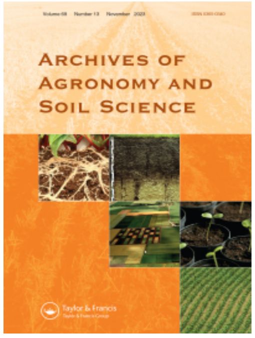

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Effects of a single biochar application in a water-stressed maize cultivation

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ABSTRACT
Biochar amendment improves crop yield and mitigates climate change, but the lasting effect of biochar application on crop and soil properties under water scarcity conditions in tropical soils remains unexplored. We examined how a one-time biochar application alone and co-applied with vermicompost, with application rates of 25 and 50 ton ha^{-1}, affected the growth of *Zea mays* L. and the related physicochemical and hydraulic properties of a clay soil after three years. Analyses included pH, electrical conductivity, the availability of cations and phosphorous, carbon to nitrogen ratio, soil water characteristics, crop growth and biomass. The results showed that 50 ton ha^{-1} of biochar co-applied with vermicompost produced more beneficial effects on the maize crop than 25 ton ha^{-1} biochar, in the first cycle and to a lesser extent in the third cropping season, caused mainly by the availability of phosphorous and potassium, and the enhancement of bulk density, porosity, and moisture retention. Our results suggest that a one-time application of biochar combined with vermicompost enhances maize growth under limited water conditions. However, further research is necessary to understand the long-term effect of biochar on the soil structure of clay soils, crucial for effectively managing crops in water-scarce conditions.

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KEYWORDS
Bamboo biochar; vermicompost; maize; clay soil, water scarcity

Introduction

Agricultural land is in danger. The increasing population is highly related to a decreasing arable land, causing soil degradation in terms of water consumption, energy used and nutrient requirements (FAO and ITPS 2015). Food security, especially in developing countries, has been threatened primarily by land use change, waste pollution, inappropriate farming practices and extreme climate conditions (Lal 2013). Small-scale family farming faces numerous challenges in producing on infertile lands and under long periods of water scarcity. The Central American Dry Corridor covers 44% of the surface from western Guatemala through northern Costa Rica, including a population of about 11.5 million (Gotlieb et al. 2019). This region suffers a prolonged dry season and excessive and intense rains. Limited water availability is common in this region, negatively impacting their main basic grain production, such

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In memory of our friend and colleague: Wagner Peña was a cathedratic professor in the Department of Agronomy, Universidad Estatal a Distancia, San José, Costa Rica.

as corn and beans (FAO 2015), and leaving families prone to hunger. Since 2009, FAO (2015) has been promoting risk management strategies focusing on sustainable agricultural systems, adapted to climate change, to decrease the economic vulnerability and food insecurity in this region.

In recent years, conversion into valuable materials of agricultural residues has gained significant attention due to their wide application in agriculture to improve the circular economy, soil fertility, and contribute to carbon sequestration (Pundir et al. 2024). Organic residues transformed into biochar and compost are recognized as sustainable farming practices, demonstrating positive effects on soil-plant productivity when used as soil amendments (Pandey et al. 2024). Both, biochar and compost are organic products utilized as soil amendments, yet they are produced through different processes and possess disctinct characteristics. Biochar is a carbon-rich material produced by pyrolysis, which occurs under limited or non-oxygen conditions at temperatures ranging from 350 °C to 1000 °C (WBC 2023). Due to its characteristics – recalcitrant, high carbon content, high surface area, and aromatic compounds — (Murtaza et al. 2024; Pandey et al. 2024) it has the potential to change soil quality, impacting soil hydrology (Bhat et al. 2022; Wu et al. 2022), fertility (Randolph et al. 2017; Zhang et al. 2017; El-Naggar et al. 2019), crop productivity (Vijay et al. 2021), and contributing to mitigate climate change through carbon sequestration (Lorenz and Lal 2014; Smith 2016; Kong et al. 2019; Semida et al. 2019). Meanwhile, compost is an organic, nutrient-rich product from the biological decomposition of waste through aerobic processes (Pandey et al. 2024), primarily used as soil conditioner and to a lesser extent as fertilizer (Khater 2015). It is known to increase crop productivity (Zulfiqar et al. 2021), and it is crucial for recycling waste into resources (Waqas et al. 2023). Many studies have used biochar-compost mixtures to improve crop yields by improving nutrient use efficiency (Agegnehu et al. 2017; Honvault et al. 2023) chemical soil quality and carbon sequestration (D'Hose et al. 2020); and soil hydraulic properties such as infiltration, water retention, aggregate stability, and crop yield (Sharma et al. 2021).

Although biochar has been proved to be an option for soil degradation amelioration, by improving soil properties and crop yields (Agegnehu et al. 2017; Murtaza et al. 2021), most of the current research is based on short-term trials with pots or field experiments, limiting the understanding of biochar's effect in the long-term (Yeboah et al. 2016; Tian et al. 2018; Minhas et al. 2020; Jiang et al. 2023). Although the International Biochar Initiative (Major 2010) does not suggest frequent biochar applications as done by other organic materials, such as manure, compost, or inorganic fertilizers, there is still limited understanding of the long-term effects of biochar in agriculture. Over the years, studies have incorporated one or multiple-time biochar applications to long-term crops, to different crop rotations, or even across multiple cropping seasons (Major et al. 2010; Haider et al. 2017; Cao et al. 2020; Cong et al. 2023). Frimpong et al. (2021) reported a yield increase of multiple crops by improving soil fertility, after a one-time application of biochar, over a three-years trial. Xue et al. (2023) reported better results for multiple low-dose biochar applications, while Blanco-Canqui et al. (2020) observed changes in soil physical properties after 6 years of a single biochar application. The main contributions of this work are: 1) the research addresses specifically the impact of biochar amendments under water scarcity conditions which is a critical and timely issue given climate change, in contrast to other works that examine biochar´s effects on standard production conditions; 2) it explores the co-application of biochar with vermicompost and its specific effects on maize growth and soil properties; 3) the three-year timeframe of our study allows for an examination of both short-term and potentially longer-term effects of biochar application, which is often a gap in existing literature; and 4) the emphasis on the effects of biochar particle size relative to clay aggregates introduces a novel perspective that could impact future application strategies and research on biochar efficacy. Therefore, this study aims to investigate (i) the impact of one-time biochar application on maize growth after three cropping cycles under water scarcity (ii) the impact of the mixture of one-time biochar-vermicompost on maize growth under water scarcity and (iii) the mechanisms through which biochar affects soil physicochemical and hydraulic properties three years after a single application of biochar. It will clarify whether the one-time application of biochar when combined with vermicompost can support maize growth under water-limited conditions, particularly as a sustainable option for small-scale farmers facing prolonged dry weather.

Materials and methods

The study was carried out between 2020 and 2022 at the Costa Rican Institute of Technology in Cartago, Costa Rica, in a greenhouse located at the School of Agricultural Engineering (951026.0900 N 8,354,044.3300 W). The average temperature inside the greenhouse was 20 °C, maximum 33 °C and minimum 15 °C, with a rainy season extended from May to November and a dry season from December to April.

Soil, biochar and vermicompost preparation

The soil in the study area was classified as Ultisol, clay, with 13% sand, 31% silt, and 56% clay (IUSS Working Group WRB 2022), initial soil chemical and physical characteristics are listed in Tables 4 and 5, respectively. The biochar was produced from bamboo stems (culms) of *Guadua Angustifolia* produced under limited oxygen supply and at an average combustion temperature of 400°C, as reported in Villagra-Mendoza et al. (2021). The biochar elemental analysis and physical characteristics are found in Villagra-Mendoza et al. (2021). Vermicompost was used as organic supplement since nutrient availability is generally higher than traditional compost (Lim et al. 2015) and the authors believed that it could stimulate better plant growth under extreme drought conditions. Vermicompost was characterized, at the beginning of each crop cycle for pH, electrical conductivity, total nitrogen, total carbon, C:N ratio, total phosphorus, calcium, magnesium, potassium, and sulfur (Table 1).

Experimental design

The experiment was conducted using a completely randomized block design with 6 treatments and 3 replicates per treatment, amounting to 18 plots (Figure 1a). All plots were first disturbed at the surface, by manually taking the upper 10 cm soil and mixing it in a container, with a shovel, with the corresponding proportion of biochar (Tables 4 and 5, respectively). After conforming the 18 plots and previous to seed incorporation, plots were irrigated for 2 weeks and the first soil samples were taken, corresponding to the soil initial condition (Cycle 0). Table 2 describes each of the six treatments.

Biochar application rates of 2.5 and 5% (dry mass), corresponding to 25 and 50 ton ha^{-1}, were selected based on results obtained from Villagra-Mendoza et al. (2021), corresponding to the best doses at which positive productivity was observed in previous studies. Vermicompost was added at the beginning of each cycle at each stand.

Table 1. Main chemical characteristics of the vermicompost used in all maize cycles I and III.

Parameters	Unit	Cycle I	Cycle III
pH		7.8	10.5
Electrical conductivity, CE	mS cm^{-1}	5.0	19.2
Total carbon, C	%	31.9	20.1
Total nitrogen, N	%	1.8	1.4
C:N ratio		18.0	14.0
Phosphorous, P	%	0.5	0.4
Calcium, Ca	%	2.1	5.6
Magnesium, Mg	%	0.4	0.8
Potassium, K	%	1.1	4.6
Sulphur, S	%	0.4	0.3

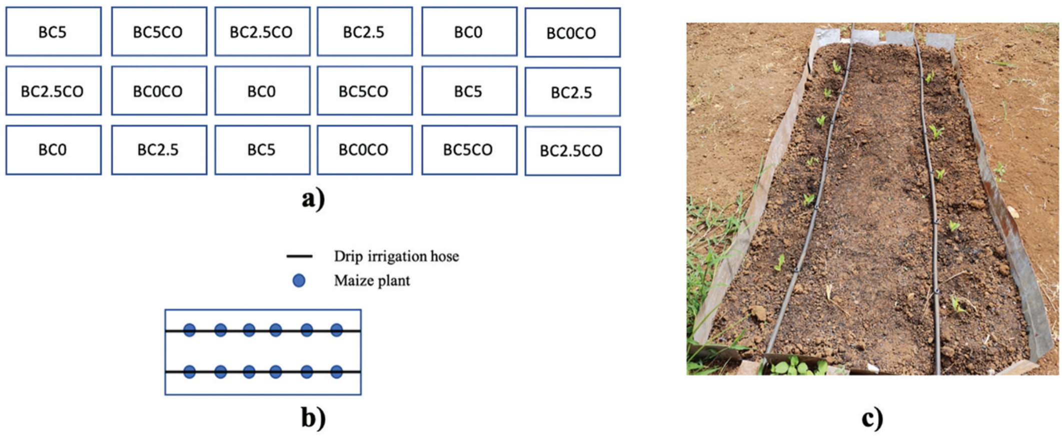

Figure 1. Experimental setup of plots in the greenhouse: a) scheme of the random block design of six treatments with three replicates; b) scheme of a plot with six plants in duplicate at each hill and the drip irrigation hose in both crop rows, c) example of a plot installed.

Table 2. Treatments in the completely randomized block design for one-time biochar application and co-applied with vermicompost.

Treatment	Biochar % (dry weight)	Biochar ton ha^{-1}	Vermicompost addition for each cycle
BC0	None	0	None
BC2.5	2.5	25	None
BC5	5.0	50	None
BC0CO	None	0	30 g at sowing at each stand
BC2.5CO	2.5	25	30 g at sowing at each stand
BC5CO	5.0	50	30 g at sowing at each stand

The area of each single plot was 2 m^2 and the spacing between plots was 2 m. Each plot was composed of two rows, each with 6 stands. Five maize seeds, from the variety DK7500, were sowed per stand at a spacing of 28 cm between stands and 40 cm between rows. Two weeks after planting, the seedlings were thinned to two per stand. Overall, each treatment plot had two rows and 12 plants per row (Figure 1b), corresponding to 120 000 plants ha^{-1}.

Three continuous maize cycles were studied from November 2020 to March 2021 (Cycle I), June to October 2021 (Cycle II), and February to June 2022 (Cycle III). Cycle II was conducted during the rainy season. Although the experiment took place in a greenhouse, direct water input occurred either through the walls or as runoff from the surrounding ditches, significantly influencing water availability. Consequently, Cycle II was excluded from the analysis due to the inability to measure excess water accurately. Throughout the maize cycles, conservation tillage was employed, and no liming applications were made between crop cycles.

Two irrigation lines, in each row, were installed across the treatment plots (Figure 1c) at ground level, with a compensated 4 L h^{-1} dripper at each stand. In all cycles, irrigation was provided only during the first 45 d (during the seedling phase) – to avoid seriously inhibiting maize growth (Song et al. 2019)—, three times a week, applying 4 L h^{-1} for 10 min at each scheduled time of 6 am, 12 md and 6 pm. Irrigation was designed to reflect scenarios of limited water availability, with water provided only during the seedling phase. Following this period, prolonged dry conditions were anticipated, simulating the extreme weather conditions that may occur in the Central American Dry Corridor. All treatments and cycles were adhered to the same nutrient schedule, applying 2 g of granulated NPK 12-11-18 fertilizer per plant twice during the growing phase.

Table 3. Description of the procedure followed to collect the soil samples at each cycle.

Cycle	Sampling description	Sample type per plot
0	Two weeks after the settlement of the treatments	Undisturbed samples in duplicate, disturbed samples in six randomized subsamples
I*	One week before first maize harvest	
III	One week before third maize harvest	

*Chemical soil sampling after first fertilization.

Soil sampling

Soil samples were first collected, prior to the configuration of the treatments, to understand the soil base condition (Table 3). Two weeks after biochar was applied to the corresponding plots, soil data was collected for all treatments before planting the first seeds (Cycle 0). Thereafter, soil sampling was performed right before harvesting, being the soil condition reported for each cycle (I and III). Undisturbed soil samples were randomly collected at 10 cm depth by duplicates in the center of each plot between the two rows (as mentioned for Cycles 0, I, and III). Disturbed soil samples were obtained from the same plots by the mixture six randomized subsamples.

Physicochemical soil analysis

The method of hydrometer was used to determine soil texture, previously removing soil organic matter (Zimmermann and Horn 2020). The pH in water and electrical conductivity (EC) were determined using 1:2.5 ratio (soil:water). Ca^{2+}, Mg^{2+} and K^{+} were quantified by atomic absorption spectroscopy and available P by the Modified Olsen method. Effective cation exchange capacity (ECEC) was obtained from the sum of bases ($SB = Ca^{2+} + Mg^{2+} + K^{+}$) and acidity using ammonium acetate pH 7.0 (Sumner and Miller 1996). Total organic carbon C_{org} and nitrogen content was quantified with the Dumas dry combustion method (Bertsch and Ostinelli 2019).

Soil hydraulic properties

In each plot, duplicate core samples with a volume of ca. 100 cm^3 were taken at 10 cm depth. The soil water retention curve was built from measuring the gravimetric water content of each sample, after each matric potential applied (−3, −6, −33, −50 kPa) using a hanging water column method and a sand/kaolin box from Eijkelkamp (Giesbeek, The Netherlands). Volumetric water content was calculated by multiplying the gravimetric water content by the bulk density of each core sample. Bulk density was determined from dividing the dry mass (105 °C) by the core sample volume. The water content at a matric potential of −1500 kPa was determined by preparing soil samples in rings of 2 cm height in triplicates, desiccated in a Richards pressure plate apparatus of 15 bar. Field capacity (FC) was associated with the water content at a matric potential of −33 kPa (Blanco-Canqui et al. 2020), and permanent wilting point (PWP) to the water content at a matric potential of −1500 kPa. Available water content (AWC) was calculated as the difference of FC and PWP (Boden 2005). Water content at saturation was assumed as the total porosity (TP). Air capacity (AC) was calculated as the difference of TP the FC. Pore size was classified as macropores with an equivalent diameter greater than 50 µm and matric potential > −6 kPa, capillary pores with diameters between 50 and 10 µm and matric potential between −6 kPa and −30 kPa, medium pores (−30 kPa to −1500 kPa) with diameters between 10 and 0.2 µm and matric potential from −30 kPa to −1500 kPa, and micropores with diameters <0.2 µm and matric potential < −1500 kPa. (Hartge and Horn 2016) A minidisk infiltrometer from METER (Pullman, U.S.A.), with a suction of 3 cm, of water column, was used to determine infiltration rate (I, mmh^{-1}) and hydraulic conductivity (*Kh*). Infiltration was fitted based on the Kostiakov model (Baver et al. 1972):

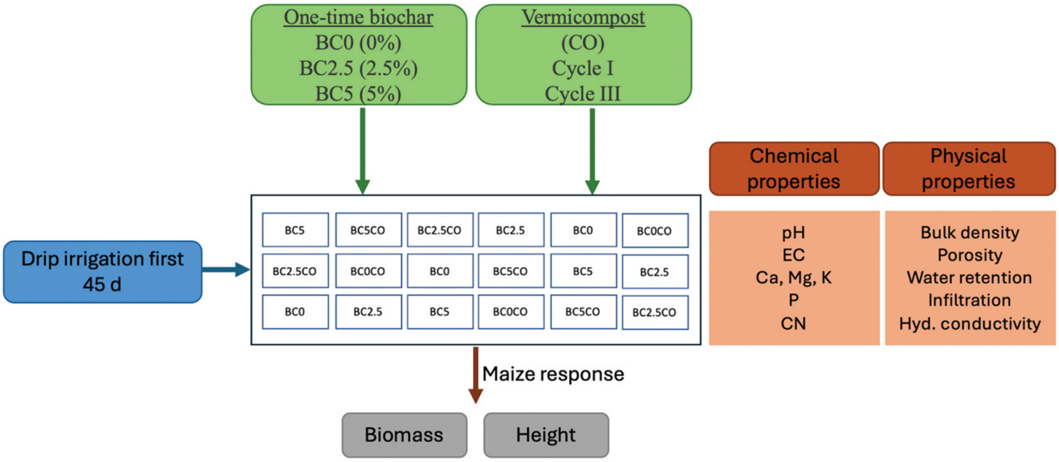

Figure 2. Diagram showing the steps involved during a three-year experiment of biochar, vermicompost, and maize growth in a greenhouse under limited water availability.

$$I = a \cdot t^b \quad (1)$$

where constants a, b are a function of texture, soil water content and bulk density; and t is the infiltration time (h).

Crop growth and aboveground biomass production

The experiment was carried out for 119 d for each cycle. Plant height was measured every 2 weeks, starting 30 d after sowing, with a steel tape. Plant height was defined as the height from the base of the maize stem to the highest point of the plant. After 119 d, the eight most representative plants per plot were collected to determine aerial vegetative biomass. Representativeness criteria, for each plot, were set as the group of eight plants with similar height and biomass as the rest of the plants growing in the same plot, taking the same number of plants from each of the two rows. Fresh weight was determined immediately after removing the aerial part from the field and dry weight biomass was obtained after 72 h by oven dry at 50 °C. Figure 2 shows the overall experiment setup including the main phases and analysis carried out to analyze the maize response in each cycle.

Statistical data analysis

The Shapiro – Wilk test ($p < 0.05$) was used to demonstrate normality. Mean and standard deviation were calculated for all soil parameters and results were statistically assessed with the analysis of variance (ANOVA). Differences between means were estimated using the HSD Tukey's test ($p < 0.05$). All the statistical analyses were run with the freeware R version 4.2.3 using the Rcmdr package version 2.8.0.

Results

Effect of biochar on soil physicochemical properties

Table 4 shows the chemical soil properties for the soil for all treatments in cycles I and III, along with the initial conditions prior to biochar application. Soil samples collected in cycle I were taken one week after fertilization, while those from cycle III were collected one week before harvest.

Table 4. Chemical soil properties at initial soil conditions without biochar (time 0) and at the end of each crop cycle (I and III) for biochar addition of 0, 2.5 and 5% and biochar-vermicompost mixtures.

Treatment	Cycle	pH H_2O	EC	Ca^{2+}	Mg^{2+}	K^+	ECEC	P	C:N
Recommended*		5.5-6.5	1.5	4-6	1-3	0.2-0.5	5-25	12-20	24:1
Units			mS cm^{-1}		cmol(+) L^{-1}			mg L^{-1}	
Initial	0	6.2	0.4	11.8	5.0	1.4	18.3	58	9.1
BC0	I	5.8^{a}	7.5^{a}	18.6^{a}	11.2^{a}	2.1^{a}	32.1^{a}	32.0^{a}	5.1^{a}
	III	6.6 ± 0.3^{fg}	0.3 ± 0.2^{fg}	11.3 ± 0.6^{gh}	4.8 ± 0.3^{gh}	1.2 ± 0.3^{gh}	17.4 ± 0.5^{gh}	41.0 ± 10.6^{ahi}	8.5 ± 0.1^{g}
BC0CO	I	5.3^{b}	6.5^{b}	16.5^{b}	8.6^{b}	2.7^{b}	27.9^{b}	46.0^{b}	6.0^{b}
	III	6.6 ± 0.1^{g}	0.3 ± 0.1^{fg}	11.3 ± 1.0^{g}	5.2 ± 0.5^{g}	1.2 ± 0.4^{gh}	17.8 ± 1.4^{gh}	32.0 ± 10.6^{bh}	8.2 ± 0.3^{g}
BC2.5	I	5.8^{a}	4.0^{c}	12.1^{c}	6.0^{c}	3.6^{c}	21.8^{c}	52.0^{c}	19.1^{c}
	III	6.6 ± 0.2^{fg}	0.4 ± 0.1^{g}	10.3 ± 0.1^{gi}	4.6 ± 0.2^{gi}	1.4 ± 0.1^{h}	16.5 ± 0.2^{ghi}	49.7 ± 14.4^{chi}	16.2 ± 4.1^{ch}
BC2.5CO	I	5.7^{c}	5.3^{d}	13.8^{d}	6.8^{d}	3.8^{d}	24.5^{d}	45.0^{d}	15.5^{d}
	III	6.5 ± 0.2^{fg}	0.4 ± 0.2^{fg}	10.3 ± 0.4^{gi}	4.5 ± 0.2^{gi}	1.7 ± 0.1^{gh}	16.7 ± 0.6^{ghi}	37.0 ± 9.2^{dhi}	14.2 ± 1.1^{dgh}
BC5	I	6.2^{d}	3.9^{e}	11.6^{e}	5.7^{e}	4.8^{e}	22.3^{e}	70.0^{e}	22.7^{e}
	III	6.3 ± 0.2^{fg}	1.0 ± 0.5^{fg}	9.9 ± 0.9^{hi}	4.3 ± 0.2^{hi}	2.4 ± 0.1^{hi}	16.8 ± 1.1^{ghi}	54.7 ± 10.1^{ghi}	18.6 ± 4.9^{ehi}
BC5CO	I	5.9^{e}	3.9^{e}	10.7^{f}	5.5^{f}	4.5^{f}	20.7^{f}	75.0^{f}	21.2^{f}
	III	6.4 ± 2^{fg}	0.5 ± 0.2^{fg}	8.6 ± 0.2^{gi}	4.0 ± 0.1^{i}	2.3 ± 0.3^{hi}	15.0 ± 0.4^{i}	63.0 ± 5.6^{gi}	25.2 ± 1.9^{fi}

EC: electrical conductivity; Ca: calcium; Mg: magnesium; K: potassium; ECEC: effective cation exchange capacity; P: phosphorous; C:N: carbon: nitrogen ratio.

No standard deviation is reported for cycle I due to composite soil sampling for the three replicates of the same treatment. Variables with the same letters on the same variable (column) are not significantly different ($p < 0.05$).

Source:* (Peña Cordero 2017).

Following fertilization, pH levels decreased more significantly in the treatments BC2.5, BC2.5CO, and BC5CO, with reductions ranging from 0.4 to 0.9 pH units, compared to treatment BC5. In cycle III, all treatments exhibited similar pH values, which were between 0.1 and 0.4 pH units higher than the initial pH conditions.

In cycle I, electrical conductivity (EC) increased across all treatments, with the highest increases observed in the unamended soils. Treatments BC5 and BC5CO experienced a much smaller increase in EC, up to nine times less than non-amended treatments BC0 and BC0CO. By cycle III, all EC values returned to levels similar to the initial conditions and remained within the recommended range.

After fertilization, the concentrations of cations Ca^{2+} and Mg^{2+} increased in all treatments; however, the increase was less pronounced with higher biochar additions, keeping their concentrations closer to the initial soil conditions. In cycle III, the concentrations of Ca^{2+} and Mg^{2+} in all treatments were similar to initial values. Meanwhile, in cycle I, K^+ increased up to 3.5 times as the dosage of biochar increased independently whether biochar was mixed with vermicompost. Although K^+ presented for all treatments a decreasing trend in cycle III, biochar decelerated this decrease and kept K^+ values above the initial soil conditions, especially for BC5 and BC5CO.

In cycle I, ECEC increased for all treatments, compared to initial soil conditions, with a greater concentration in the non-amended soils. However, in cycle III, ECEC for BC0 and BC0CO presented similar concentrations to the initial values, while the amended treatments exhibited lower concentrations than the ones reported for initial soil conditions. Stronger positive effects were observed for P concentration and C:N ratio, as the higher biochar doses produced higher values for those parameters at the end of all studied cycles.

Figure 3 shows the fertility condition for all treatments in cycles I and III compared to soil conditions without biochar (Time 0) and was based on the relation between exchangeable bases Ca^{2+}, Mg^{2+} and K^+. The Ca/Mg ratio shows low levels of Ca^{2+} to Mg^{2+} during cycle

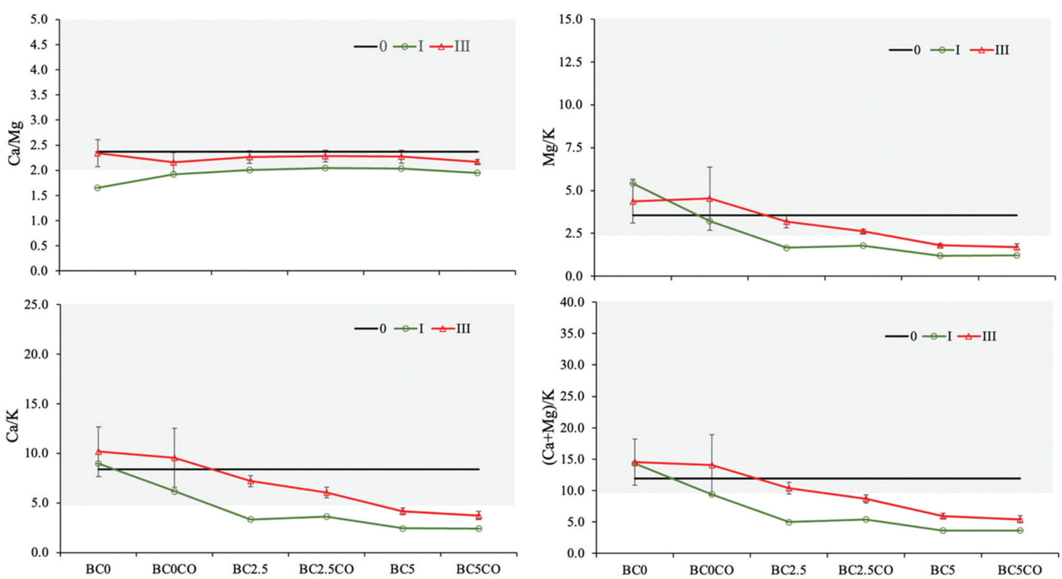

Figure 3. Fertility indicators based on exchangeable bases Ca^{2+}, Mg^{2+}, and K^+ at the end of each crop cycle (I and III) for each treatment 0, 2.5 and 5% biochar and their respective biochar-vermicompost mixtures compared to a soil condition without biochar (horizontal black line). Shadowed areas represent recommended values.

I (after fertilization) for all treatments, producing low ratios compared to the recommended values between 2—5 suggested by Peña Cordero (2017), while moving towards the recommended range during cycle III. Compared to initial soil conditions, the addition of biochar decreased the ratio Mg/K, Ca/K and (Ca+Mg)/K keeping them below the recommended values, 2.5—15, 5—25, and 10—40, respectively for all biochar combinations with 2.5% and 5% (Peña Cordero 2017).

Table 5. Physical and water content parameters of the unamended soil BC0 in cycles I and III.

Treatment	Cycle	BD	TP	AC	AWC	FC	PWP
			Saturation	> −33 kPa	−33 kPa and −1500 kPa	−33 kPa	−1500 kPa
		g cm^{-3}			cm^3 cm^{-3}		
BC0	I	1.15 ± 0.13^a	57.05 ± 3.80^a	15.97 ± 8.11^a	12.07 ± 4.36^{cd}	41.05 ± 4.36^a	29.00 ± 0.00^d
	III	1.20 ± 0.00^a	53.45 ± 0.07^a	10.70 ± 0.85^a	8.90 ± 0.85^{df}	42.80 ± 0.85^a	33.790 ± 0.00^{gh}

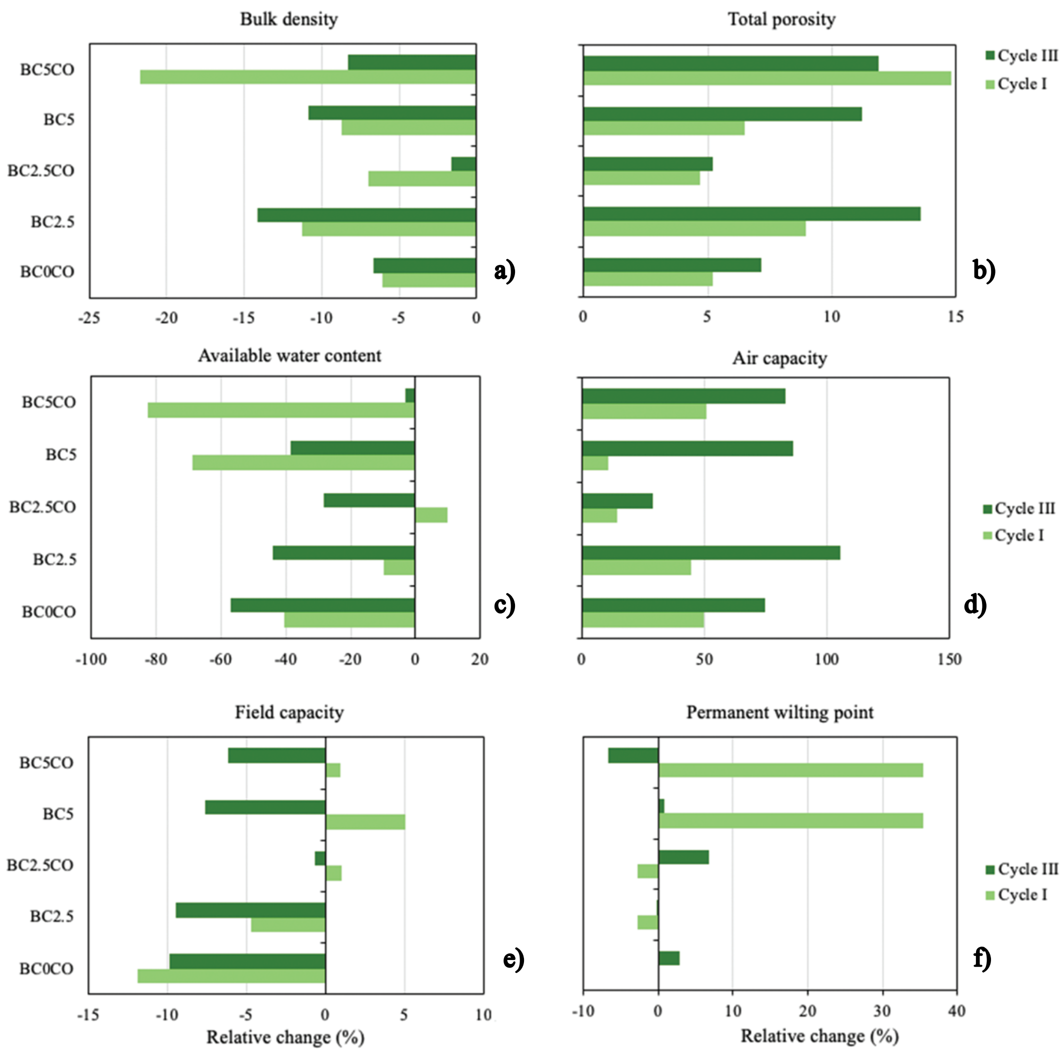

Figure 4. Relative changes (%) of main soil physical properties of the amendments for bulk density, total porosity, available water content, air capacity, field capacity, and permanent wilting point for the maize crop after cycles I and III.

The effect of biochar on soil hydraulic properties

Table 5 shows the initial soil physical and water content parameters for BC0 in cycles I and III, while Figure 4 illustrates the relative average changes for each soil parameter, comparing each treatment to the values obtained in BC0 for each cycle. Bulk density (BD) exhibited a moderate but non-significant decreasing trend with increasing biochar doses, particularly in treatments BC5 and BC5CO. Notably, BC5CO presented the greatest reduction at 22%, followed by BC2.5 at 11% and BC5 at 9% compared to BC0 in cycle I. In cycle III, although BD continued to decline relative to BC0, the decrease was less pronounced, with changes over 8% for BC2.5, BC5, and BC5CO (Figure 4a). Total porosity (TP) also showed an increasing trend in soil amendments though the changes were not statistically significant. In cycle I, BC5CO had the most substantial increase of approximately 15%, followed by BC2.5, concerning BC0. In cycle III, BC2.5 showed the highest increased at 14%, with BC5 and BC5CO exhibiting relative changes of 11% and 12%, respectively (Figure 4b). Available water content (AWC) decreased in all treatments compared to BC0, except for BC2.5CO, which increased by 10%. In cycle I AWC decreased significantly in BC5 and BC5CO by 69 and 83%, respectively. In cycle III, while in BC2.5 and BC2.5CO AWC decreased up to 44%, in BC5 and BC5CO AWC decreased less than 40%, compared to BC0 (Figure 4c). Air capacity (AC) was not remarkably different in cycle I. On average, AC was 48% higher than BC0 for treatments BC0CO, BC2.5, and BC5CO, and relatively low for BC2.5CO and BC5 (14 and 11%, respectively). Conversely, in cycle III, AC increased by more than 50% for all treatments except BC2.5CO, which had a 29% increase, with BC2.5 showing the highest AC at 105% compared to BC0 (Figure 4d). Field capacity increased by up to 5% in BC5, compared to BC0 in cycle I. However, in cycle III, all treatments showed a decrease in FC ranging from 5 to 10% compared to BC0 (Figure 4e). Permanent wilting point (PWP) showed significant changes in cycle I. A 2.5% biochar addition resulted in a 3% decrease in PWP, while a 5% application increased soil water retention at PWP by up to 35%. In cycle III, changes were less than 10% across all treatments (Figure 4f).

Figure 5 shows the soil pore size distribution, as an indicator for soil water capacity. Most of the treatments presented a higher fraction of micropores followed by macropores and a small fraction of capillary and medium pores. Initially, micropores dominated, on average, with a fraction of 40%, but after cycle I, increased up to 60% in BC5 and BC5CO, while stabilizing to a fraction of approx. 60% for all treatments, in cycle III. Macropores increased for the cycle I, mainly for BC0CO and BC5CO, but decreased for the cycle III, like cycle 0. Meanwhile, biochar did not drastically change capillary pores, in average they passed from 10 to 5% during cycle I, and in cycle III they occupied again an average volume of 10% for most of the treatments. During cycle I, mesopores faced a strong decay to a volume of less than 5% mainly for BC5 and BC5CO, while in the other treatments occupied a volume ranging between 10 and 20%. However, during cycle III it was observed a homogenous decay for all treatments occupying a volume close to 10%.

Effect of biochar on soil water dynamics

Figure 6 presents two comparisons of hydraulic conductivity (*Kh*). The first comparison illustrates the relative changes *Kh* between the treatments and the initial soil condition without biochar at Time 0 (Figure 6a). The second comparison shows the relative change in *Kh* for the treatments in cycles I and III compared to the same treatment in cycle 0 (after biochar application and plot preparation) (Figure 6b). In Figure 6a, all treatments exhibited an increase in *Kh* relative to the condition prior to biochar application. Notably, BC5 and BC5CO showed a more significant increase in *Kh* during cycle I, while BC2.5 and BC2.5CO demonstrated a greater effect in cycle III. In Figure 6b it is evident that *Kh* increased for BC2.5 in cycle III, whereas BC2.5CO exhibited a consistent decrease regardless of the cycle.

Figure 7 shows the average values infiltration rates for all treatments in cycles I and III. Overall, the combination of biochar and vermicompost resulted in higher infiltration rates compared to

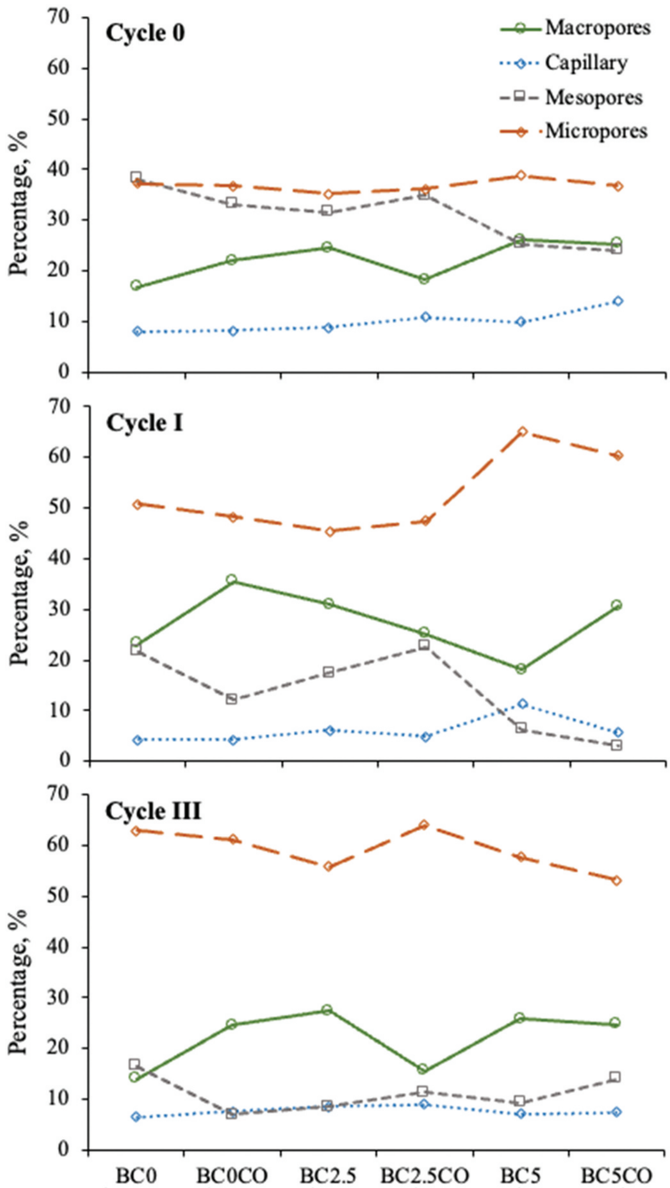

Figure 5. Pore size distribution of the soil amendments at biochar application rates 0, 2.5 and 5%, and biochar-vermicompost mixtures for cycles 0, I and III. Pore size for macropores > −6 kPa, capillary pores −6 kPa to −30 kPa, mesopores pores −30 kPa to −1500 kPa, micropores < −1500 kPa.

treatments that included only biochar, with the BC2.5CO treatment achieving the highest infiltration rate in cycle I. In cycle III, treatments with 5% biochar increased the infiltration rates compared to cycle I, with the highest infiltration observed in the treatment containing vermicompost. All curves exhibited a gradual decrease in penetration rates from the outset, with minimal variation between the initial and the constant final infiltration rates.

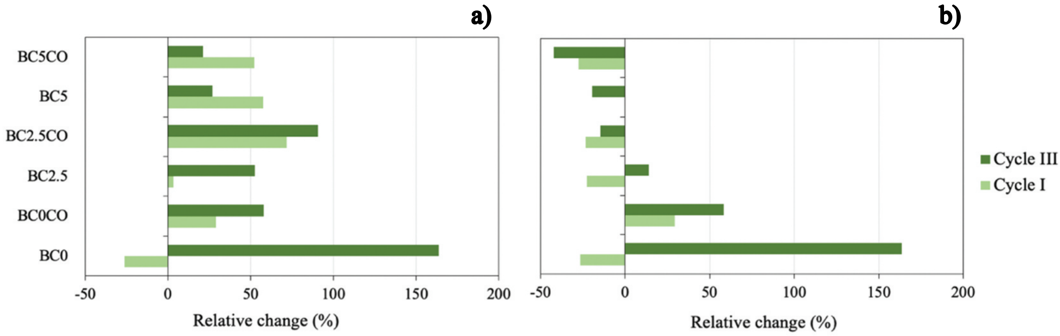

Figure 6. Relative change (%) of the hydraulic conductivity (*Kh*) in the soil amendments at biochar application rates 0, 2.5 and 5% and biochar-vermicompost mixtures for cycles I and III with respect to initial soil conditions: a) changes of all treatments with respect to initial soil conditions without biochar, b) differences of all treatments with respect to initial soil conditions after applying biochar (cycle 0).

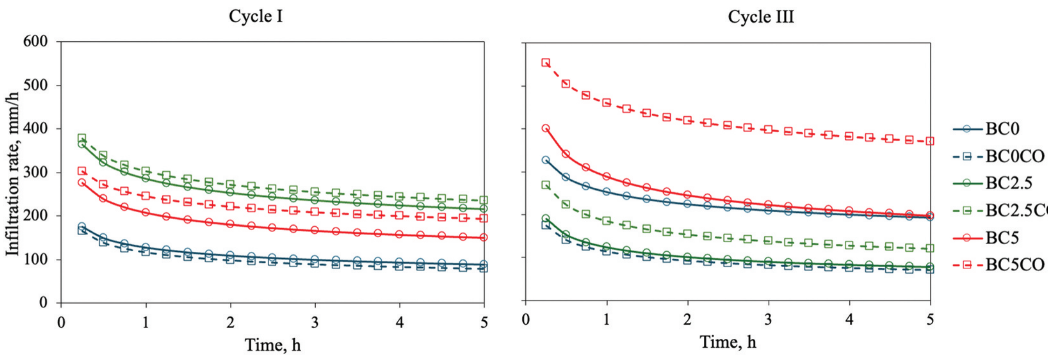

Figure 7. Infiltration rate as a function of time for the biochar treatments alone and co-applied with vermicompost of 0, 2.5 and 5% biochar in the cycles I and III.

Maize response to water stress and biochar application

Figure 8 shows the fresh and dry biomass of maize plants aboveground for cycles I and III (accounted for a total water input of 42 mm m^{-2} during the first 45 d). During dryness, the biochar effect on the maize growth was observed at the harvest of cycle I, both in fresh and dry mass. In cycle I, fresh weight of BC5 was 330% and 200% and dry mass 400% and 213% higher than BC0 and BC2.5, respectively, while BC5CO fresh weight was 545% and 240% and dry mass 745% and 298% higher than BC0CO and BC2.5CO. In contrast to cycle III, neither differences nor any trend was identified between the biomass of all treatments.

Figure 9 compares maize growth measured every two weeks for cycles I and III under dry conditions. In cycle III, the plants were, on average, 50% taller than those in cycle I at the same measurement intervals. In cycle I, treatments with biochar alone and those combined with vermicompost consistently resulted in taller plants compared to the unamended soils. In cycle III, plants in the BC2.5CO and BC5CO treatments surpassed those in the BC2.5 and BC5 treatments.

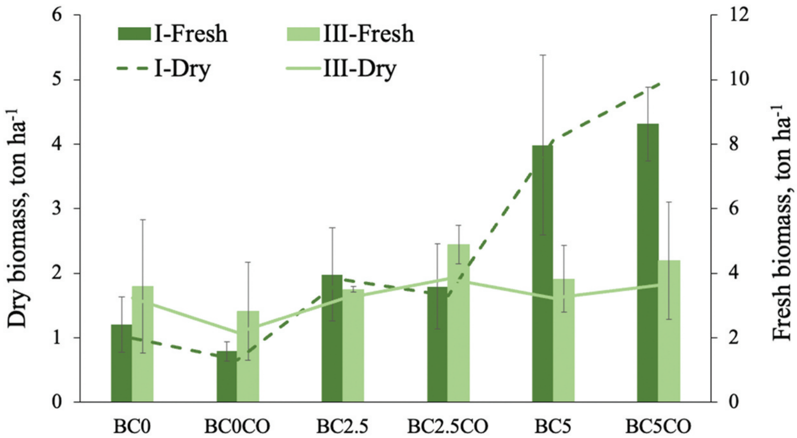

Figure 8. Aboveground fresh and dry biomass of the maize plants in ton ha^{-1} at the end of cycles I and III for each treatment 0, 2.5 and 5% biochar and biochar-vermicompost mixtures.

Discussion

Effect of soil chemical properties on the maize crop growth

From all chemical soil parameters, available K^+ and P were the main variables reflecting an effect on plant growth and biomass. Increasing values of P and K^+ in the amendments, at a biochar application rate of 5% produced more biomass under water scarcity. Available phosphorus (P) may have been enhanced through various mechanisms, (i) by desorption, anion exchange, or dissolution, or by (ii) a reduction in the complexation of P with soil components (Zhao et al. 2023), promoting P intake by plants. However, the favorable pH levels in the clay soil could have led to some P fixation, attributed to increased alkaline oxides of Ca^{2+}, Mg^{2+} and K^+ which decrease the solubility of Al^{3+} (Bornø et al. 2018; Jindo et al. 2020). This interaction may have negatively impacted maize biomass in cycle III.

Bilias et al. (2023) reported a positive correlation between biochar and K^+ availability, and a strong influence of cation exchange capacity and soil type on K^+ dynamics. Although biochar improved K^+ availability, studies show different effects in the long-term. Rasuli et al. (2022) suggested that the retention of K^+ released by biochar due to the high presence of clay content —but the relatively low biochar surface area and high Ca^{2+}— caused a short positive effect on the maize growth after the first cycle. Rogovska et al. (2014) reported a biochar effect on maize grain and biomass yields during the first year due to enhancement of plant uptake of K^+, but no significant effects during the second year under severe drought. Contrarily, Jindo et al. (2020) indicated a long-term effect of biochar-based K supplementation in crops like maize and cotton under drought conditions. Despite the positive K^+ availability effect, reduction in crop yield —especially under adverse conditions—, could be also attributed to an imbalanced ratio of the cations $Ca^{2+} + Mg^{2+}$ with respect to K^+, considered as a fertility indicator (Antonangelo et al. 2024).

Higher C:*N* values of biochar alone or mixed with vermicompost at rates of 2.5% and 5% displayed beneficial conditions for plant growth, compared to low C:*N* values of the unamended soils (Pérez and Torres-Bazurto 2020). According to Villagra-Mendoza et al. (2021) the C:N ratio of the biochar was in average 124, and the C:N ratio of the vermicompost was 18 and 14 for cycles I and III, respectively. Although high C:N ratios of the materials were added to the soil, optimal C:*N* values (USDA 2011), mainly in BC5 and BC5CO may have contributed to N-mobilization, facilitating N-uptake and consequently increasing crop yield. According to Phillips et al. (2022), N-mineralization tends to increase with the C:N ratio of the soil + biochar mixtures, mainly by the stimulation of microorganisms (specially rhizobia) (Schmidt et al. 2021), however the

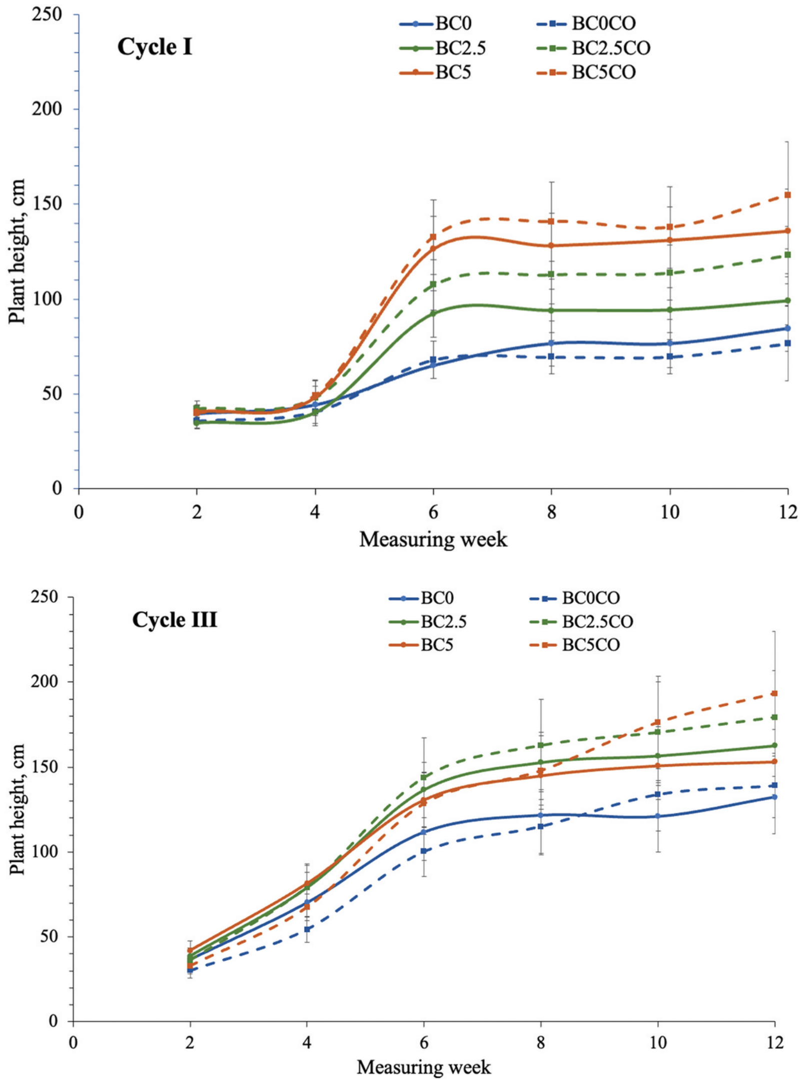

Figure 9. Plant height in cm for cycles I and III for each treatment 0, 2.5 and 5% biochar and biochar-vermicompost mixtures.

mineralization intensity might have been weakened in cycle III as the C:N ratio increased, because of the decrease of the soil enzyme activity (Xu et al. 2021; Han et al. 2023). Zhang et al. (2023b) indicated that bamboo biochar can increase soil available nitrogen, total and available K^+ and P, organic carbon content, and enzymatic activity, when combined with organic fertilizer; condition that could have contributed to produce more biomass in the amendments, especially with vermicompost.

Biochar effects on soil water conditions after three years

Although biochar promoted some favorable chemical soil conditions by providing more P and K^+ to the soil, and by keeping acceptable pH levels to avoid plant toxicity (Peña Cordero 2017), the soil ameliorating effect of biochar, on the maize resilience to water stress in clay soil, was not strong enough due to the favorable initial soil conditions (Al-Wabel et al.

2018). Thus, the contribution of biochar to the soil's physical and hydraulic properties and the frequency of biochar applications may require a deeper explanation for maize resilience under water scarcity conditions.

Hydraulic and hydrological soil properties are highly dependent on texture, structure, and pore characteristics (Hartge and Horn 2016). Although the decreasing trend of bulk density oscillated with biochar alone or mixed with vermicompost, it was notable the effect of biochar in both cycles. The enhancement of bulk density, in cycle I, may have been caused by the addition of organic matter from the vermicompost, which augments total porosity and macro-aggregate formation (Cooper et al. 2020), and by the lower density of the biochar, which modifies the skeletal density of solid particles (Brewer et al. 2014). However, the lower decrease in bulk density of the treatments with vermicompost, in cycle III compared to cycle I, suggests an acceleration of the decomposition due to the input of organic matter, which may have produced a net carbon effect between organic carbon addition and rapid decomposition (Liu et al. 2020), and additionally, it may have been possible that the natural aggregate structure induced a partial infilling of biochar particles in pores between aggregates (Rasa et al. 2018).

Biochar application increased air capacity in the clayey soil but the intensity was greater in cycle III, when compared to BC0. Macroporosity, the lower bulk density, and the interaction with the root system may have enhanced solute exchange (Wang et al. 2023) contributing to a better soil environment for plant growth. These results agree with Bayabil et al. (2015) that reported an improvement in soil permeability caused by the formation of macropores due to the addition of biochar with a larger particle size than clay particles. A consequence for a better permeability was observed in the positive change of hydraulic conductivity in the amendments compared to soil conditions without biochar, however the behavior of the soil after one-time application and three-years, experimented a reasonable decrease of the hydraulic conductivity, affected by the micropore formation, the rearrangement of soil particles, clogging of macropores and disturbance of soil aggregates (Bayabil et al. 2015), influenced by the harvest process. Therefore, pore size distribution and re-accommodation of soil aggregates were not persistent, probably impacted by the mixing effect and possible biochar loss during harvest (Cong et al. 2023). As biochar may reduce shrinkage and cracks, which is commonly reported for clayey soils (Wong et al. 2022; Wang et al. 2023), the relatively high change in intensity of hydraulic conductivity in BC0 may be related to a higher susceptibility to deformation under dry soil conditions (Peng and Horn 2007; Villagra-Mendoza and Horn 2018).

Biochar increased the intensity at which soil water retention changed at the dry-end of the curve (−1500 kPa), mainly in cycle I, indicating a shift-effect of biochar amendments on the pore size distribution toward micropores (Rasa et al. 2018). The less formation of capillary pores at matric potentials between −6 kPa and −30 kPa compared to a small increase in macroporosity (at matric potentials near saturation) was directly influenced by the soil-biochar interaction and the infilling of soil pores with a smaller biochar particle size, reducing the linked pores and altering soil water-holding capacity (Villagra-Mendoza and Horn 2018; Ghorbani et al. 2022). Despite the high-water storage capacity in the amendments, the increased microporosity and less capillary and mesopores, produced a constraint in AWC, promoting an unfavorable environment for water availability under the dry cycles. This water retention condition may have imposed a higher energy expense for water uptake, increasing plant water stress.

Infiltration is an important parameter for irrigation management and overall, for water use efficiency. Infiltration was high for the amendments coinciding with the presence of macropores, improvement of soil aggregation, and soil organic matter (contributed by the vermicompost) (Blanco-Canqui 2017; Bergeson et al. 2022) and presented similar curve-shape characteristics like those found in fine-textured soils, in terms of a slow decreasing curve which may facilitate most of the input water to turn in surface runoff if exceeding the infiltration capacity of the amendments (Kuok et al. 2023).

How biochar contributed to maize resilience under water scarcity?

The co-application of biochar and vermicompost positively impacted plant growth, primarily due to the increase in organic matter and improvements in soil aggregation and macroporosity. Early-stage plant growth may have been affected by water stress (Song et al. 2019), highlighting the importance of ensuring water availability during the seedling stage. In the first cycle, both biochar alone and in combination with vermicompost resulted in similar maize biomass, even under conditions of limited water availability after the seedling phase, comparable to maize crops receiving low irrigation throughout all the growth stages as reported by Song et al. (2019). While fresh biomass varied between cycles, maize growth did not reflect these differences. In this context, water stress may have reduced the rate of photosynthesis (Song et al. 2019; Wu et al. 2023). However, due to the limitations of this study, further investigation into photosynthetic interactions would be necessary to better understand crop response over time. The positive growth response of maize can be attributed to the application of biochar with organic amendments, which enhanced nutrient availability and improved the microbial environment (Rivelli and Libutti 2022; Zhang et al. 2023a). Additionally, the formation of stable soil aggregates likely contributed to improved soil physical and hydraulic properties (Sharma et al. 2021). Under limited water conditions, fertilization did not induce significant salt stress in treatments with biochar and vermicompost, making them less prone to negative impacts on biomass and plant growth while maintaining soil salinity within tolerable electrical conductivity (EC) levels (Vennam et al. 2024). The detrimental effects of salinity may have been alleviated by biochar treatments due to its sodium absorbing potential, resulting from its porous structure high surface area (Kanwal et al. 2018).

Conclusions

The results obtained in a three-year greenhouse experiment after a single biochar addition with vermicompost revealed a short-term impact on the growth resilience of maize under water stress conditions, evidenced by improved soil properties and maize characteristics. Biochar was effective in improving soil physical and hydraulic properties of the clay soil mainly during the first cropping cycle, though. We observed as well, enhanced K^+ and P availability amounts, and improved bulk density, hydraulic conductivity, and formation of macropores, all of which contributed to crop resilience under dry conditions. The apparent negative effects of the biochar additions seem related to the effects of harvesting and smaller particle sizes of the biochar. Thus, biochar ground to sizes larger than the clay aggregates can be repeatedly applied at intervals to maintain its soil ameliorating and resilience effects. In agricultural regions characterized by fine-textured soils and exposed to extreme water shortages, the application of doses higher than 50 ton ha^{-1} of biochar will likely be necessary to observe a positive response in maize over longer drought periods. Moreover, further studies should be focused on assessing the addition of biochar with particle size greater than clay, quantifying the crop photosynthetic efficiency under water scarcity and crop productivity when applied biochar combined with organic amendments.

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