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Biochar

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Composted biochar versus compost with biochar: effects on soil properties and plant growth

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Abstract

Biochar is widely recognized as an amendment that enhances soil properties and sequesters carbon, particularly in degraded soils. However, biochar applied solely to soil may also hinder plant development due to toxic by-products generated during pyrolysis or nutrient retention. To mitigate these adverse effects, it has been suggested to either mix biochar with compost or to process it by composting with fresh organic materials. To date, there is a lack of comparative studies evaluating the performance of these two approaches. In this study, three types of biochar, differing in their initial feedstocks (beech wood, hornbeam/beech/oak mixture, and digestate/cereal straw mixture), were investigated. These biochars were applied solely, mixed with green waste compost, or processed as composted biochar in two soils of different fertility (a Luvisol and a gleyic Fluvisol). A pot experiment was conducted under controlled conditions where lettuce was grown for three months. After harvesting, plant biomass, and soil microbial and physicochemical properties were measured. Composted biochar and compost additives maintained a neutral soil pH, contrary to biochar applied solely or mixed with compost. The dissolved organic carbon and total nitrogen were higher in composted biochar treatments, leading to a higher proportion of humified material with a high degree of condensed aromatic groups compared to other treatments. Microbial activities were higher in the composted biochar treatments compared to those in the compost with biochar, and more specifically in the less fertile Luvisol. Finally, composted biochar increased plant growth by almost six times compared to the control without amendments, whereas the mix of biochar and compost increased it by only three times. Solely applied biochars did not affect lettuce growth. This study demonstrates that biochar composting is more beneficial than mixing biochar with compost in terms of improving soil fertility and mitigating the negative effects associated with pure biochar application.

Highlights

- The positive effects of composted biochar application on soil properties and plant growth are higher than biochar and compost co-application.
- The composting process lessened the initial properties' differences among biochars differing in initial feedstock and physicochemical qualities.
- The beneficial effects of composted biochar on soil properties were more pronounced when applied to less fertile soils.

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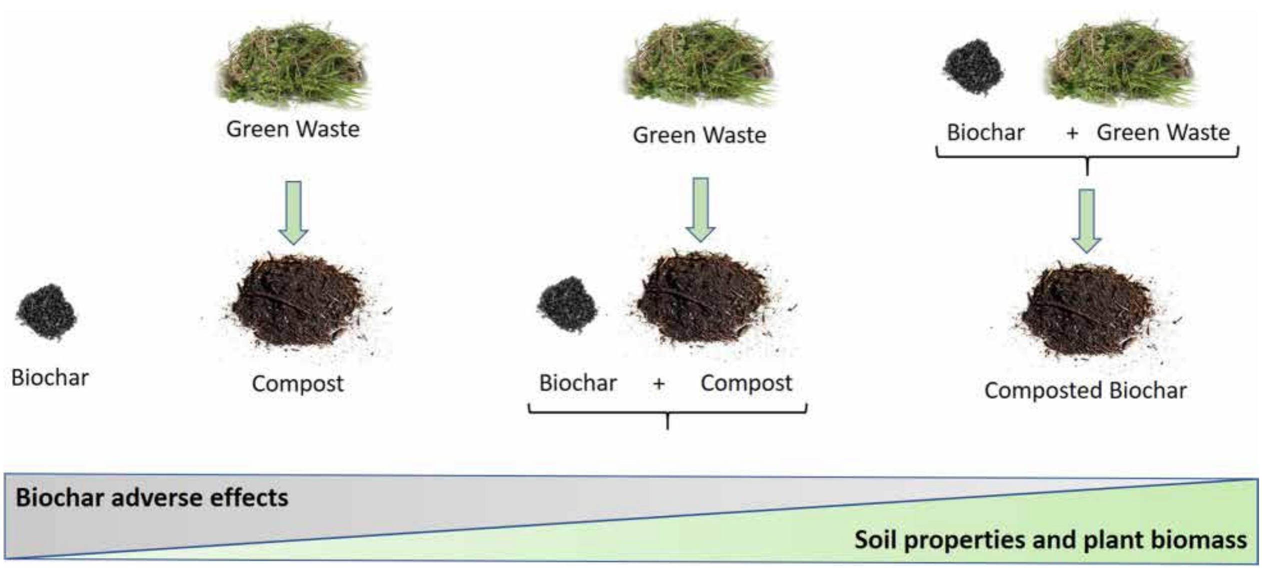
Keywords Biochar, Compost, Composted biochar, Lettuce, Soil

Graphical Abstract



1 Introduction

The decrease in soil organic matter (SOM) causes a strong depletion in agricultural soil fertility, which is associated with reduced crop productivity (Lal 2001; Lehmann et al. 2006; Wani 2016). Increasing SOM stocks with biochar could help achieve several sustainability goals, such as carbon sequestration, improved soil properties, and enhanced plant growth (Sohi et al. 2010; Manyà 2012; Spokas et al. 2012; Glaser and Birk 2012). Biochar is a carbon-rich product of biomass pyrolysis (Lehmann and Joseph 2009) that remains stable in soil for hundreds of years and is one of the most recalcitrant forms of carbon derived from organic matter (Kuzyakov et al. 2009). The positive effect of biochar on plant growth and soil fertility has been attributed to its micro-porous structure and large reactive surface area (Cao et al. 2017), which influence nutrient concentrations in the soil (Hagemann et al. 2016). Biochar quality highly depends on the feedstock and pyrolysis temperature (Kookana et al. 2011; Budai et al. 2016). However, pure biochar does not directly enrich the soil with nutrients but induces an elevation in the C/N ratio, which can increase nitrogen retention (Hagemann et al. 2017b) and consequently deplete the nutrient availability for plants (Mikajlo et al. 2022b). Biochar application can even result in decreased plant biomass (Asai et al. 2009; Glisczynski et al. 2016; Torchia et al. 2023). Thus, co-amendment of organic matter with biochar has been suggested to mitigate its negative impact.

Adding organic matter, such as compost, to biochar is one of the possibilities to improve soil characteristics such as pore volume, water content, water conductivity, bulk density, pH and exchangeable cations (Han et al. 2016; Bass et al. 2016; Wang et al. 2019; Aubertin et al. 2021). These improvements consequently promote yield benefits (Ywih et al. 2014; Abideen et al. 2020; Bouqbis et al. 2021). The combination of biochar mixed separately with compost has been shown to be beneficial (Fischer and Glaser 2012; Schulz and Glaser 2012; Ghosh et al. 2015), notably due to improved aeration of compost materials, enhanced microbial assimilation, and reduced nitrogen (N) loss (Gao et al. 2023). Another effective approach is to compost biochar with organic matter to create co-composted biochar. This composted biochar can considerably promote plant growth compared to pure biochar (Kammann et al. 2016), owing to

Table 1 Biochar (B1, B2, B3) and composted biochar (CB1, CB2, CB3) physical, chemical and microbial properties

	Compost	Biochar			Composted biochar		
		B1	B2	B3	CB1	CB2	CB3
Corg (%)	20.7 ± 1.3^{e}	68.5 ± 5.5^{c}	95.6 ± 2.6^{a}	86.5 ± 0.6^{b}	45.1 ± 1.3^{d}	49.6 ± 0.7^{d}	48.9 ± 3.2^{d}
TN (%)	1.9 ± 0.1^{c}	0.3 ± 0.1^{d}	0.4 ± 0.1^{d}	0.2 ± 0.1^{d}	3.1 ± 0.1^{a}	2.8 ± 0.1^{b}	2.7 ± 0.3^{b}
C/N	11 ± 1^{c}	212 ± 24^{b}	253 ± 36^{b}	502 ± 175^{a}	15 ± 1^{c}	18 ± 1^{c}	19 ± 1^{c}
pH (H_2O)	7.5 ± 0.2^{b}	9.8 ± 0.1^{a}	9.9 ± 0.1^{a}	10.1 ± 0.1^{a}	6.9 ± 0.1^{c}	6.8 ± 0.1^{c}	6.7 ± 0.1^{c}
CEC (cmol kg^{-1})	83.5 ± 15.2^{ab}	59.5 ± 16.6^{cd}	39.9 ± 3.5^{d}	103.5 ± 7.7^{a}	63.2 ± 8.3^{bc}	56.9 ± 18.9^{cd}	59.4 ± 3.3^{cd}
Exchangeable Ca (g kg^{-1})	6.7 ± 0.6^{c}	1.8 ± 0.1^{d}	0.9 ± 0.1^{d}	0.6 ± 0.2^{d}	10.5 ± 0.6^{b}	12.4 ± 1.6^{a}	11.6 ± 0.5^{ab}
Exchangeable K (g kg^{-1})	11.8 ± 1.2^{ab}	6.6 ± 0.2^{c}	1.3 ± 0.1^{d}	3.8 ± 1.1^{d}	14.4 ± 0.3^{a}	11.9 ± 3.1^{ab}	10.7 ± 1.8^{b}
Exchangeable Mg (g kg^{-1})	1.4 ± 0.1^{cd}	1.2 ± 0.1^{d}	0.1 ± 0.1^{e}	0.3 ± 0.1^{e}	2.6 ± 0.1^{a}	1.6 ± 0.2^{bc}	1.7 ± 0.2^{b}
Exchangeable Na (g kg^{-1})	0.9 ± 0.1^{a}	0.1 ± 0.0^{d}	0.1 ± 0.0^{d}	0.1 ± 0.0^{d}	0.2 ± 0.0^{b}	0.2 ± 0.1^{b}	0.3 ± 0.0^{b}
Exchangeable P (g kg^{-1})	1.9 ± 0.1^{d}	1.1 ± 0.1^{e}	0.6 ± 0.1^{f}	0.2 ± 0.1^{g}	3.2 ± 0.3^{a}	2.3 ± 0.1^{c}	2.6 ± 0.2^{b}
Mean Weighted Diameter (µm)	1.1 ± 0.1^{d}	1.7 ± 0.1^{a}	1.4 ± 0.2^{c}	1.8 ± 0.1^{a}	0.5 ± 0.1^{f}	0.9 ± 0.1^{e}	1.6 ± 0.1^{b}
Bacterial abundance (AWCD*)	0.7 ± 0.1^{a}	0.3 ± 0.1^{b}	0.2 ± 0.1^{b}	0.1 ± 0.0^{b}	0.8 ± 0.1^{a}	0.7 ± 0.1^{a}	0.5 ± 0.0^{ab}
Functional richness	22.3 ± 3.1^{a}	14.0 ± 3.6^{bc}	10.0 ± 1.7^{cd}	7.3 ± 1.5^{d}	18.0 ± 3.0^{ab}	15.7 ± 3.2^{b}	13.3 ± 2.1^{bc}
Functional evenness (%)	39.1 ± 0.5^{b}	81.7 ± 1.1^{b}	74.6 ± 2.7^{b}	82.9 ± 1.1^{a}	39.5 ± 1.3^{b}	38.6 ± 0.4^{b}	42.7 ± 0.5^{b}

* AWCD – average weighted color detection

Data are the mean ± standard deviation of 3 replicates (n = 3). Different letters indicate significa t differences among treatments given by the post hoc LSD test

its nutrient-rich organic coating (Hagemann et al. 2017a) and a reduced amount of disadvantageous aromatic compounds. Composting accelerates the surface oxidation of biochar (Wiedner et al. 2015), overcoming the inherent nutrient deficiencies of biochar (Schulz et al. 2013). The temperature fluctuations during the composting process also alter the C/N ratio, enhancing microbial community turnover and leading to higher N retention in the final composted biochar product (Farid et al. 2022). The cation-exchange capacity (CEC) is also modified as organic and inorganic chemicals dissolve, transitioning from solid phases to the compost pore solution (Prost et al. 2012). Recent studies have confirmed the effectiveness of co-application of biochar and compost or composted biochar compared to biochar applied alone (Wang et al. 2019; Antonangelo et al. 2021; Ajibade et al. 2022; Qian et al. 2023). To our knowledge, a direct comparison of composted biochar versus biochar and compost co-application is lacking, with only one study addressing N cycling and plant growth (Kammann et al. 2015).

The main objective of this study was to evaluate the impact of composting on biochar characteristics and compare the effects of solely added biochar, composted biochar, and biochar mixed with compost on soil properties and plant growth. For this aim, three different biochars, differing in feedstock composition and production methods, were composted with green waste. We then tested the effects of composted and non-composted biochars on two soil types with distinct fertility potentials: a Luvisol and a Fluvisol, using lettuce cultivation as an experimental model. It was hypothesized that: i) co-composted biochar will be a more beneficial additive compared to solely or co-applied amendments; ii) co-composting process will reduce the initial differences in biochar properties; and iii) positive changes after co-composted biochar application will be more pronounced in the poor depleted soil.

2 Materials and methods

2.1 Materials collection and preparation

Three types of biochar differing in their production methods and origins were studied. The first biochar (B1) was manufactured by BIOUHEL.CZ s.r.o. (Brno, Czech Republic) from beech wood (*Fagus sylvatica L.*) biomass, using a pyrolysis temperature of 470 °C for 1 h. The second biochar (B2) was produced by La Carbonery (Crissey, France) from a hardwood mixture of hornbeam, beech, and oak, with a pyrolysis temperature of 400 °C for 12 h. The third biochar (B3) was also manufactured by BIOUHEL.CZ s.r.o. (Brno, Czech Republic) from a feedstock consisting of 80% digestate derived from a biogas station processing corn silage and 20% cereal straw, using a pyrolysis temperature of 470 °C for 17 min. The main physicochemical and biological characteristics of the biochars, compost, and composted biochars are summarized in Table 1. The nine-month matured green waste compost "Černý drak" was obtained from a central composting plant operated by SUEZ (Brno, Czech Republic). This compost contained 20% organic carbon (Corg), 1.9% TN, a low C: N ratio of 11.0, a neutral pH of 7.5, and was abundant in exchangeable elements (Ca, K, Mg, Na and P).

2.2 Biochar composting process

The biochar composting was conducted in a ThermoKing® 400 L composter. The bottom of the composter was filled with grass and straw biomass to enhance the composting process and facilitate interaction between the biochar mixtures. To prepare the composted biochar, 1 kg of fresh grass and wheat straw from Banín plots, 200 g of "Černý drak" compost (SUEZ, Brno), and 37 mL of urea solution ($CH_4N_2O = 568$ g L^{-1}) were mixed. Finally, 240 g of each type of biochar was added, corresponding to 20% (m/m) of the total mixture (fresh biomass to biochar ratio of 5:1). The three types of biochar were mixed separately with the aforementioned components (n = 4), placed into perforated plastic bags, and then put into the composter for four months. The mixtures were thoroughly stirred every week and maintained at 50% humidity. The maximum temperature in the composter reached 55.7 °C. After four months, the temperature inside the composter decreased and stabilized at room temperature (18 °C). The maturity of the composted biochar was verified following ISO standard 17126:2005 by conducting a screening test for the emergence of lettuce seedlings.

2.3 Material analyses

Before the soil experiment, the compost, biochars, and composted biochars underwent the same physical, chemical, and microbial analyses. The particle size distribution was determined by sieving through 2000, 1000, 800, 500, 400, 200, 100, and 50 µm sieves. Mean weight diameter (MWD, mm) of the materials was calculated following the method of Kemper and Rosenau (1986). The Corg and TN contents were measured using an elemental analyzer (Thermo Fisher Scientific FlashHT). Elemental analysis was further conducted with X-ray fluorescence (Bruker S1 Titan 800 Handheld XRF Analyzer). The molecular composition was characterized using mid-infrared spectroscopy (MIRS) with a Fourier Transform Spectrophotometer (FTIR 660, Agilent Technologies, Santa Clara, CA, USA). The pH measurement was conducted with a 1:5 ratio of ultra-pure water to sample using a pH meter (Mettler Toledo®) in accordance with ISO 10390:2021. The cation exchange capacity (CEC) and exchangeable cation concentrations were measured using hexamine cobalt (III) chloride solution, following ISO 23470:2018, on an Agilent 7500cx quadrupole ICP-MS spectrometer. Microbial characterization was performed using Biolog® MicroPlates and a microplate reader (BioTek EL-800). The "single-point reading" approach from Garland et al. (2001) was adopted. The average well-color development (AWCD), catabolic richness, and evenness (E) were calculated as described by Kheir et al. (2020). Finally, the biochar surface was thoroughly examined with a variable pressure Scanning Electron Microscope (SEM) EVO® LS15 (Zeiss).

2.4 Soil preparation and cultivation experiment

Soil samples were collected from the topsoil horizon (0–30 cm) of two experimental sites. The first soil originated from the grassland permanent experimental plot located in the protection zone of the underground drinking water source "Banín" (49°40.409″N, 16°27.545″E, Czech Republic). This soil is classified as a sandy loam Luvisol (WRB, FAO). The second soil was sampled from the "Žabčice" agricultural plot (49°0′24.600″N, 16°35′41.840″E, Czech Republic), which has been continuously cultivated with grain crops, mainly wheat (*Triticum aestivum L.*), using mineral fertilizers. This soil belongs to a sandy loam gleyic Fluvisols (WRB, FAO), carbonated, with a clay content of 55–65%. After sampling, the soils were homogenized, dried, and sieved through a 10 mm mesh. The Banín Luvisol (L) has a slightly acidic pH of 6.3, while the Žabčice Fluvisol (F) has a closer-to-neutral pH of 6.9. The soil organic carbon (SOC) content was similar in both soil types, ranging from 11 to 11.3 mg g^{-1}, and the total nitrogen (TN) content ranged from 1.2 to 1.6 mg g^{-1}, with phosphorus (P) content around 0.18–0.2 mg g^{-1} in both soils. The chemical fertility of the Fluvisol was higher compared to the Luvisol: 2709 and 1449 mg kg^{-1} Ca, 332 and 168 mg kg^{-1} K, 192 and 53 mg kg^{-1} Mg, 198 and 181 mg kg^{-1} P, respectively. Additionally, the cation exchange capacity (CEC) in the Fluvisol (10.9 cmol kg^{-1}) was almost twice that of the Luvisol (6.2 cmol kg^{-1}). For the experiment, 700 g of each soil type was placed into square 1L pots (n = 4). Each soil type received 11 treatments: 3 biochar applications (B1, B2, or B3) (14 g each); 3 composted biochars (CB1, CB2, and CB3) (52 g each); compost (38 g) combined with 3 different biochars (B1 + C, B2 + C, and B3 + C) (14 g biochar each); 60 g of "Černý drak" compost (C); and a control soil without amendments (No). The pots were placed in a growth chamber (phytotron CLF PlantClimatics®) with controlled conditions: daytime temperature of 21 °C, nighttime temperature of 18 °C, 65% humidity, 16-h day length, and light intensity of 380 µmol m^{-2} s^{-1}. The following day, lettuce plants (*Lactuca sativa var. capitata*) were seeded, with one plant per pot. Lettuce was chosen due to its rapid growth cycle, making it suitable for the laboratory experiment where changes in aboveground biomass reflect soil condition changes. Throughout the experiment, pots were watered with 50 mL of deionized water every 2 days, with an increased irrigation to 75 mL every 2 days during plant growth. After 90 days of planting, the lettuce plants were harvested for further analysis.

2.5 Plant and soil analyses

The aboveground biomass of lettuce was harvested and placed on plastic trays, then dried at 40 °C in an oven until reaching a constant weight. The plant roots were washed with osmotic water and dried under the same conditions. The dry weight (DW) of both aboveground and root biomass was determined. The soil without roots was sieved to 2 mm, with one portion dried at 40 °C for physicochemical analysis and another stored at 4 °C for biological measurement. Prior to physicochemical analyses, the dried soil was sieved to 250 µm. pH (H_2O) was measured after mixing the soil with deionized water (1:5, v/v), following ISO 10390 standards. Cation exchange capacity (CEC) was analyzed by percolating CH_3COONH_4 (1 M, pH = 7) solution through soil samples, followed by extraction of ammonium ions (NH_4^+) with sodium chloride (NaCl, 1 M), in accordance with the French NF X31-130 standard. SOC was extracted and quantified according to ISO 14235 standards, using the sulfochromic oxidation method (NF X 31–109, 1993). Dissolved organic carbon (DOC) was extracted in 0.5 M NaOH solution prepared as per Zbytniewski and Buszewski (2005), and quantified via sulfochromic oxidation (NF ISO 10694). UV–Vis spectroscopy (Thermo Scientific Multiskan®, GO, Finland). The absorbances at λ = 280 nm (A280) and 664 nm (A664) were used to characterize DOC quality, calculating the ratio $Q_{2/6}$ (A280/A664), which denotes the relationship between non-humified and strongly humified material (Zbytniewski and Buszewski 2005).TN content was measured by the dry combustion method according to ISO 13878. Available phosphorous (P_2O_5) concentration was measured following French NFX 31–161 standards and the Joret and Hébert (1955) procedure, using extraction in ammonium oxalate solution ($(NH_4)_2 \cdot C_2O_4$, 0.1 M, pH = 7). Urease activity was assessed following the method of Kandeler and Gerber (1988). Fluorescein diacetate hydrolytic activity (FDA) was analyzed as described by Green et al. (2006). Soil respiration was measured using the OxiTop® system in accordance with Platen and Wirtz (1999) procedures. Soil nitrogen availability from microbial mineralization (N_{mic}) (Bundy and Meisinger 1994) was determined according to Peoples et al. (1989). Ammonium NH_4^+ and nitrate nitrogen NO_3^- leaching was measured using mixed selective cation (CER) and anion (AER) ion exchangers (IERs) captured in round disks (Binkley and Matson 1983) under the pots (Záhora 2001; Novosádová et al. 2011), and trapped mineral N was analyzed after via the distillation-titration method (Peoples et al. 1989).

2.6 Statistical analysis

All statistical analyses were conducted using R software version 3.3.1 (R Development Core Team, 2016). After the normality and homoscedasticity verifications (Shapiro and Bartlett test), the soil and plant parameters were analyzed using a two-way analysis of variance (ANOVA). When significant ($P < 0.05$) effects were found, the comparisons among means were performed using the Least Significant Difference (LSD) test ("agricolae" package). The biochar chemical (MIRS), elemental (XRF), physical (sieving) and microbial (Biolog) profiles were analyzed using Principal Component Analysis followed by Between-Class Analysis (BCA) using the "ade4TkGUI" package. Differences among treatments were tested with the Monte Carlo Permutation Test with 999 permutations. The similarity between profiles before and after biochar composting was evaluated using a Mantel test with 1000 permutations using the "vegan" package. All graphical representations were performed using SigmaPlot 14.0 software.

3 Results

3.1 Biochar and composted biochar properties

All three types of biochar significantly differed in their physical, chemical, and microbiological characteristics. The multivariate analyses based on granulometry (Fig. 1, left) showed distinct differences among the 3 biochars: B1 consisted mainly of smaller particles (50–400 µm), whereas larger particles (2000 µm) were predominant in B3. The MWD was significantly lower in B2 (Table 1). The B1 biochar had the highest ash content (32.7%), contrary to B2 (8.3%) and B3 (6.9%), which is usually revealed in wood-derived biochar that was produced at high temperatures (Domingues et al. 2017). Inversely, Corg was higher in B2 and B3, compared to B1. Three biochars did not differ significantly in total nitrogen (TN), so the C/N ratio in B3 was twice higher compared to B1 and B2 (Table 1). Middle infrared spectrometry (MIRS) showed distinct molecular compositions among the biochars (Fig. 1, left). X-ray fluorescence (XRF) analysis revealed

(See figure on next page.)

Fig. 1 Differences in physical, elemental, chemical and biological properties among biochars (left) and composted biochars (right). Between Class Analysis (BCA) is based on granulometry, XRF analyses, MIRS analyses and Biolog profiling. The ellipses represent 60% of the variability. Letters represent the barycenter of the replicates (n = 3) for each biochar (B1, B2, B3) or composted biochar (CB1, CB2, CB3). Monte Carlo test simulated *P* values (lower left corner) revealed significant differences among biochars. The relationship between biochar and composted biochar BCA is indicated with the double arrows (Mantel tests)

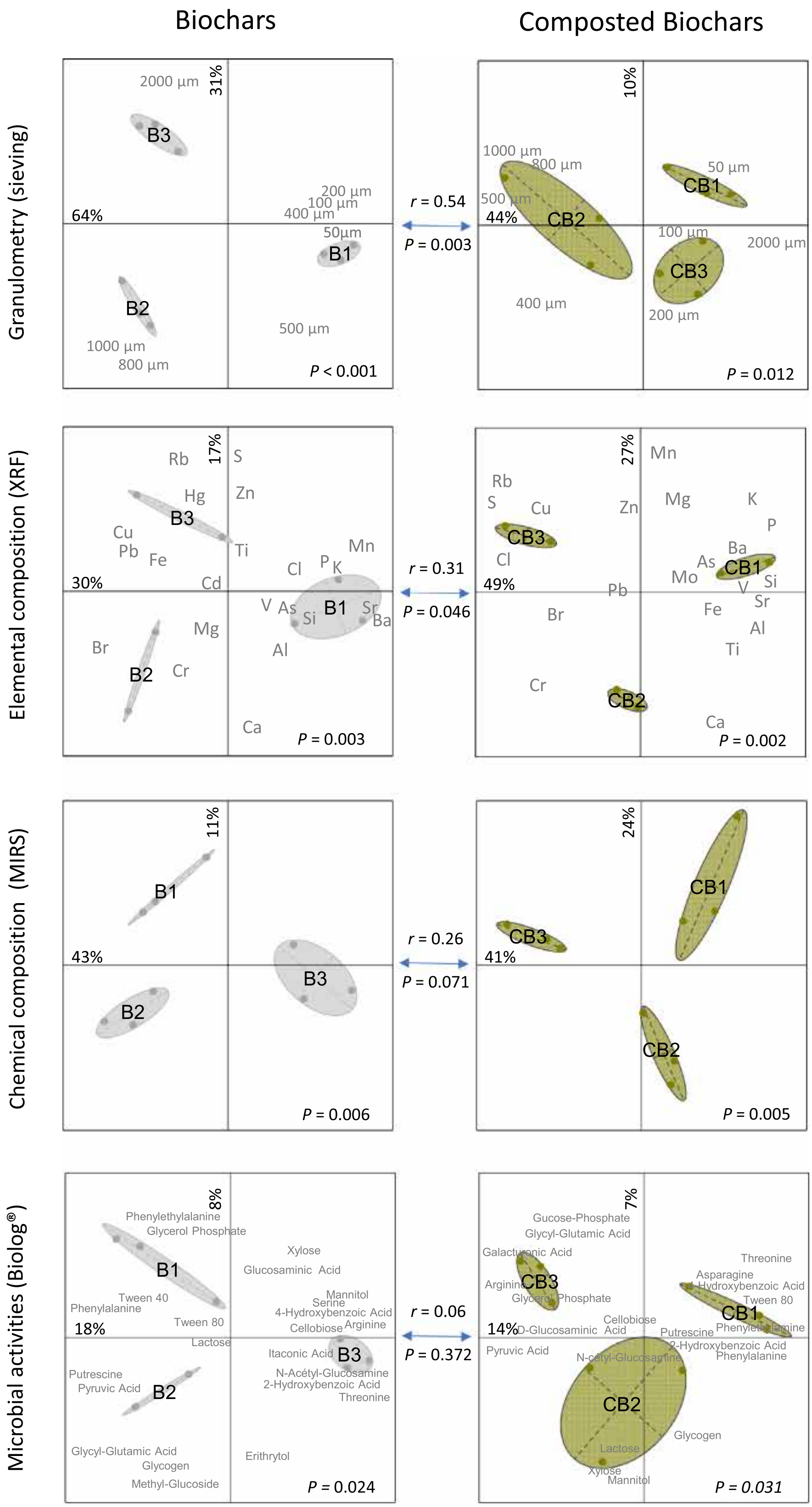


Fig. 1 (See legend on previous page.)

differences in elemental composition: B1 was enriched in macro-elements (Mn, K, P, Si, Al), while B3 contained higher levels of trace metals (Cu, Pb, Hg, Zn) (Fig. 1, left and Table S1). pH values were similar across all biochars, while the CEC was twice higher in B3 compared to B1 and B2 (Table 1). Exchangeable cation concentrations were similar among biochars, except for slightly higher K, Mg, and P in B1 (Table 1).

In terms of biological properties, bacterial abundance (AWCD) did not vary significantly among the biochars, though functional richness was higher in B1 and functional evenness was higher in B3. Metabolic profiles indicated distinct functional diversity among the biochars. The comparison SEM images illustrated changes in biochar structure before and after the composting process (Fig. 2). The original porous woody structure of biochar and the varying feedstocks (beech wood in B1, hornbeam/beech/oak mixture in B2, corn silage with cereal straw in B3) were evident. After composting, the images depicted an altered biochar surface with surrounding organic material integrated into the amendment. The composting process changed significantly biochar properties (Table 1, right). It reduced Corg content in composted biochar treatments to < 50% but increased N content tenfold, resulting in C/N ratios of 15 to 19. pH levels became more neutral, and although CEC changes were minimal, there was a significant increase in exchangeable cation concentrations, particularly Ca, K, and Mg. Composting also affected granulometry by slightly decreasing the MWD. Bacterial abundance and functional richness increased, while functional evenness declined, suggesting homogenization of these parameters after composting. Multivariate analyses still revealed substantial differences among the three composted biochars in physical, chemical, and biological profiles (Fig. 1, right). The Mantel test indicated a similar pattern for MIRS and Biolog fingerprints before and after composting, though this differed for XRF and granulometry.

3.2 Changes in soil physicochemical properties

The chemical properties were significantly affected by the treatment, soil type, and their interaction, except for total P, which was not influenced by the soil type (Table 2). Variations in SOC, TN, pH, DOC and $Q_{2/6}$ ratio were primarily influenced by the treatment, while the CEC varied mainly due to soil type. TP variation was predominantly caused by the interaction between treatments and soil types. Between-class analysis revealed substantial differences among all treatments, explaining 49% of the variability in Luvisol and 47% in Fluvisol (Fig. 3). Higher pH, $Q_{2/6}$ ratio, and SOC values were associated with pure biochar treatments, whereas higher DOC and TN values were linked to composted biochar (CB) treatments in both soils. The pH correlated negatively with DOC content in both soil types (Figure S1). Composted biochar neutralized soil pH in both soil types that was equal to control soil, whilst the other treatments with solely applied biochar and biochar mixed with compost revealed no dramatic differences, resulting in slightly alkaline values (Table 3). The CB1 had more elevated pH than CB2 and CB3. The highest CEC values were found in treatments combining biochar with compost (B + C), pure compost, and CB1. Other treatments showed lower values, equal to the control. In Fluvisol CB1 and C had the highest values, contrary to Luvisol, the rest of the treatments including B + C were similar to the control. pH correlated positively with CEC in Luvisol and SOC in both soils (Figure S1). SOC amount in Luvisol was significantly higher in B3 and B3 + C treatments, approximately 1.4 times greater than the control. Other treatments showed SOC concentrations similar to the control, except B1 and B1 + C treatments (Table 3). A similar trend was observed in Fluvisol treatments, where the highest SOC content was found in B3 + C and B3 compared to the control. DOC content followed a similar pattern in both soil types, with CB treatments showing the highest values compared to the control. The latter had the same DOC contents as B treatments and B + C treatments. Regarding DOC quality, $Q_{2/6}$ ratio was the highest in B and the lowest in CB treatments. It correlated negatively with DOC and positively with pH (Figure S1). Luvisol treatments had the highest TN content in CB1 and B3 + C, while other treatments showed TN contents similar to the control (Table 3). In Fluvisol, only B2 and B3 had significantly lower TN content compared to CB1 treatment. The P content in unamended Luvisol did not significantly differ from most treatments, except B1 + C, which had nearly six times higher P content. In Fluvisol, no substantial differences were found between the control and other treatments, except for B1 and compost treatments, which had 2.5–3.3 times higher P content compared to the control. The P content in Fluvisol correlated positively with pH and $Q_{2/6}$ ratio (Figure S1).

3.3 Changes in soil biological parameters

The partition of variance showed that treatment, soil type, and their interaction significantly influenced all biological parameters except for ammonium and nitrates, and the soil type for FDA (Table 2). FDA and N_{mic} variability were primarily explained by treatments, while urease and soil respiration were affected by the interaction between treatments and soils. Between-class analysis clearly illustrated differences among amendments, explaining 51% and 41% of the variability in Luvisol and Fluvisol, respectively (Fig. 3). In both cases, CB was associated with higher FDA and

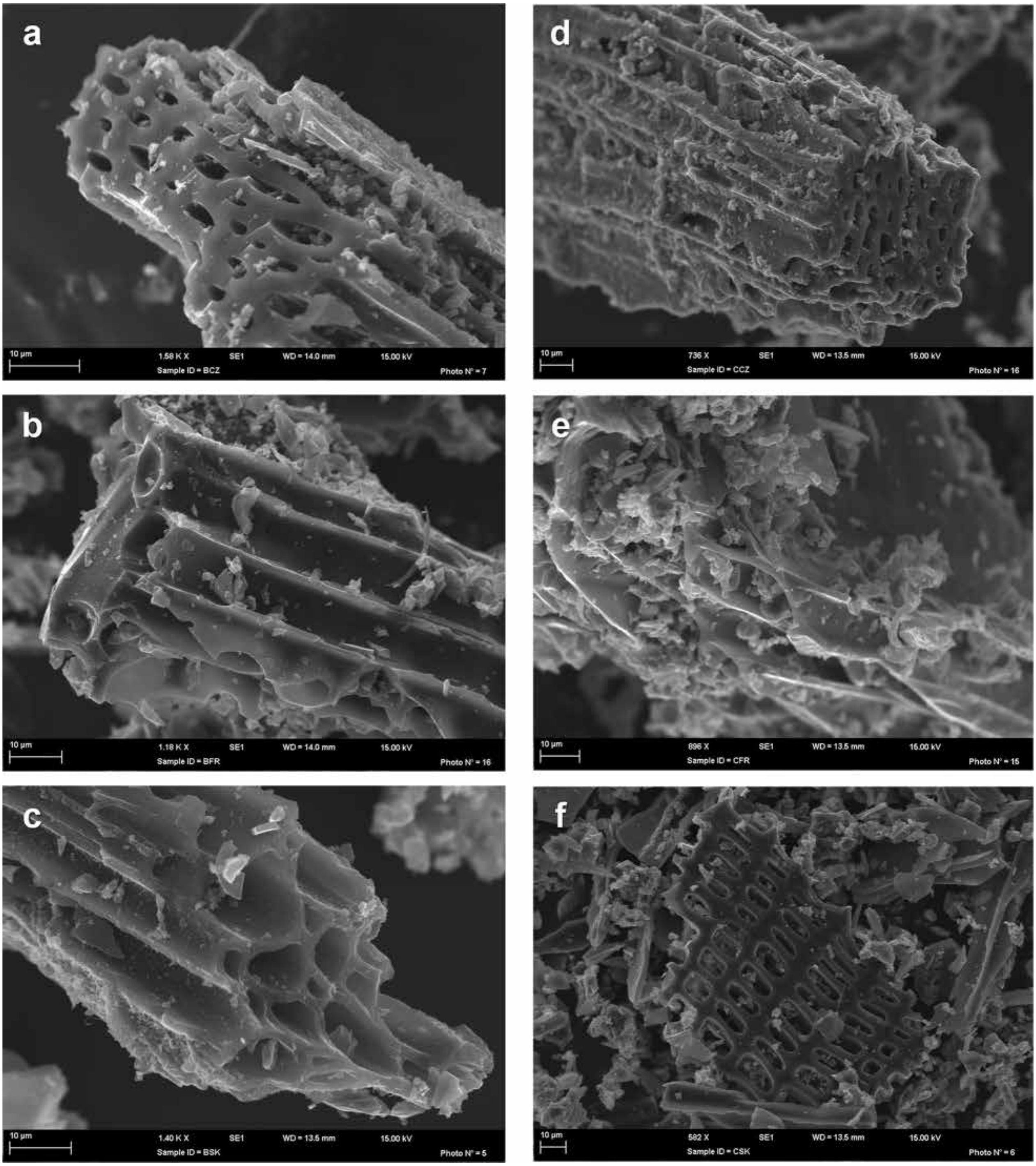


Fig. 2 Scanning Electron Microscopy pictures of biochars (**a**: B1; **b**: B2; **c**: B3) and composted biochars (**d**: CB1; **e**: CB2; **f**: CB3)

N_{mic} values. Biochar amendments generally influenced Luvisol and Fluvisol differently (Table 3). No considerable differences were found in urease activity between the control, B2 and B + C treatments in Luvisol. CB3 exhibited the highest urease activity in Luvisol, yet decreased activity in Fluvisol. Similarly, CB2 showed the highest urease activity in Fluvisol. Urease activity in CB3 was 2.4 times higher in Luvisol compared that in Fluvisol. Additionally, urease activity correlated positively with NO_3^- leaching in Fluvisol (Figure S2).

Table 2 Proportion (%) of the variance explained by the different amendments, the soils studied and the interactions between the two latter factors for each chemical or biological parameter (n = 3)

		Treatment	Soil	Interaction
Chemical properties	SOC	57.6***	20.4***	8.7***
	TN	35.1***	12.4***	12.2*
	pH	89.5***	2.7***	4.1***
	CEC	1.8***	96.5***	0.5*
	DOC	68.1***	6.7***	4.1**
	$Q_{2/6}$	54.2***	20.7***	5.8*
	TP	3.6***	1.1	5.1***
Biological properties	Urease	19.1***	10.9***	39.8***
	Nmic	71.7***	7.5***	6.7**
	FDA	89.5***	0.1	4.9***
	CO_2	28.6***	9.1***	42.0***
	NH_4^+	13.8	0.6	13.6
	NO_3^-	2.4**	2.3	1.6

Significa t effects are represented as follows: "***": $P < 0.001$; "**": $P < 0.01$; "*": $P < 0.05$

FDA in both control soils was equal to B amendments, except for B3. The highest FDA values in both soil types were observed in CB treatments, especially in those amended with CB1. Solely applied compost influenced microbial activity differently in Luvisol and Fluvisol (Table 3). B + C treatments showed FDA activity comparable to B-applied treatments. N_{mic} in Luvisol control was similar to compost additive and B3 treatment, contrary to the CB additives that had elevated values. A similar trend was observed in Fluvisol, with slightly lower N_{mic} compared to similar Luvisol treatments. CB1 treatments in both soil types showed higher N_{mic} compared to the control. In Luvisol, leached NH_4^+ was higher in CB with compost additives compared to the control, while equal in other treatments. NO_3^- leaching was higher in B + C, compost, and CB3 compared to the control, which did not differ significantly from other additives. In Fluvisol, the highest NH_4^+ leaching was found in B1 + C compared to CB, but otherwise, treatments did not significantly differ from the control. NO_3^- leaching was elevated in CB1 and CB2, while similar in other treatments. The highest soil respiration was detected in B1, B2 and CB1 treatments in Luvisol and C1 and B2 + C in Fluvisol (Table 3). Overall, microbial biomass (N_{mic}) and activities (CO_2, FDA) showed positive correlations (Figure S2).

3.4 Changes in plant aboveground and root biomass

Significant differences were observed in the aboveground and belowground dry biomass of lettuces cultivated in both soils (Fig. 4), irrespective of soil type. In Luvisol, B modalities showed no significant differences compared to control plants. However, B + C treatments exhibited biomass levels 2–3 times higher than the control. CB treatments showed significantly higher biomass, approximately five times greater than the control, with CB3 particularly surpassing compost-only treatments. In Fluvisol, B + C treatments resulted in biomass levels about 3 times higher than control plants, while CB treatments showed approximately 4 times higher biomass and B equaled the control. CB and B + C treatments showed similar biomass outcomes, contrasting with Luvisol where CB treatments outperformed B + C treatments. The combined application of biochar and compost resulted in lower plant biomass compared to the sum of biomasses from individual biochar and compost treatments, suggesting a negative interaction when both amendments were applied together. Similar trends were observed in root biomass, indicating that the root-to-shoot ratio did not vary significantly among treatments (Fig. 4).

4 Discussion

4.1 Effects of composted biochar on soil physicochemical properties

In this study, significant improvements in most physicochemical parameters were observed in composted biochar treatments compared to biochar mixed with compost and other treatments. Initially neutral soil pH was maintained by composted biochar, whereas treatments with pure biochar and compost addition resulted in a slightly alkaline pH, consistent with prior findings indicating biochar's tendency to increase pH after compost addition (Chung et al. 2023). Our findings are aligned with the results of Nain et al. (2024) on various co-composted biochars, which reported lower pH values in composted biochar treatments compared to sole biochar applications. The results are in line with the study of Iqbal et al. (2015) on forest slash biochar, co-composted biochar and compost in leaching columns with sandy media, noting higher pH with biochar alone and lower pH with co-composted biochar. B1 consistently increased pH values across all treatments in

(See figure on next page.)

Fig. 3 Differences (Between Class Analysis) in chemical (upper) and biological (lower) properties among soil treatments for the Luvisol (left) and Fluvisol (right). The ellipses represent 60% of the variability. Letters represent the barycenter of the replicates (n = 3) for each biochar alone (B1, B2, B3), biochars with compost (B1 + C, B2 + C, B3 + C), composted biochars (CB1, CB2, CB3), compost (C) and control (No). Monte Carlo test simulated P values (lower left corner) revealed significant differences among biochars

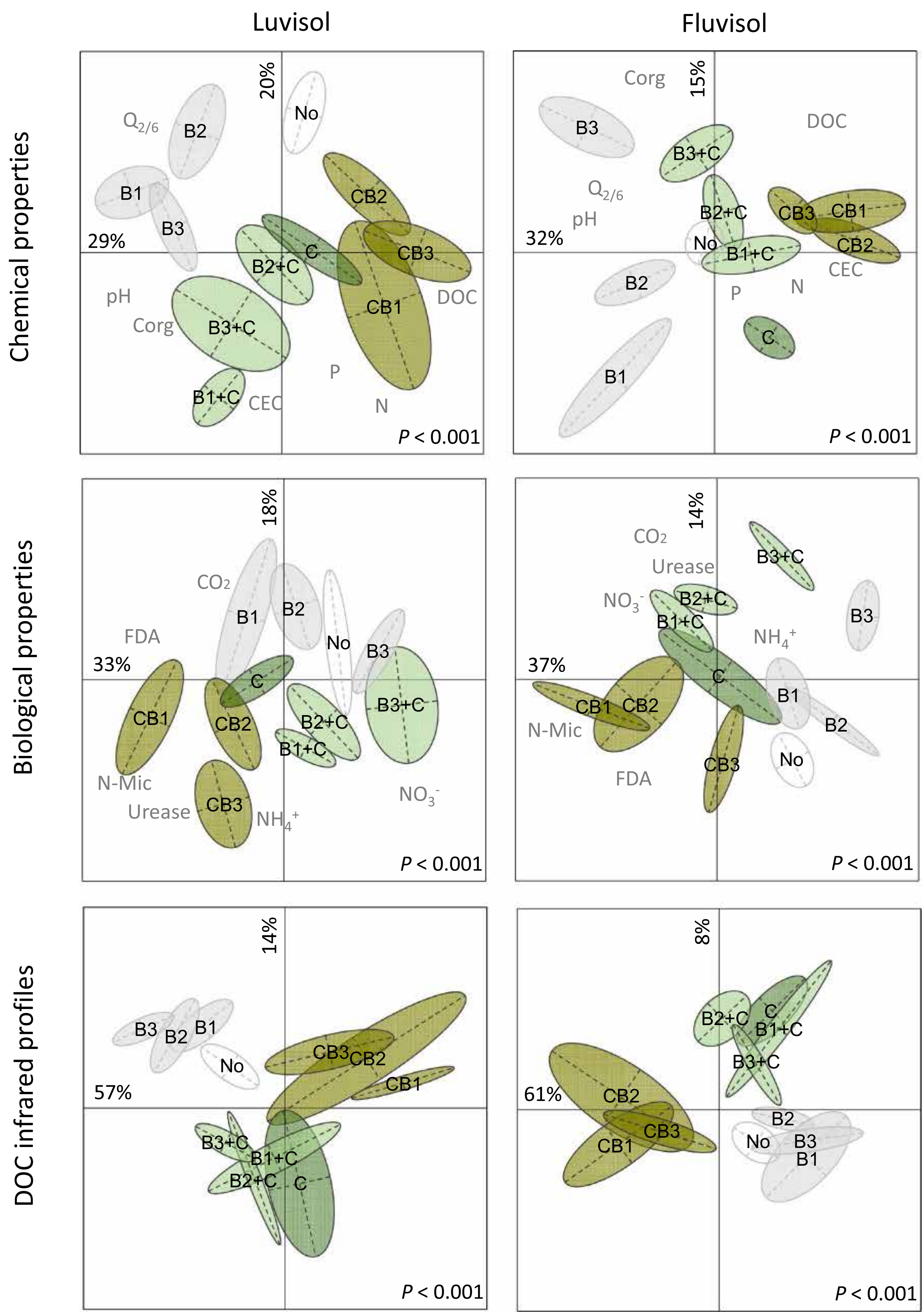


Fig. 3 (See legend on previous page.)

Table 3 Chemical properties of the Luvisol and the Fluvisol not amended (No) or amended with biochar (B1, B2, B3), biochar and compost (B1 + C, B2 + C, B3 + C), composted biochar (CB1, CB2, CB3) or only compost (C)

	Treatment	pH (H_2O)	CEC (cmol kg^{-1})	SOC (g kg^{-1})	DOC (mg g^{-1})	TN (g kg^{-1})	TP (mg kg^{-1})	$Q_{2/6}$
Luvisol	No	6.8 ± 0.0^{f}	6.2 ± 0.2^{def}	28.5 ± 2.3^{ef}	1.25 ± 0.1^{d}	0.3 ± 0.0^{cd}	49.5 ± 3.1^{cd}	4.6 ± 0.2^{abc}
	B1	8.0 ± 0.1^{a}	6.5 ± 0.2^{bcd}	34.2 ± 4.2^{bcd}	1.13 ± 0.1^{d}	0.4 ± 0.1^{bc}	52.0 ± 3.4^{cd}	4.7 ± 0.1^{a}
	B2	7.6 ± 0.1^{cb}	6.3 ± 0.3^{cde}	30.0 ± 4.5^{def}	1.15 ± 0.0^{d}	0.2 ± 0.1^{bc}	11.6 ± 2.1^{d}	4.7 ± 0.1^{ab}
	B3	7.7 ± 0.1^{b}	6.3 ± 0.2^{cde}	40.1 ± 3.8^{a}	1.17 ± 0.1^{d}	0.4 ± 0.0^{d}	71.8 ± 17.3^{c}	4.7 ± 0.2^{a}
	CB1	7.0 ± 0.0^{e}	6.6 ± 0.3^{abc}	31.4 ± 1.8^{cdef}	1.93 ± 0.1^{a}	0.6 ± 0.2^{a}	59.3 ± 2.5^{cd}	3.7 ± 0.9^{f}
	CB2	6.9 ± 0.1^{f}	6.1 ± 0.3^{ef}	32.3 ± 1.5^{cde}	1.86 ± 0.3^{ab}	0.5 ± 0.0^{bc}	58.2 ± 4.0^{cd}	4.0 ± 0.2^{e}
	CB3	6.8 ± 0.1^{f}	5.9 ± 0.2^{f}	29.8 ± 3.6^{ef}	1.72 ± 0.2^{ab}	0.4 ± 0.0^{bc}	216.4 ± 54.5^{b}	4.2 ± 0.1^{de}
	B1 + C	8.0 ± 0.1^{a}	6.9 ± 0.2^{a}	35.7 ± 3.4^{bc}	1.33 ± 0.1^{cd}	0.5 ± 0.1^{bc}	275.5 ± 46.8^{a}	4.4 ± 0.1^{bcd}
	B2 + C	7.5 ± 0.1^{c}	6.7 ± 0.1^{ab}	30.4 ± 1.4^{def}	1.33 ± 0.2^{cd}	0.5 ± 0.0^{bc}	59.6 ± 1.8^{cd}	4.4 ± 0.1^{cd}
	B3 + C	7.7 ± 0.0^{b}	6.9 ± 0.1^{a}	38.1 ± 2.1^{ab}	1.33 ± 0.3^{cd}	0.5 ± 0.1^{ab}	96.0 ± 10.9^{c}	4.5 ± 0.1^{abc}
	C	7.3 ± 0.1^{d}	6.9 ± 0.1^{a}	27.7 ± 1.4^{f}	1.58 ± 0.3^{bc}	0.4 ± 0.1^{bc}	58.3 ± 5.7^{cd}	4.3 ± 0.1^{cde}
Fluvisol	No	7.1 ± 0.0^{e}	10.9 ± 0.2^{cde}	33.4 ± 1.9^{e}	1.05 ± 0.3^{d}	0.5 ± 0.1^{b}	68.9 ± 4.8^{c}	4.9 ± 0.1^{a}
	B1	8.1 ± 0.0^{a}	10.7 ± 0.2^{e}	34.5 ± 2.7^{de}	0.94 ± 0.2^{d}	0.9 ± 0.2^{b}	224.4 ± 49.6^{a}	4.9 ± 0.1^{a}
	B2	7.7 ± 0.2^{c}	10.9 ± 0.3^{de}	33.1 ± 1.6^{e}	0.77 ± 0.4^{d}	0.5 ± 0.0^{bc}	68.9 ± 5.7^{c}	4.9 ± 0.1^{ab}
	B3	7.9 ± 0.1^{b}	10.9 ± 0.5^{cde}	43.7 ± 5.2^{a}	0.73 ± 0.2^{d}	0.4 ± 0.1^{c}	52.3 ± 7.6^{c}	4.9 ± 0.1^{a}
	CB1	7.4 ± 0.2^{d}	11.6 ± 0.4^{ab}	37.3 ± 0.8^{bcd}	1.75 ± 0.2^{a}	0.6 ± 0.1^{a}	68.8 ± 2.0^{c}	4.4 ± 0.1^{de}
	CB2	7.1 ± 0.1^{e}	11.2 ± 0.5^{bcd}	33.4 ± 0.5^{e}	1.96 ± 0.1^{ab}	0.5 ± 0.0^{ab}	68.1 ± 0.7^{c}	4.3 ± 0.2^{e}
	CB3	7.1 ± 0.1^{e}	11.0 ± 0.3^{cde}	38.4 ± 2.6^{b}	1.61 ± 0.1^{ab}	0.6 ± 0.0^{ab}	68.9 ± 0.8^{c}	4.5 ± 0.1^{d}
	B1 + C	7.9 ± 0.1^{b}	11.4 ± 0.4^{bcd}	37.6 ± 0.9^{bc}	1.24 ± 0.4^{cd}	0.5 ± 0.0^{ab}	72.1 ± 0.9^{c}	4.7 ± 0.2^{c}
	B2 + C	7.4 ± 0.1^{d}	10.9 ± 0.5^{cde}	36.1 ± 3.6^{bcde}	1.14 ± 0.1^{cd}	0.5 ± 0.1^{b}	61.0 ± 7.1^{c}	4.7 ± 0.1^{c}
	B3 + C	7.7 ± 0.1^{c}	11.4 ± 0.3^{bc}	50.2 ± 3.3^{a}	1.23 ± 0.2^{cd}	0.5 ± 0.1^{ab}	73.7 ± 0.6^{c}	4.7 ± 0.1^{abc}
	C	7.3 ± 0.1^{d}	12.0 ± 0.4^{a}	35.1 ± 1.2^{cde}	1.14 ± 0.1^{bc}	0.5 ± 0.0^{ab}	175.9 ± 9.1^{b}	4.7 ± 0.1^{bc}

Values are the mean ± standard deviation of 3 replicates (n = 3). Different letters indicate significa t differences among treatments for a given soil

both soil types, despite similar initial and final pH values of amendments (Table 3). Moreover, high pH provided by the biochar also correlates with high CEC as reported by Carter et al. (2013) in studies involving rice husk char in soil with planted lettuce and cabbage. Both composted biochar and biochar with compost increased soil CEC due to organic matter input. According to Prost et al. (2012), the increasing CEC resulted not only from the amount of the organic matter sorbed to the biochars that contributed to their higher degree of functional groups, but also from the increasing functionalization of organic matter during composting. However, our results showed a lesser effect contrary to studies on composted biochar from hardwood shavings, macadamia nutshells, and chicken litter, which increased CEC up to six times compared to biochar (Khan et al. 2016). In the study of Bass et al. (2016), composted willow wood biochar increased CEC in red ferralsols by almost 25%, nevertheless reporting a higher 27.5% rise in compost-amended treatments. In the current study, soil type primarily influenced CEC and amendments influenced less, with Fluvisol showing values twice as high as Luvisol. Composting mitigated initial CEC differences among biochars, particularly evident with B3 biochar. The composting process likely altered intrinsic properties of biochar through physicochemical interactions, including surface oxidation (Wiedner et al. 2015) and organic coating (Hagemann et al. 2017a). While available nutrients grew in composted biochars, elemental and chemical compositions remained stable, as also showed in the study of Khan et al. (2016). It was hypothesized that the co-composting process would reduce the initial differences among biochar properties. It was partially the case but some discrepancies throughout the three biochars were still visible with the finer analysis depending on the feedstock (Fig. 1).

The SOC increase was the highest with the B3 biochar addition in any combination across both soils due to the biochar nature, which is in line with the findings of Zhang et al. (2020) on co-composted biochar influence on *T. hemsleyanum* growth and Glisczynski et al. (2016) on the biochar-compost substrates in Luvic Stagnosol with planted poplar, willow, robinia and alder. SOC values were slightly higher in Fluvisol compared to Luvisol. Contrary to the findings of Zhang et al. (2016), who noted lower DOC with straw biochar in pig manure composting, our study found elevated DOC in soils with composted biochar treatments. DOC was lower

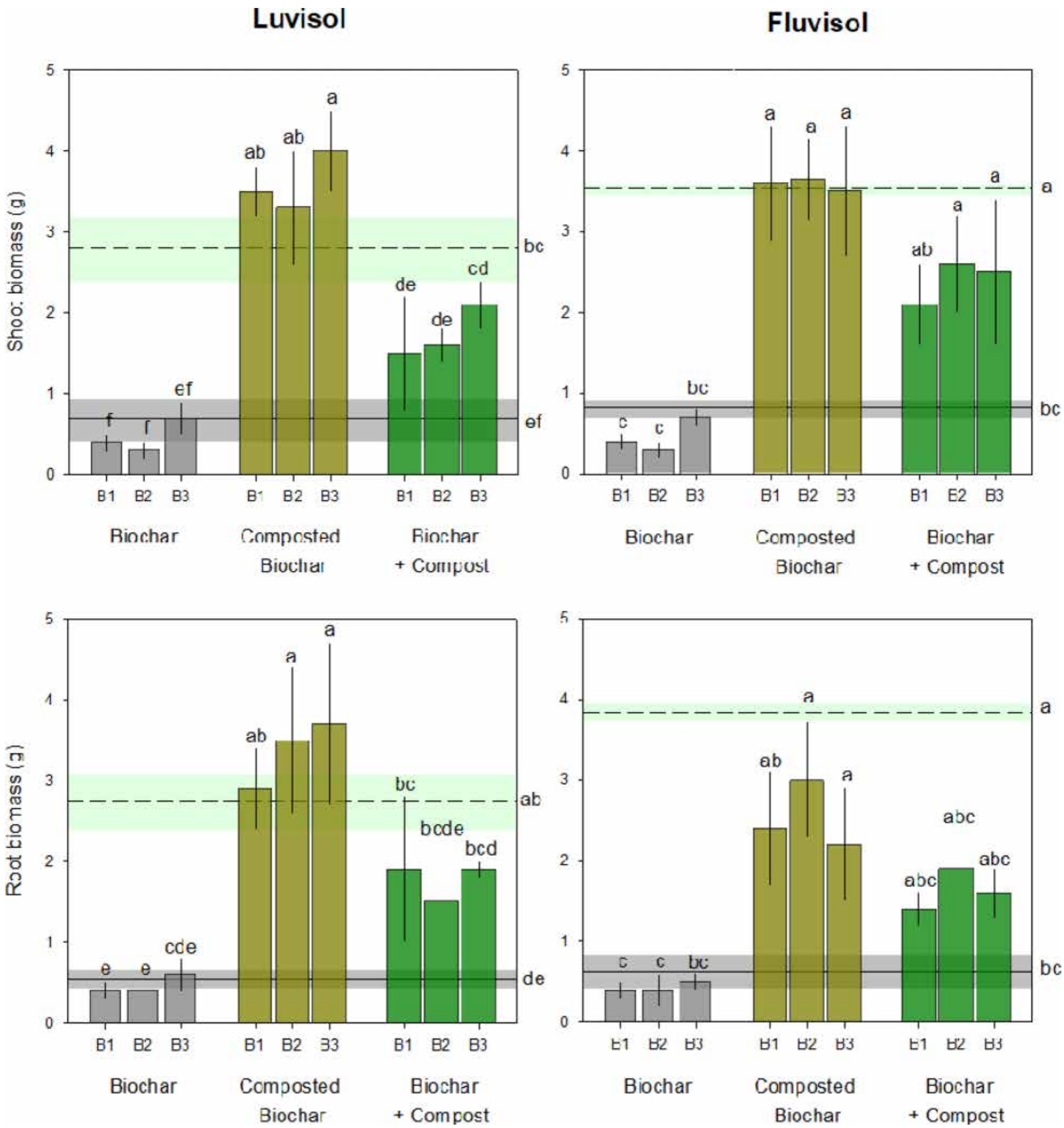


Fig. 4 Shoot (upper) and root (lower) biomasses according to soil treatments for the Luvisol (left) and Fluvisol (right). The error bars are the standard deviation of 3 replicates (n = 3) for each biochar alone (B1, B2, B3), biochars with compost (B1 + C, B2 + C, B3 + C), composted biochars (CB1, CB2, CB3), compost only (C) and control not amended (No). Different letters indicate significant differences among treatments given by the post hoc LSD test

in B treatments, which could be attributed to the indirect effect of biochar on microbial decomposition (Cui et al. 2021). Additionally, the surface properties and high porosity of biochar could have absorbed the DOC (Yang et al. 2020), whereas in composted biochar treatments, the grown microbial biomass was related to the rise in labile OC, such as DOC, which represents a substrate for microbial nutrition (Becagli et al. 2022). TN and P did not significantly differ between amended soils and controls, except for the highest TN value in CB1 that

Table 4 Biological properties of the Luvisol and the Fluvisol not amended (No) or amended with biochar (B1, B2, B3), biochar and compost (B1 + C, B2 + C, B3 + C), composted biochar (CB1, CB2, CB3) or only compost (C)

	Treatment	Urease NH_4^+ g^{-1}	FDA (mg fluo g^{-1} soil h^{-1})	CO_2 (mg Corg $days^{-1}$)	Nmic (mg kg^{-1})	NH_4^+ (mg kg^{-1})	NO_3^- (mg kg^{-1})
Luvisol	No	20.9 ± 1.7^{de}	0.17 ± 0.01^{b}	18.0 ± 1.5^{cd}	295.2 ± 30.8^{f}	0.62 ± 0.3^{bcd}	0.1 ± 0.1^{bcd}
	B1	28.1 ± 3.8^{b}	0.16 ± 0.00^{bcd}	30.0 ± 7.9^{a}	410.1 ± 47.2^{bcd}	0.53 ± 0.5^{cd}	0.04 ± 0.0^{de}
	B2	20.7 ± 3.6^{de}	0.16 ± 0.00^{bc}	27.1 ± 8.7^{ab}	379.5 ± 41.6^{de}	0.30 ± 0.1^{d}	0.03 ± 0.0^{e}
	B3	27.7 ± 0.1^{b}	0.09 ± 0.01^{e}	6.1 ± 3.8^{f}	292.9 ± 32.5^{f}	0.65 ± 0.2^{c}	0.05 ± 0.0^{de}
	CB1	26.4 ± 4.2^{bc}	0.20 ± 0.01^{a}	23.8 ± 3.3^{abc}	598.6 ± 38.4^{a}	0.88 ± 0.2^{abc}	0.07 ± 0.0^{cde}
	CB2	21.0 ± 1.6^{de}	0.19 ± 0.01^{a}	17.1 ± 5.4^{de}	466.5 ± 22.3^{b}	0.94 ± 0.2^{ab}	0.08 ± 0.0^{cde}
	CB3	39.7 ± 7.9^{a}	0.16 ± 0.01^{bc}	20.6 ± 0.8^{bcd}	458.7 ± 46.2^{bc}	$1.19 \pm 0.^{2a}$	0.11 ± 0.0^{abc}
	B1 + C	24.6 ± 3.3^{bcd}	0.14 ± 0.01^{d}	10.6 ± 3.8^{ef}	416.3 ± 41.4^{bcd}	0.75 ± 0.2^{bc}	0.16 ± 0.1^{ab}
	B2 + C	19.4 ± 1.7^{e}	0.15 ± 0.02^{cd}	9.7 ± 2.6^{f}	404.5 ± 44.3^{cd}	0.68 ± 0.2^{bcd}	0.16 ± 0.0^{a}
	B3 + C	21.2 ± 0.5^{de}	0.07 ± 0.01^{f}	10.8 ± 4.8^{ef}	273.3 ± 67.6^{f}	0.71 ± 0.0^{bc}	0.13 ± 0.0^{abc}
	C	22.7 ± 1.9^{cde}	0.19 ± 0.01^{a}	20.0 ± 2.0^{cd}	333.6 ± 40.8^{ef}	0.83 ± 0.1^{abc}	0.12 ± 0.0^{abc}
Fluvisol	No	18.5 ± 2.7^{cd}	0.18 ± 0.01^{cd}	5.5 ± 1.8^{f}	222.1 ± 48.1^{g}	0.57 ± 0.2^{ab}	0.07 ± 0.0^{c}
	B1	20.6 ± 1.3^{bcd}	0.17 ± 0.00^{de}	9.8 ± 2.2^{ef}	282.6 ± 43.7^{efg}	0.71 ± 0.3^{ab}	0.06 ± 0.0^{c}
	B2	18.2 ± 4.7^{cd}	0.16 ± 0.01^{ef}	5.8 ± 1.0^{f}	237.7 ± 15.5^{fg}	0.58 ± 0.1^{ab}	0.08 ± 0.0^{bc}
	B3	18.1 ± 3.6^{cd}	0.06 ± 0.01^{g}	8.9 ± 2.6^{ef}	106.8 ± 37.8^{h}	0.82 ± 0.3^{ab}	0.09 ± 0.0^{bc}
	CB1	22.2 ± 2.9^{abcd}	0.24 ± 0.02^{a}	23.6 ± 2.5^{a}	569.9 ± 76.9^{a}	0.54 ± 0.2^{b}	0.28 ± 0.1^{a}
	CB2	27.8 ± 4.2^{a}	0.21 ± 0.03^{b}	12.5 ± 6.3^{de}	490.8 ± 82.4^{ab}	0.56 ± 0.3^{b}	0.27 ± 0.1^{a}
	CB3	16.7 ± 2.8^{d}	0.19 ± 0.02^{bc}	10.1 ± 2.5^{ef}	334.0 ± 142.9^{cde}	0.57 ± 0.1^{b}	0.12 ± 0.1^{bc}
	B1 + C	22.7 ± 3.5^{abc}	0.14 ± 0.01^{f}	13.6 ± 1.5^{cde}	423.2 ± 19.8^{bc}	0.92 ± 0.1^{a}	0.19 ± 0.0^{ab}
	B2 + C	18.9 ± 4.1^{cd}	0.14 ± 0.01^{f}	19.8 ± 1.0^{ab}	376.3 ± 30.7^{cd}	0.75 ± 0.0^{ab}	0.19 ± 0.1^{ab}
	B3 + C	25.9 ± 8.1^{ab}	0.07 ± 0.01^{g}	17.5 ± 0.6^{bc}	210.8 ± 49.8^{g}	0.61 ± 0.2^{ab}	0.12 ± 0.0^{bc}
	C	19.4 ± 0.7^{cd}	0.17 ± 0.02^{de}	15.7 ± 7.1^{bcd}	321.1 ± 48.6^{def}	0.84 ± 0.1^{ab}	0.15 ± 0.1^{bc}

Values are the mean ± standard deviation of 3 replicates (n = 3). Different letters indicate significa t differences among treatments for a given soil

correlated with the initial TN content in composted biochar. Composted biochar had a lower C/N ratio, compared to the solely added biochar, owing to a rich N input with organic matter abundant in easily bioavailable C and N sources (Antonangelo et al. 2021). As expected, a relative decrease in SOC and a relative increase in TN with a consequent reduction in the C/N ratio (Hagemann et al. 2017a) led to the parameters flattening in composted biochars. It is known that biochar composting can reduce the N losses in the composting process (Mujtaba et al. 2021). Total P values in soil varied within several biochar additives, but there was no general trend. The CB1 in Luvisol and B1 in Fluvisol biochar exposed the most efficient P input throughout soil modalities, which was in line with the initial P content. Gao et al. (2023) explained positive soil P response by the direct P sorption on co-composted biochar surfaces with subsequent P retention and microbial community responsible for organic P mineralization or phosphatase activity. The $Q_{2/6}$ ratio correlated negatively with DOC. The increased $Q_{2/6}$ ratios were found in biochar-amended soils and controls in both soil types, indicating the high abundance of compounds with phenolic and benzene-carboxylic groups in the structure of humic substances. The decreased $Q_{2/6}$ values were found in CB, B + C and compost treatments indicating that more organic matter via humification was produced within these treatments. These results align with the study of Wang et al. (2014) that investigated the compost-blended biochar effects on polymerization during composting, indicating rapid aromatic polymer formation due to humic substances sorption on biochar surfaces. The study of Zhang et al. (2014) on fruitwood biochar found the highest humification materials content and its potential growth within the compost product, or also on wood biochar that had a favorable effect on sludge composting via high humification.

4.2 Effects of composted biochar on soil biological properties

The biological properties of soil were ultimately altered due to the physicochemical changes induced by the additives after biochar composting (Table 4). Urease activity did not change drastically under any amendment, however, compost input contributed to elevated urease values in composted biochar and biochar mixed with compost. Partly, our results are in line with previous findings by

Abujabhah et al. (2016) in an apple orchard site where biochar and compost had no influence on soil microbial urease activity. Conversely, Lu et al. (2015) reported increased urease activity in saline soil amended with biochar poultry manure compost under maize cultivation, consistent with studies by Yadav et al. (2019) showing enhanced urease activities in sandy loam amended with biochar and planted geranium. Ameliorated composted biochar which underwent the composting process demonstrated higher FDA activity values, whereas biochar mixed with compost exhibited lower FDA values in soil. FDA reflects overall microbial activity in the soil, and thus the composted biochar additive promoted bacterial development in the soil more effectively than co-applied amendments. Studies on beech wood biochar mixed with compost confirm the FDA rise in Andisols (Iacomino et al. 2022); nevertheless, the composted biochar provides a beneficial environment of energy sources for microbial communities. The type of biochar did not influence microbial community richness and evenness (Table 1). Enrichment of composted biochar with nutrients from organic matter increased bacterial abundance without altering their functional balance, as observed by Hale et al. (2021). In contrast, B3 biochar in every treatment type, with or without compost, decreased the soil FDA and N_{mic} values of microbial activity. Initially, the B3 additive had the lowest ash and nutrient content that impacted microbial development (Akhter et al. 2015) with the elevated amount of trace metals, assuming that B3 had a higher harmful compounds ratio generated during the fast pyrolysis that might have led to the suppressed microbial activity (Yang et al. 2019).Soil N_{mic} values reflected this trend, with B3 treatments showing microbial activity levels similar to the control (Table 4). Composted biochar, particularly CB1, contributed to elevated microbial development in the soil. Differences in biological properties between Luvisol and Fluvisol were minimal, with amendments primarily driving observed differences. These findings on B3 biochar and the beneficial effect of CB1 on microbial activity were corroborated by CO_2 data linked to microbial respiration. NH_4^+ and NO_3^- values differed between composted biochar and co-applied amendments, showing an inverse correlation upon soil application. Overall, biochar addition reduced N loss by compost, with higher TN concentrations in composted biochar treatments, similar to findings by Qiu et al. (2019). The high surface area of biochar provides a conducive habitat for microbial growth, while composted organic matter provides a source of carbon and retained nutrients (Hagemann et al. 2018). Variations in mineral N may also be linked to differences in plant N consumption. The effect of composted biochar on the release and storage of nutrients by microbial activity could be beneficial for plant growth (Kammann et al. 2017).

4.3 The effects of composted biochar amendments on plant growth

The advantageous effect of composted biochar amendments on soil parameters had a consequent positive effect on both aboveground and belowground biomass production, strongly correlated. Solely applied biochar did not affect lettuce growth in either soil, as previously demonstrated in the same Luvisol and Fluvisol (Mikajlo et al. 2022a). In contrast, all other amendments distinctly stimulated plant growth, with composted biochar exhibiting the highest increase in lettuce biomass, approximately doubling the growth compared to control levels (Fig. 4). Biochar mixed with compost showed moderate plant growth enhancement in Luvisol and more pronounced effects in Fluvisol, while untreated biochar did not enhance plant growth. The addition of compost to amendments significantly boosted plant growth compared to control and solely applied biochar treatments, underscoring composted biochar as the most efficient treatment and growth enhancer. Several studies confirm our results: co-composted sugarcane bagasse biochar promoted zucchini growth in sandy arid soil (Farid et al. 2022) on quinoa and sandy loam soil where composted woody chip biochar increased the plant growth up to fivefold compared to the solely applied biochar and up to threefold compared to the control (Kammann et al. 2015) or on oats planted in sandy and loamy soil where beech wood composted biochar increased grain yield and pure compost did not significantly contribute to this effect (Schulz et al. 2013).. In addition to improving soil pH values, the enhanced plant growth with composted biochar amendments can be attributed to nutrient inputs from both compost and composted biochar. These results suggest that while compost plays a crucial role in short-term plant growth enhancement, composted biochar may offer more sustainable benefits compared to co-applied compost and biochar in the long term.

5 Conclusion

The conducted experiment demonstrated the differences in the impacts of biochar, composted biochar, separately added compost with biochar, and compost amendments on soil physicochemical properties, biological activity, and lettuce yield. Our findings underscore the advantage of composting biochar over co-applying compost and biochar separately. Composting biochar extended the interaction period between biochar and compost, resulting in equalizing initial differences among the three biochar types. Compared to individually added amendments, co-composted biochar enriched soil with nutrients, neutralized pH levels, stimulated microbial communities, and consequently, enhanced plant growth. These positive effects were particularly notable in the less fertile Luvisol compared to Fluvisol. Future studies should focus on field conditions to validate these findings, especially in degraded soils where composted biochar amendments could potentially provide more substantial benefits. Furthermore, comprehensive comparative studies are needed to evaluate composted biochar across different crops and biochar types derived from various feedstocks and pyrolysis temperatures. While composting biochar appears to be an effective strategy for restoring soil fertility without adverse biochar effects, its field implementation requires thorough life-cycle analysis and carbon footprint assessments to accurately estimate economic and environmental gains.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s42773-024-00379-2.

Supplementary Material 1.

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Author contributions
IM performed all steps of the study from conception to manuscript drafting, data acquisition. TZL contributed to additive analyses, acquisition and interpretation of data, statistical analysis, and critical revision of the manuscript. JH, JZ and BP contributed to the conception and design of the study, the acquisition of data, the critical revision of the manuscript and the approval of the final version. All authors read and approved the final manuscript.

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Availability of data and materials
The authors declare that the data supporting the findings of this study are available within the article and its additional information files.

Declarations

Competing interests
The authors 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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