when compost is limited in N or when microbes preferentially decompose compost [9, 10]. These conflicting mechanisms for soil C priming highlight the importance of examining the effect of compost on the soil C content.

Combined application of biochar and compost into soil can have diverse effects on the decomposition of C from compost and biochar [11, 40]. Compared to the individual application of biochar and compost, decomposition from the co-application of biochar and compost may be lower causing a net negative priming [39]. The reduction may occur due to stabilisation of compost C within biochar's pores, making it more resistant to microbial decomposition, thus reducing microbial decomposition. As a result, microbes may have a harder time accessing the compost organic material, and thus, a fraction of compost C may remain locked in the soil for a longer period of time. Thus, co-application of biochar and compost could help to sequester C in the soil, potentially promoting long-term C sequestration and mitigating climate change. Conversely, positive priming may occur when biochar stimulates the microbial activity in the soil accelerating the decomposition of both native soil C and compost C [22]. The positive priming is often supported with biochar having relatively more surface area for microbial colonisation. Therefore, the net CO₂ release from the biochar-compost interactions is influenced by factors like feedstock type, pyrolysis temperature, soil conditions, and microbial activity [20].

Considering the diversity in biochar properties, our study aimed to investigate potential interactions of biochar and compost additions on decomposition and how these interactions change due to changes in biochar properties. By measuring decomposition in soils amended with biochar and compost separately and combined, as well as without any amendments, allowed us to examine the additive and interactive effects of biochar and compost on decomposition. We conducted a 120-day laboratory incubation study where we added compost (derived from sugarcane) and three types of biochar (derived from poultry, rice husk, and Eucalyptus wood) separately and combined to a soil with low C content. We measured decomposition (soil respiration) during the incubation at different times, microbial biomass, and soil pH. We hypothesised that the co-application of biochar and compost would increase decomposition (*i.e.*, positive priming) compared to the additive effects of biochar and compost alone. We further hypothesised that the interactive effect of biochar and compost on decomposition rates would depend on the type of biochar. Specifically, biochar with a higher pH and greater N content (poultry manure and rice husk) would enhance decomposition more than biochar with a neutral pH (Eucalyptus wood).

2 Material and methods

2.1 Composting

Compost was produced from ~30 kg of sugarcane (*Saccharum officinarum*) residue consisting of leaves and trash. The material was chopped into small pieces (<1 cm), finely ground, and placed in a container. The material was kept in plastic buckets for four months at 20 °C and 60% moisture to facilitate microbial decomposition of organic materials. The composting materials were turned around every week when water was added to accelerate the decomposition process. At the end of composting, a fraction of the matured compost was air-dried, shredded, and subsamples were collected for the determination of physico-chemical properties. The remaining material was kept without drying for the incubation experiment. The compost contained ~52% C, and 0.64% N while the pH was 7.11 (Table 1).

2.2 Biochar sources

We used three types of biochar, categorized by their sources: poultry, rice husk, and Eucalyptus. The biochar was produced at 550 °C for 4 h at the specific pyrolysis facility [31]. The C content of biochars varied from 41.1% in poultry litter to 64.8% in Eucalyptus biochar. The pH of the biochars was also variable, ranging from 6.65 to 10.7.

2.3 Incubation experiments

We conducted a laboratory soil incubation experiment with biochar (poultry, Eucalyptus, and rice husk biochar), compost, and their combination (Table 2) to examine their

Table 1 Major physico-chemical properties of soil, different types of biochar and compost

Property	Control soil	Poultry biochar	Rice husk biochar	Eucalyptus biochar	Compost
pH	4.21	9.54	10.7	6.65	7.11
EC ($\mu\text{S}/\text{cm}$)	293	2260	218	47	1365
Total C (%)	0.12	41.4	46.5	64.8	51.5
Total N (%)	0.02	1.71	0.71	0.05	0.64
C:N	9.64	20.5	43.3	62.7	31.5
CEC (mmolc kg^{-1})		67.7	57.9	74.8	

decomposition. We also included a control treatment without any organic amendments. The experiment was laid out following a randomized complete block design while each treatment was replicated four times.

We used an artificial soil by mixing 10% kaolinite, 5% montmorillonite, and 2% goethite with quartz sand [14]. The sand was procured from a commercial supplier and acid-washed to remove inorganic C, but it contained 0.12% organic C. To 300 g of the artificial soil, we added 6 g (2%) of compost, 6 g (2%) of each of the three biochar types, or 3 g of compost and 3 g of each of the biochar types. The compost and biochar were thoroughly mixed into the artificial soil and placed in 1.2-L glass jars, maintaining a bulk density of 1.2 g cm^{-3} , sealed and incubated for four months at $20 \text{ }^\circ\text{C}$.

Within each incubation jar, a CO_2 -trap containing 40 ml of 2.5 M NaOH in a 70-ml beaker was placed to absorb the CO_2 produced, while another beaker of deionized water (40 ml) was utilized to maintain a constant humidity level. To account for headspace CO_2 , four empty incubation jars were included. To support microbial growth during the incubation period, the samples were supplemented with microbial inoculum and nutrient solution. The inoculum was collected from a native eucalyptus forest and a wheat field soil to introduce a diverse range of microbial communities. Briefly, the microbial inoculum was collected by shaking 50 g of soil with 100 ml of water and then sieved through a $< 100 \text{ }\mu\text{m}$ filter paper. The inoculum was applied to the soil along with nutrient solution (inoculum: nutrient solution, 1:125 v/v). The nutrient solutions included a mixture of macro and micronutrients (i.e., N: 89 mg kg^{-1} , P: 13 mg kg^{-1} , K: 100 mg kg^{-1} , S: 39 mg kg^{-1} , Ca: 35 mg kg^{-1} , Mg: 29 mg kg^{-1} , B: 0.09 mg kg^{-1} , Fe: 0.4 mg kg^{-1} , Cu: 0.09 mg kg^{-1} , Mn: 0.7 mg kg^{-1} , Mo: 0.4 mg kg^{-1} , and Zn: 0.4 mg kg^{-1}). All treatments were maintained at 70% of their maximum water-holding capacity throughout the experiment. The CO_2 traps were replaced at specific intervals (i.e., at 1, 2, 7, 14, 21, 30, 60, and 120 d).

2.4 Biochar-compost decomposition

The amount of $\text{CO}_2\text{-C}$ (mg C kg^{-1}) respired from biochar-compost-amended and control soils was determined by titrating 1 mL NaOH solution used for CO_2 trapping with 0.1 M HCl, using phenolphthalein as an indicator. Titrations were performed directly after the collection of the traps. The amount of CO_2 respired (R) was determined using the following equation:

$$R = \text{Number of moles of acid consumed} \times \left(\frac{12}{2}\right) \times 1000 \times \left(\frac{1000}{\text{soil weight}}\right) \quad (1)$$

With *soil weight* in g.

Table 2 Treatments used in the incubation experiment

Treatment	Abbreviation
Soil only	S
Soil + compost	SC
Soil + poultry biochar	SB1
Soil + poultry biochar + compost	SB1C
Soil + rice husk biochar	SB2
Soil + rice husk biochar + compost	SB2C
Soil + Eucalyptus biochar	SB3
Soil + Eucalyptus biochar + compost	SB3C

2.5 pH, electric conductivity and microbial biomass carbon measurements

At harvest, we measured soil pH and electric conductivity (EC) in water (1:5 m/v) using a pH/EC meter (Mettler Toledo, Melbourne, VIC, Australia). Soil microbial biomass was measured at day 60 and day 120 using a modified fumigation method [6]. For each sample, we prepared 3 subsamples- a) a subsample of 10 g for determining gravimetric soil moisture, which was determined by drying the samples for 48 h at 105 °C, b) a non-fumigated sample of 5 g, and c) a fumigated sample of 5 g. Fumigated samples were fumigated in glass beakers for 48 h with chloroform in a vacuum desiccator. Fumigated and non-fumigated subsamples were placed in 50 ml centrifuge tubes with 40 ml 0.05 M K₂SO₄ and were shaken for 1 h. After shaking, they were filtered through Whatman No. 42 filter paper and the extracts were kept in a freezer at – 20 °C until analysis. Total dissolved organic C was determined on a TOC-TN analyzer (Shimadzu Scientific Instruments, Sydney, NSW, Australia). We calculated microbial biomass C (C_{mic}) as the difference in dissolved organic C between fumigated and nonfumigated samples divided by 0.45 [2].

2.6 Interactive effects of compost and biochar on organic matter decomposition and priming effect

Cumulative soil respiration or decomposition (mg C kg⁻¹) over a given period was calculated as the average CO₂-C measured between two time points multiplied by the time interval, and by adding the preceding cumulative CO₂-C in all traps after corrections for background CO₂-C from empty control jars. To assess the interactive effects of compost and biochar on organic matter decomposition, we compared actual cumulative soil respiration in treatments with combined applications of compost and biochar to predicted cumulative soil respiration based on measurements in treatments with soil only (*S*), soil and compost only (*SC*) and soil with biochar only (*SB_i*, with *i* either poultry, rice husk, or Eucalyptus biochar).

$$Predicted = S + (SC - S) \times 0.5 + (SB_i - S) \times 0.5 \quad (2)$$

The 0.5 factor was included because the treatment with combined application of compost and biochar had half the amount of biochar (1%) and compost (1%) applied compared to the treatments with compost only (2%) and biochar only (2%). If there are no interactions between biochar and compost, then the predicted values should match the actual measurements. If there are deviations from the predicted values, then there are interactive effects. When predicted values are larger than actual values, this indicates that combined application of compost with biochar decreased overall decomposition, while when predicted values are smaller than actual values indicate enhanced decomposition when compost and biochar are applied together. We do not know which component of organic matter was decomposed faster (compost, biochar, or organic matter in the artificial soil). However, this accelerated decomposition, when two or more different organic matter sources are combined, can be regarded as a priming effect (*PE*):

$$PE = Actual - Predicted \quad (3)$$

2.7 Statistical analysis

To assess treatment effects on cumulative respiration, pH and C_{mic} , we used one-way ANOVA. When tests indicated significant differences, Tukey's Honest Significant Difference (HSD) test was used to compare the treatment means. Prior to analysis, data were evaluated for normal distribution of residuals using the Shapiro Wilk test and log-transformed where needed (i.e., when the p-value of Shapiro Wilk test was <0.05). We used t-tests to examine whether the actual respiration in each biochar treatment was different from the predicted values. Moreover, we also used linear regressions to examine the association between C_{mic} and pH with cumulative respiration and PE. Unless otherwise stated, all statistical analyses were considered significant at $p \leq 0.05$. All analyses were conducted using R environment, while we used Sigmaplot (version 10.0, Systat Software) to generate the plots.

3 Results

3.1 Decomposition from soil, biochar, and compost

Biochar and compost application significantly affected decomposition (Table 3 and Fig. 1, $p < 0.01$). Overall, the cumulative respiration or decomposition after 120 days was higher in compost application (1048 mg C kg⁻¹ soil) than biochar (average of 648 mg C kg⁻¹ soil across all three biochar types), and co-application of biochar and compost (average of 882 mg C kg⁻¹ soil across all three biochar types). Moreover, the average cumulative decomposition was relatively lower in co-application of rice husk biochar and compost than co-application of the other two types of biochar and compost

Table 3 Analysis of variance of the cumulative carbon dioxide emission from different biochar and compost treatments at different dates

Source of variance	Degrees of freedom (df)	Sum square (SS)	Mean square (MS)	F value	p value
After day 1					
Treatment	7	2939	419.9	1.328	0.28
Residuals	24	7588	316.2		
After day 2					
Treatment	7	17,050	2435.8	5.006	0.001
Residuals	24	11,678	486.6		
After day 7					
Treatment	7	19,545	2792.1	4.039	0.005
Residuals	24	35,687	1189.6		
After day 14					
Treatment	7	47,775	6825	8.692	<0.0001
Residuals	24	18,845	785		
After day 21					
Treatment	7	46,681	6669	9.498	<0.0001
Residuals	24	16,850	702		
After day 30					
Treatment	7	119,354	17,051	18.86	<0.0001
Residuals	24	21,699	904		
After day 60					
Treatment	7	278,981	39,854	27.45	<0.0001
Residuals	24	34,840	1452		
After day 120					
Treatment	7	928,829	132,690	58.88	<0.0001
Residuals	24	54,086	2254		

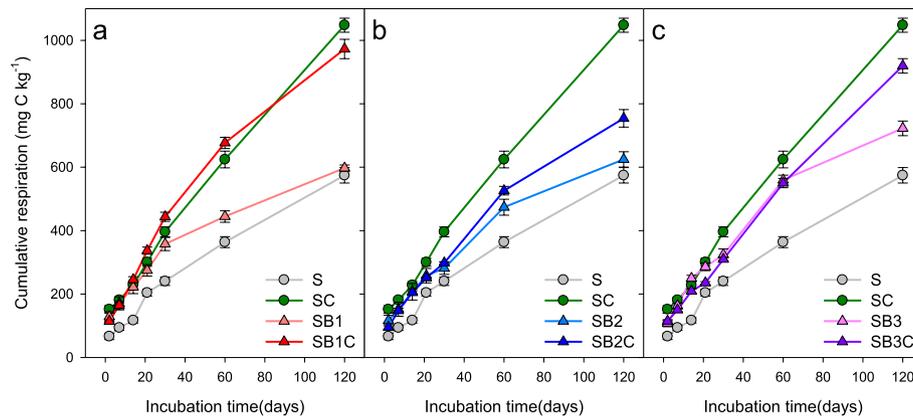


Fig. 1 Cumulative decomposition (cumulative CO_2) from soil only (S), soil+compost (SC) and **a** poultry (B1), **b** rice husk (B2), and **c** Eucalyptus biochar (B3) treatments over 120 days of incubation. Note that soil only (S) and soil+compost (SC) are shown in each panel for comparison. For explanation of all treatment abbreviations see Table 1. The error bars represent the standard error of means, $n=4$

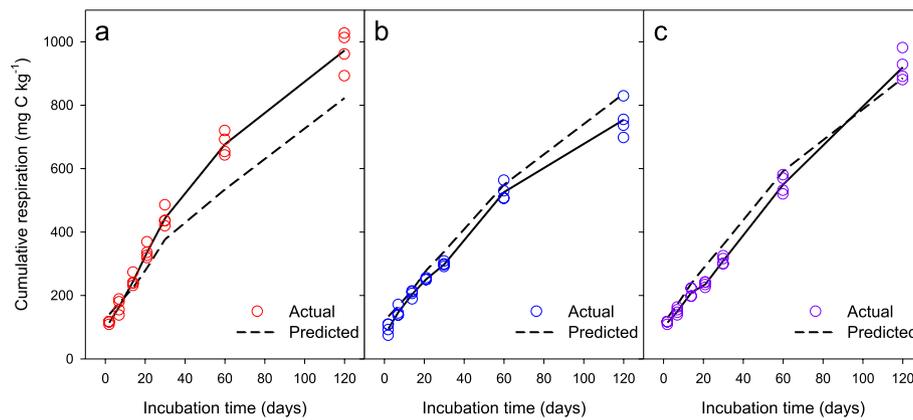


Fig. 2 Actual (solid line) and predicted cumulative decomposition (cumulative CO_2 , dashed line) in co-application treatments of compost with **a** poultry biochar, **b** rice husk biochar or **c** Eucalyptus biochar

(Fig. 1). Decomposition remained high throughout the incubation period for treatments with compost and in combination with poultry and Eucalyptus biochar, but levelled off after 30–60 days for all three biochars applied alone and for the co-application of rice husk biochar and compost. The soil-only treatment released the smallest amount of CO_2 throughout the incubation period.

3.2 Priming effect

In our study, co-application of compost and biochar significantly affected decomposition. Compared to the predicted decomposition, the actual decomposition after 120 days was higher in the poultry biochar treatment (by 18%, $p=0.007$), suggesting a positive priming effect (Fig. 2). In contrast, the priming effect was negative after 120 days when compost was combined with rice husk biochar (by 10%, $p=0.03$), while there was no significant difference between actual and predicted decomposition with the Eucalyptus biochar.

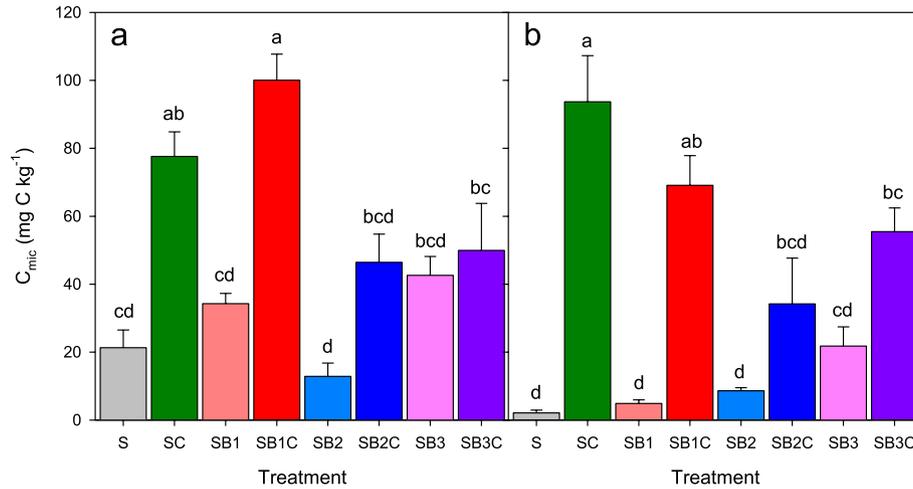


Fig. 3 Microbial biomass carbon at **a** day 60 and **b** day 120. For explanation of treatment abbreviations see Table 1. The error bars represent the standard error of means, n=4. Letters above bars indicate significant differences among treatments based on Tukey's Honest Significant Difference (HSD) test

Table 4 pH and electrical conductivity in different treatments (mean ± SE), n=4

Treatments	pH in H ₂ O (1:5)	EC (µS/cm)
S	^a 4.2 ± 0.02	^a 293 ± 12
SC	^d 4.3 ± 0.01	^c 418 ± 16
SB1	^b 6.7 ± 0.05	^{ab} 546 ± 29
SB1C	^c 5.91 ± 0.05	^c 480 ± 15
SB2	^{cd} 4.53 ± 0.01	^{cd} 309 ± 12
SB2C	^e 4.36 ± 0.01	^{cd} 397 ± 17
SB3	^f 5.16 ± 0.02	^d 383 ± 16
SB3C	^{cd} 4.68 ± 0.05	^{bd} 399 ± 24
p value	< 0.001	< 0.001

Letters before values indicate significant differences among treatments based on Tukey's Honest Significant Difference (HSD) test. For explanation of treatment abbreviations see Table 1.

The p-values are based on one-way ANOVA

3.3 Microbial biomass carbon (C_{mic}) and pH

At day 60, the C_{mic} levels were significantly different among treatments (p < 0.05) highest in the co-application of poultry biochar and compost (SB1C) followed by the compost alone treatment (SC) and lowest in the soil only and rice husk application (S and SB2, respectively, Fig. 3). At day 120, C_{mic} remained high in the SC and SB1C treatments, significantly outperforming all other treatments (p < 0.05).

The pH values ranged from 4.2 to 6.7 (Table 4). It was highest in the poultry biochar (SB1) and lowest in the soil alone (S) and soil with compost (SC) treatment. EC values ranged from 293 µS/cm to 546 µS/cm, with the highest EC observed in the poultry biochar (SB1) treatment.

3.4 Relationships between C_{mic} and pH with cumulative respiration and the priming effect

We observed significant positive relationships between C_{mic} and cumulative respiration after 60 (r² = 0.65, p < 0.001) and 120 days (r² = 0.76, p < 0.001), but no significant relationship between pH and cumulative respiration after 120 days (p > 0.05, Fig. 4a, b). Soil pH was not related to C_{mic}, and soil EC was not related to either cumulative respiration or C_{mic} after 120 days (p > 0.05, not shown). There was further a significant positive

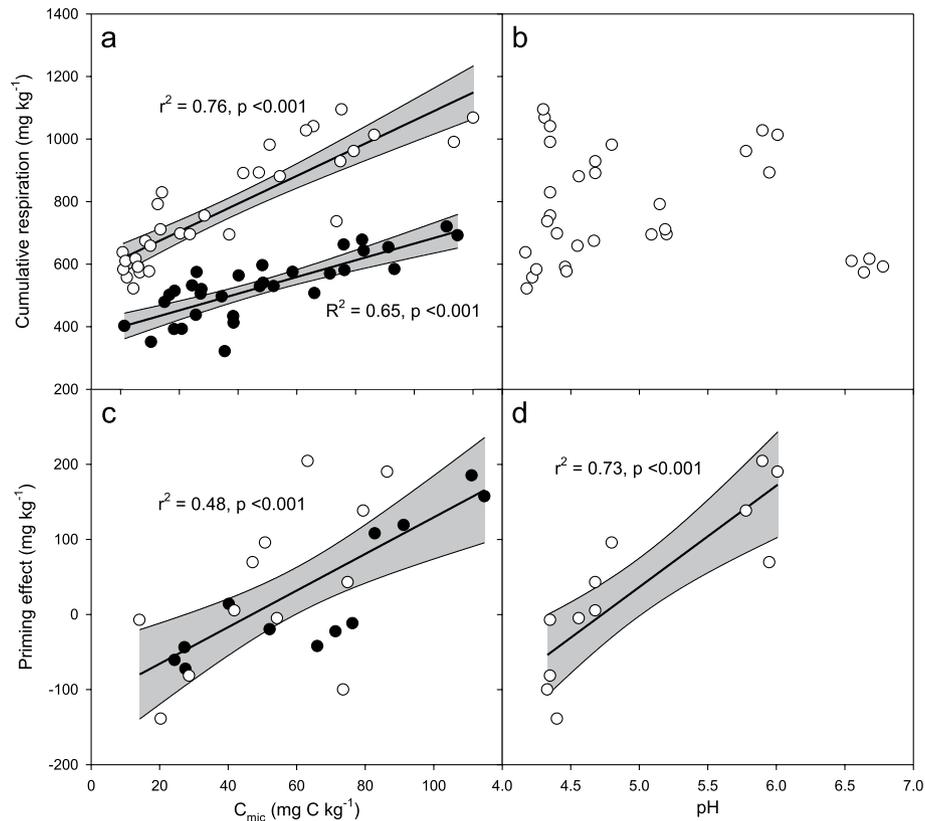


Fig. 4 Relationship between microbial biomass carbon (C_{mic}) and cumulative CO_2 respiration (**a**), microbial biomass carbon and priming effect (**c**). **b** and **d** represent the relationship between soil pH with cumulative CO_2 respiration and priming effect, respectively. Note that for the relationships with the priming effect only treatments with combined applications of compost and biochar were used. Linear regressions (black line) with 95% confidence intervals (shaded bands) are shown when significant

relationship between soil pH (after 120 days) and C_{mic} (across day 60 and 120) with the PE in the co-application treatments (Fig. 4c, d). The strength of the relationship was stronger with pH ($r^2 = 0.73$, $p < 0.001$) than with C_{mic} ($r^2 = 0.48$, $p < 0.001$). For the relationship between C_{mic} and PE the linear regressions were not significantly different for each day.

4 Discussion

Adding biochar and compost showed variable decomposition throughout the entire incubation period (Table 1, Fig. 1). It is not surprising that compost decomposed faster compared to all three biochar types, due to the presence of labile C in compost, which decomposes rapidly compared to a more stable and recalcitrant nature of C present in biochar [38, 46]. It further indicates that any labile C in the three types of biochar (poultry, rice husk, and Eucalyptus) was relatively small compared to what was added as compost.

After 120 days of incubation, the single treatment of Eucalyptus biochar application released more C as CO_2 (on average 723 mg C kg^{-1}) than the poultry (597 mg C kg^{-1}) and rice husk biochar applications (625 mg C kg^{-1} , Fig. 1), which may reflect the differences in the chemical properties of these biochars. For instance, poultry and rice husk biochar had a relatively high pH (> 9.50 , Table 1) and we observed significant differences in soil pH among all treatments after 120 days (Table 4), but we observed no significant

relationship between soil pH and cumulative respiration after 120 days (Fig. 4a). This suggests that biochar-induced changes in pH did not influence decomposition. The lack of a relationship between EC and C_{mic} or cumulative respiration after 120 days further suggests that biochar-induced changes in soil EC did not influence decomposition either. It was suggested that biochars that contain more nutrients, such as N, can stimulate microbial activity [24, 30], but Eucalyptus biochar had the lowest N content (Table 1), and therefore, this cannot explain the higher decomposition with Eucalyptus biochar than with poultry or rice husk biochar either. We can therefore only speculate about what caused the higher decomposition with Eucalyptus biochar application compared to the other two biochars. One possibility is that Eucalyptus biochar contained more labile C compared to the poultry and rice husk biochars, thereby contributing more to the cumulative C respiration measured during the 120-day incubation period. Unfortunately, we don't have information on whether this was the case. Another possibility is that the Eucalyptus biochar had a relatively high surface area and porosity, providing a favourable refuge for microbes that can protect them from grazing [17, 19]. As a consequence, microbial biomass and decomposition can increase. Of the three biochar-alone treatments, the treatment with Eucalyptus biochar had the highest C_{mic} after 60 and 120 days (Fig. 3), supporting this notion.

Co-application of compost with poultry biochar resulted in a positive priming effect (i.e., actual decomposition rate was higher than expected based on individual applications), in part supporting our first hypothesis. Positive priming effects with co-application of compost and biochar can occur because the labile component of compost can provide an energy source for microbes to decompose the more recalcitrant component of biochar, also referred to as co-metabolism [4]. It is also possible that the compost increased the decomposition of native soil C. Although the artificial soil that we used contained little organic C (0.12%), decomposition of this C was substantial (Fig. 1), suggesting that this C was relatively labile and may have been susceptible to priming. Unfortunately, our method of calculating PE based on differences between actual and predicted values does not allow us to assess which of the three C sources (compost, biochar, native soil C) accelerated in decomposition when they were combined, only that there was an overall increase in decomposition compared to the sum of decomposition of the sources measured separately.

A possible explanation for the positive PE when compost was applied in combination with poultry biochar to soil is that the porous structures of these biochar types provided a suitable habitat and refuge for microbes [5, 42]. Poultry also contains more N and a low C:N ratio (Table 1) compared to other types of biochar, which might also mediate microbial activity due to microbial N demand. A proliferation of microbial growth inside biochar pores may have occurred when compost (made from sugarcane) is applied at the same time, which might favour microbes by providing energy and possibly nutrients for their growth, and thereby stimulating decomposition. The C_{mic} values were among the highest in the co-application of compost with poultry biochar after 60 and 120 days, respectively (Fig. 3), while the positive relationship between C_{mic} and PE (Fig. 4d) further supports this notion. Co-application of compost with poultry biochar also reduced soil acidity after 120 days compared to soil only or soil with compost addition (Table 4). The PE tends to be highest in soils with neutral pH [37] and we also observed an increase in PE when soil pH increased from acidic (pH of 4.3) to near neutral (pH of 6.0, Fig. 4c),

suggesting that the biochar-induced increases in soil pH may have increased the PE when co-applied with compost.

Conversely, rice husk biochar exhibited a negative priming effect, supporting our second hypothesis that the interactive effect of biochar and compost on decomposition rates would depend on the type of biochar. A negative priming effect indicates that the release of C from rice husk biochar reduced the overall decomposition in the co-application treatment with compost compared to what would be expected based on the decomposition of individual sources. Rice husk biochar might have reduced the microbial activity, as we observed a significantly lower C_{mic} after 60 days when only rice husk biochar was applied to soil (Fig. 3). However, when combined with compost, C_{mic} was similar to the co-application treatment with Eucalyptus biochar after 60 and 120 days. Therefore, changes in microbial activity cannot fully explain why the rice husk biochar addition caused an overall negative effect. Instead, as mentioned above, this may be more related to pH changes. Unlike co-application of compost with poultry and Eucalyptus biochars, co-application of compost with rice husk caused only a small and insignificant increase in soil pH (compared to soil with compost) after 120 days (Table 4), which was surprising given that the rice husk biochar by itself had the highest pH (of 10.7, Table 1). The strong positive relationship between soil pH and PE (Fig. 4c) suggests that soil pH may be a more dominant factor in regulating the PE and decomposition dynamics than C_{mic} alone. For instance, a higher soil pH can enhance diversity in microbial communities, thereby accelerating the decomposition of organic matter [1, 28].

However, while a lack of an increase in soil pH in the co-application of compost with rice husk biochar may not have caused a positive PE, it does not fully explain why we observed a negative PE in the co-application treatment with rice husk biochar. To explain a negative PE, we speculate that the properties of rice husk biochar stimulated the adsorption of organic matter (from compost or the soil), thereby protecting organic matter from further decomposition. There is increasing evidence that organic compounds can adsorb onto biochar surfaces, thereby protecting them from further decomposition [3, 43, 45]. On the other hand, the variation in C:N ratio of different amendments could have also played a role in the decomposition rate and PE. For instance, the relatively high C:N ratio of Eucalyptus and rice husk biochar might have slowed down the decomposition compared to compost (which had a lower C:N ratio) and their combined application (Fig. 1B, C). However, we did not find any significant relationship between C:N ratio and cumulative CO_2 . Moreover, the co-application of rice husk biochar with compost may have caused the negative PE because the addition of compost can increase the formation of aggregates [8] and therefore the likelihood for fresh organic matter to be protected from further decomposition. Further research is required to better understand what specific biochar properties in rice husk biochar would cause protection of organic matter, and whether this also depends on compost properties.

5 Conclusion

The co-application of biochar and compost caused interactive effects on decomposition that cannot be explained by their single effects on decomposition. Moreover, the interactive effect between compost and biochar depended on biochar type. Decomposition increased more than predicted (i.e., a positive PE) when compost was combined with poultry biochar, but decreased more than predicted (i.e., negative PE) when compost

was combined with rice husk biochar, while it caused no significant differences between actual and predicted decomposition when compost was added with Eucalyptus biochar. The PE was strongly positively correlated to C_{mic} and pH. Therefore, the compost-biochar co-application effects on decomposition were mediated by their effects on C_{mic} and pH, but possibly also other factors, such as nutrient availability and adsorption of organic matter from the soil/compost on biochar. We note that we only conducted this study in an artificial soil that was inherently low in organic C, and only under specific moisture and temperature conditions. Further research is warranted to assess these interactions in different and more natural soil types and different moisture and temperature conditions. We further note that here we only assessed the effects of biochar and compost on decomposition, but that future research should also consider their combined effects on C stabilisation. Nevertheless, our results highlight that co-application of compost and biochar can lead to non-additive effects on decomposition and that biochar properties such as porosity, pH, adsorption capacity, and nutrient content play important roles in their interactive effects with compost on decomposition.

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Author contributions

SS, BB, and FAD designed the study. BB and FAD supervised the experiment. SS conducted the lab work and collected the data. SS, FAD, and SM performed the data analysis and interpreted the results. SS wrote the manuscript. All authors reviewed and approved the final version of the manuscript.

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Data availability

The data of the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interest

Shamim Mia is one of the Editors for the special issue on Biochar–Soil–Plant interactions: enhancing soil health and promoting environmental sustainability. He will not be involved in the peer review or any decision-making process for this paper. The authors have no further conflicts of interest to declare.

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