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Biochar reduces early-stage mineralization rates of plant residues more in coarse than fine-texture soils – an artificial soil approach.

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Abstract. Quantifying the impact of biochar on carbon persistence across soil textures is complex, owing to the variability in soil conditions. Using artificial soils with precise textural and mineral composition, we could disentangle the effects of biochar from the effects of soil particle size. We can show that biochar application significantly reduces early-stage carbon mineralization rates of plant residues in various soil textures (from 5 to 41% clay) but more significantly in sandy soils. This finding suggests that biochar can compensate for the lack of clay in promoting C persistence in soil systems. This short report significantly contributes to our understanding of soil texture and biochar application interactions.

1 Introduction

Biochar application in agriculture has been recognized to enhance carbon sequestration and improve soil quality (Lehmann, 2007). In this regard, soil texture may play a fundamental role in the overall effectiveness of biochar in promoting carbon persistence, mainly due to influences on soil structural properties (Wang et al., 2017). However, the mechanisms behind the interaction between biochar and soil texture in promoting C storage are not fully understood due to the high heterogeneity in soil properties and climate conditions of natural soils. As a result, the findings in the literature on this topic can vary depending on the specific experimental conditions used (Gross et al., 2021). Therefore, more systematic analyses of these factors are necessary to understand how biochar can affect overall C dynamics in soil.

In this sense, using artificial soil with known particle size and mineral composition provides an excellent base for understanding the mechanisms behind soil processes (Pronk et al., 2012). These artificial soils can be mixed to mimic the composition of typical arable soils of the temperate region, while their individual properties, like soil texture, can be freely adjusted (Bucka et al., 2021).

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This short communication explored the interactions between soil texture and biochar application in the early-stage soil organic matter mineralization using artificial soils with precise mineral and textural composition in a controlled microcosm. We hypothesized that biochar could reduce organic soil mineralization, especially in coarser textured soils.

2. Material and methods

2.1 Artificial soils preparation: texture range

For producing the different textures of artificial soils, we have used quartz grains of varying particle sizes (Euroquarz, Laußnitz, Germany, and Quarzwerke, Frechen, Germany). We added goethite, illite, and bentonite (Aspanger, Aspang, Austria) to create soil-like reactive surfaces in the clay-size fraction. The C-content of the artificial soils was considered negligible due to the insignificant C concentration of the ingredients. The soil mixtures were prepared according to the proportions presented in Table 1. The texture classes were defined as: 1) Loamy Sand, 2) Sandy Loam, 3) Loam, 4) Clay Loam, and 5) Silty Clay.

Table 1: Composition of the artificial soils.

Fraction	Ingredients	Soil 1 Loamy Sand	Soil 2 Sandy Loam	Soil 3 Loam	Soil 4 Clay Loam	Soil 5 Silty Clay
		------------------ Proportion (mass %) ------------------				
Sand	Quartz Sand	81	61	45	21	8
Silt	Quartz Silt	14	29	39	48	51
Clay	Quartz Clay	4.45	8.9	14.24	27.59	36.49
	Goethite	0.05	0.1	0.16	0.31	0.41
	Illite (MICA SFG 75)	0.25	0.5	0.8	1.55	2.05
	Bentonite	0.25	0.5	0.8	1.55	2.05
	Total	100	100	100	100	100

The artificial soils were prepared by mixing the ingredients in a dry state from coarser to finer scale particles. As each component was added, 10 manual turns were executed to combine them. After all the ingredients were mixed, the containers were added to a horizontal shaker and shaken overnight at 140 rpm. After the overnight shaking period, each soil mix container was manually turned 30 times.

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2.2 Incubation Experiment and Treatments

The experimental setup was a 5 x 2 factorial design testing 5 different textures of artificial soils with and without biochar application with three replicates. We used 20 g of artificial soil per experimental unit in 120 ml glass flasks for the incubation experiment. We added ball-milled air-dried clover biomass (*Trifolium sp.*) (C:N ratio of 18) as an organic matter source to all samples at a rate of 27 mg C g^{-1} soil to mimic a natural background OC content of arable topsoils. We have used dissolved organic matter extracted from a local crop field as an inoculum of soil microorganisms to the artificial soils at a rate of 0.06 ml g $soil^{-1}$, according to (Pronk et al., 2012). The artificial soils were incubated under 60% of the maximum water hold capacity to ensure microbial activity (Supplementary Figure 1). The water used to add the inoculum was accounted for in the amount of water added. Biochar was produced from Norwegian Spruce under a temperature of 700° C and added to the soil at a rate of 50 mg of biochar g^{-1} soil. The basic biochar properties are described in the Supplementary Table 1.

2.3 CO_2 respiration measurements

We measured CO2 production over 115 hours using an automated incubation system described in detail by Molstad et al. (2007) with modifications in Molstad et al. (2016). The system consists of an autosampler (CTC PAL) connected to an Agilent gas Chromatograph (Model 7890A, Agilent, Santa Clara, CA, USA). The system allows for high-resolution analysis of headspace gas concentrations in airtight 120 ml serum bottles. Corrections were applied to adjust for sampling dilution, leakage, and CO_2 equilibrium state as a function of the material pH and soil solution volume (Appelo and Postma, 2005).

3. Results

3.1 Early plant mineralization affected by particle size and biochar applications

We observed significant effects of both biochar application and texture on C mineralization and a significant interaction between these variables in the analysis of variance (ANOVA) at $p < 0.01$. Biochar application significantly reduced C-mineralization rates compared to control in the coarser-textured soils: 1) Loamy Sand, 2) Sandy Loam, and 3) Loam (Figure 1). However, no differences were observed between biochar and control treatments for the finer-textured soils:4) Clay Loam and 5) Silty Clay (Figure 1).

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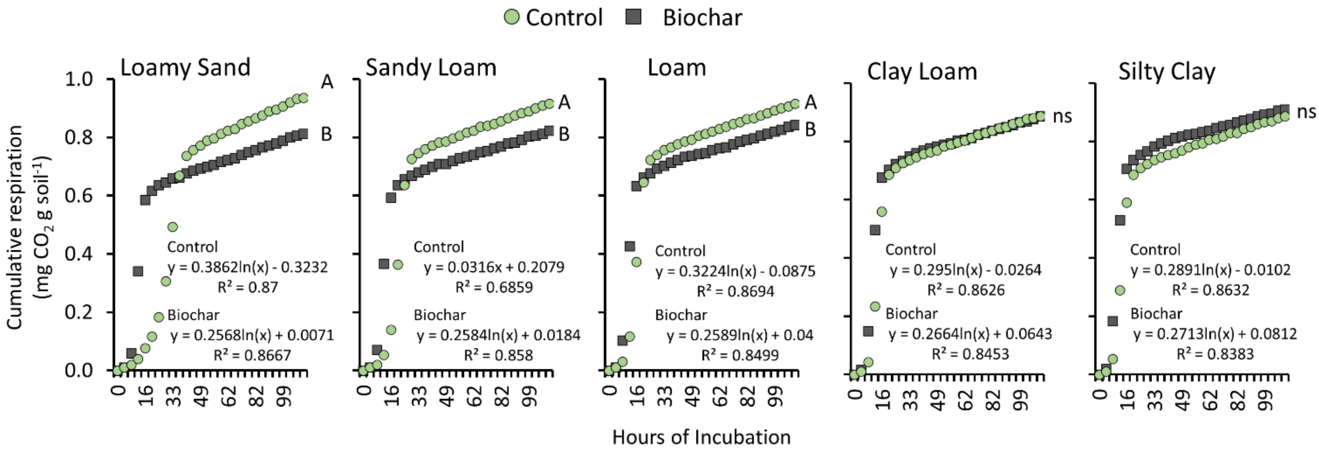

Figure 1: Biochar effect on the CO_2 cumulative respiration in artificial soils with different textures in a 5-day incubation experiment. For a given soil, different uppercase letters indicate a significant difference in the cumulative respiration between control and biochar-amended soils by the LSD test at $p < 0.05$. NS = not significant.

The reduction in C mineralization promoted by biochar in the Loamy sand (Soil 1) was over 6-fold higher than in the Silt Clay soil (Soil 5). The influence of clay and silt content on C mineralization also differed depending on whether biochar was applied or not (Figure 2). Control samples' clay and silt content generally decreased C mineralization (Figure 2).

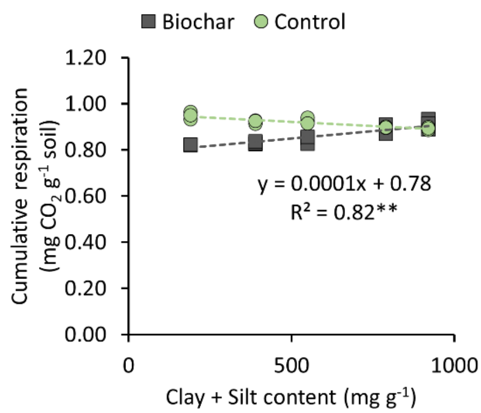

Figure 2: Influence of clay and silt fraction from artificial soils on the cumulative respiration in soils with and without biochar in a 5-days incubation experiment. ** $p < 0.01$.

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3.2 Soil pH affected by particle size and biochar application

Soil pH ($CaCl_2$) was significantly influenced by increased soil texture and biochar application (Figure 3). Increases in pH due to biochar addition were overall higher with increasing clay and silt contents, i.e., 0.68 in the Silt Clay and 0.24 in the Loamy Sand (Figure 3a). The increase of silt and clay particles alone also promoted increases in soil pH ($p<0.05$) (Figure 3b). Every mg of clay and silt fraction promoted an increase of 0.0003 in soil pH ($CaCl_2$). This increase was three times higher (0.009) when biochar was applied ($p<0.01$) (Figure 2b).

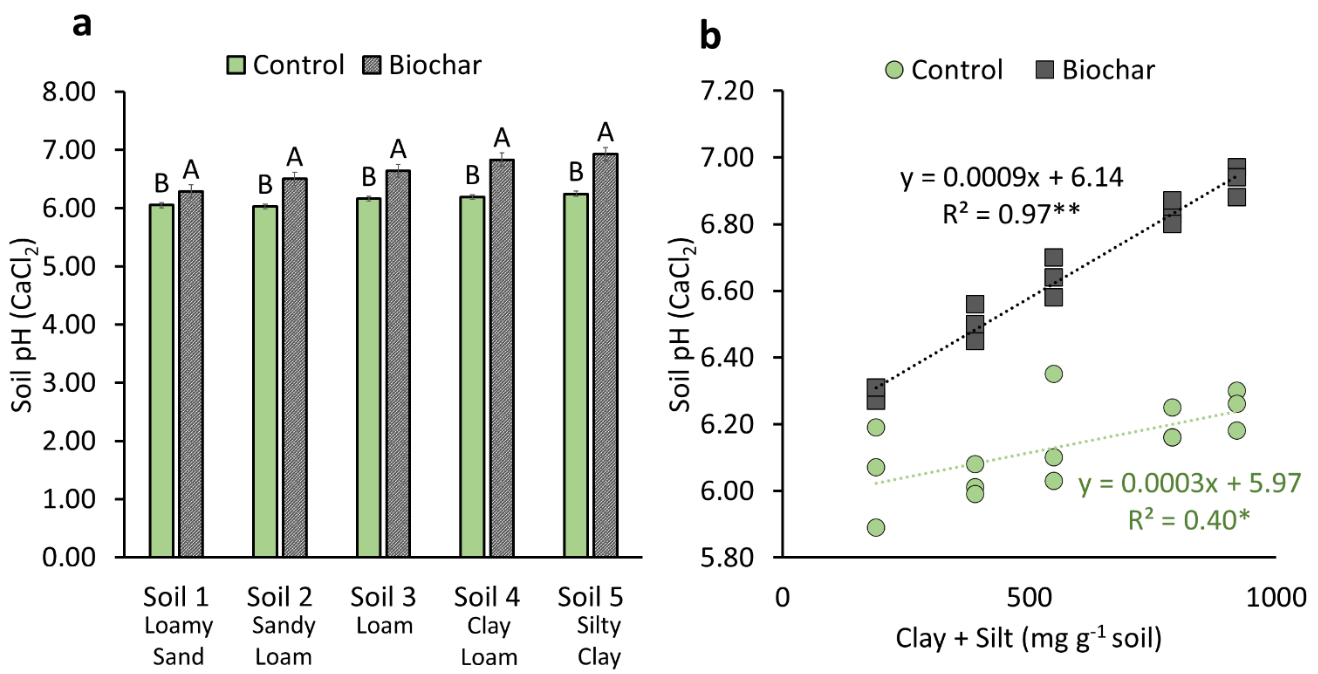

Figure 3: Soil pH as affected by the biochar application and soil texture in artificial soils incubated for 5 days. a) Influence of biochar application on soil pH ($CaCl_2$) under different textures. For a given soil, different letters indicate significant differences by the LSD test at $p < 0.05$. b) Influence of soil texture (clay+silt proportion) on soil pH (CaCl2) in soils with and without biochar. ** significant at $p < 0.01$. * Significant at $p < 0.05$

4. Discussion

4.1 Interactions of clay + silt content and biochar application in reducing early mineralization of plant residues.

The significant interaction between biochar application and soil texture suggests that the extent of biochar's impact on the mineralization of plant residues depends on soil texture. Likewise, the observed effects of soil texture on clover mineralization depended on the biochar application. The differences in the magnitude of early plant mineralization depending on soil texture suggest that biochar had a higher impact on reducing early C-mineralization from clover residues in sandier textures than in clay-rich soils. Biochar has known benefits in enhancing soil properties associated with promoting C protection, such as aggregation (Wang et al., 2017; Juriga et al., 2021), sorption capacity (Siedt et al., 2021), water retention, and porosity (Obia et al., 2016). in natural soils. Such effects may have potentially influenced the decrease of early mineralization of the added clover plant residues since the improvement of soil structure in artificial soils, such as aggregate formation, is already observed within the first days of their development (Pronk et al., 2012). Also, the increase of fine particles in soils is assumed to decrease organic matter decomposability due to the increased opportunity for physicochemical protection (Hassink, 1992; Kravchenko and Guber, 2017), which justifies the influence of clay and silt particles in reducing mineralization in the control soil.

Especially in sand-rich soil, where the available mineral surface area (as well as the permanently charged surfaces of clay minerals) is low, biochar can deliver additional surface area for adsorption processes. The biochar effect is probably diminished with increasing clay content as the higher clay mineral surface area and the smaller pores may overrule the biochar effect on the physicochemical protection of OM.

Nonetheless, the results on texture controlling soil organic matter mineralization are contrasting in the literature, with results being dependent on soil moisture and other experimental conditions (Li et al., 2020; Li et al., 2022). Our experiment using artificial soils with precise composition and early formation stage helped shed light on texture's and particle size effects on organic matter decomposition. In our experiment, significant correlations were observed between the clay + silt content with the cumulative CO_2 respiration ($p<0.01$) (Figure 1b). Every mg of silt and clay size particles in the artificial soils reduced clover residue mineralization by 0.00007 mg g^{-1} soil under a constant moisture level (60% of the water hold capacity). The clover mineralization after a 5-day incubation in the Silt Clay soil (Soil 5) was 0.06 mg CO_2 g^{-1}

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soil lower than in the Loamy Sand soil (Soil 1) ($p<0.05$ LSD test). Our results suggest that the increase of clay and silt size particles have a role in reducing early-stage C mineralization of crop residues. This effect was likely related to improved soil physical characteristics, as the water-holding capacity of clay soils was higher than the sandy soils (Supplementary Fig. 1).

4.2 Interactions between clay and biochar in enhancing soil pH, and the consequences of early mineralization of plant residues

The pronounced biochar effect on pH is likely due to its high acid buffering capacity. Biochar consists of both alkaline functional groups and mineral ash containing both base cations and secondary carbonates (Fidel et al., 2017), explaining why the biochar and clay + silt content have increased soil pH.

The higher pH of the soil solution promotes the dissolution of CO_2 gas, thereby reducing the amount of gas released from soils. This mechanism can result in a measurement artifact of lower-than-actual mineralization rates in pH-enhanced soils (Ma et al., 2013). However, this effect was accounted for in our study, as mineralization rates were corrected for amounts of CO_2 dissolved in solution as a function of solution volume and pH (Appelo and Postma, 2005). Direct sorption of CO_2 into biochar has also been reported alongside N_2O adsorption and can also be considered a mechanism through which biochar can reduce the presence of these gases in the atmosphere (Cornelissen et al., 2013). Our study suggests a higher capacity of biochar in promoting reductions in the early mineralization of clover residues in sandy soils. This potential is diminished as the clay and silt content increase in the soil.

4. Conclusions

We report the results of a screening study using an experimental setup for high-frequency short-term measurements. We have observed significant effects of biochar and soil texture in reducing early mineralization of clover residues in artificial soils and a significant interaction between these factors. Biochar has demonstrated the potential to reduce the early mineralization of plant residues, especially in sandy soils. This effect is diminished with increased clay and silt content in the soil, suggesting that biochar may compensate for the lack of clay in sandy soils by promoting lower mineralization of organic matter. Results on soil organic matter persistence and carbon sequestration must be confirmed using longer-term experiments. However, this first set of results demonstrates the power of using standardized multi-texture artificial soils to

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study biochar and organic matter interaction in soils. Here we suggest that this artificial soil setup is a valuable platform for understanding mechanisms associated with forming Terra Preta soils.

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Author contribution

TI, SW, FB, EF, and DR designed the experiment. TI and SW carried out the analyses. TI wrote the manuscript with the support of the other authors.

Competing interests

The authors declare that they have no conflict of interest.