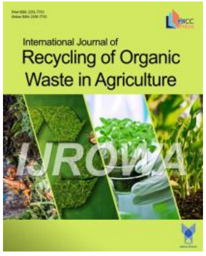

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Research Article

Application of Biochar and Impacts on Corn (*Zea Mays L.*) Agronomic Development and Nutrient Availability in Soil Under Tropical Climate

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Abstract

Purpose: Soil amendments such as biochar, a by-product of renewable energy production from organic waste, have the potential to improve crop yields by increasing water-holding capacity and soil nutrient content. However, data on the impact of biochar on corn and tropical environments are rare. The aim of this work was to evaluate the effect of biochar produced from coffee residues on maize (*Zea mays L.*) in acid soils exposed to a tropical climate.

Method: A field experiment quantifying maize growth was conducted in a randomised complete block design with four replications. Acid soils were amended with four biochar rates (0%, 1%, 2% and 10% by volume). After maize harvest, soil was collected and soil properties, phenological and performance variables were measured.

Results: The physico-chemical effects of the biochar applied to the soil showed that acidic soils changed to neutral or moderately acidic soils. Water holding capacity, cation exchange capacity, organic carbon, phosphorus and potassium contents increased significantly.

Conclusion: Our results show that biochar has positive effects on soil properties and plant growth, suggesting that biochar as a soil amendment has the potential to improve the quality of poor soils and nutrient availability. These results could theoretically support the idea of applying biochar to soils to increase nutrient stocks, reduce nutrient leaching and improve crop yields.

Keywords: Biochar, Corn crops, Physico-chemical properties, Plant growth, Recycling, Tropical environment

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1. Introduction

Globally speaking, organic soil amendments offer a promising potential to improve soil properties, plant growth and production. Biochar is the solid material (pyrolysed biomass) that remains after exposing biomass to high temperatures (between 400-600 °C), plus little or no oxygen supply (Lehmann and Joseph, 2015). Yet biochar is more than that because it has the potential to improve agricultural soil by modifying physico-chemical properties, such as soil pH, cation exchange capacity (CEC), surface area, and nutrient retention and availability (Jeffery et al., 2011; Deenik and Cooney, 2016; Clough and Condron 2010).

The beneficial effect of biochar amendments on soil fertility has long since been well-known. This is the case of the so-called Terra Preta (Glaser, 2014; Kukwa et al., 2025). It is not, therefore, surprising that biochar has been proposed to be employed as a soil amendment in agricultural lands to improve soil quality (Kizito et al., 2019; Laghari et al., 2015; Tanure et al., 2019), to reduce organic waste, and to recover nutrient and energy from what would otherwise be an unused by-product (Basiri Jahromi et al., 2018; Kizito et al., 2019). Martínez-Gómez et al. (2022) state that biochar is a precious product that can be used as a soil amendment with many positive environmental effects, such as carbon sequestration, fewer greenhouse gas emissions, soil improvement or plant growth promotion.

Biochar manifests the properties of carbon content (23.6–87.5%), pH (5.2–10.3), surface area (0–642 m2/g) and CEC (10–69 cmolc/kg) (Kim et al. 2014). Adding biochar to soil produces multiple benefits, including the amelioration of physico-chemical and biological properties (He et al., 2020), the promotion of soil fertility and crop yields (Ding et al. 2016), the control of plant diseases, and the immobilisation of toxic metals and organic pollutants. Biochar also increases soil nutrient availability, CEC and water-holding capacity (WHC), and improves soil microbial community and microbe activity (Chen et al., 2017). A decline in nutrient loss in soil associated with biochar addition has been reported by Xiao and Meng (2020). Biochar promotes seed germination, crop growth and crop production (Jeffery et al., 2017).

Biochar also has the potential to improve soil properties, including porosity, available water, soil aggregate stability, hydraulic conductivity, infiltration rate, and water retention at higher and lower tensions (Alkhasha et al., 2018; Obia et al., 2016). Plenty of studies have evaluated the effect of biochar application on several soil properties (Brockhoff et al., 2010; Zhang et al. 2016). However, very few studies have focused on the biochar effects on acid soils and equatorial conditions, particularly in Colombia.

High-quality biochar can generally be obtained in a residence time of only a few hours at temperatures around 400 °C (Wang et al., 2021;Kukwa et al., 2023). However, the physico-chemical characteristics and quality of biochar depend on the plant material or type of waste used to produce it because they influence macro- and micropore sizes and carbon, nitrogen, oxygen, hydrogen and sulphur contents (Sánchez-Reinoso et al., 2020). Biochar plays an important role in soil ecosystem functions by acting in a similar way to that of plant residue. Biochar functions have been revealed on numerous occasions (Gorovtsov et al. 2019; Gul et al. 2015; Nkoh et al., 2021; Lu et al., 2022). It has been reported to prevent the leaching of soil nutrients (it is really a source of nutrients for microorganisms), reduce gas emissions, and increase not only water-holding capacity, but also the absorption of organic and inorganic pollutants. Furthermore, biochar proves valuable in the current environmental context by reducing greenhouse gas emissions (Dong et al., 2021) and immobilising heavy metals and organic contaminants in soil (Qin et al., 2018; Qian et al., 2021; Wang et al., 2018). Biochar is considered a habitat for the soil microbiome by providing a large surface area with abundant porosity. Specifically, Uchimiya et al. (2011) and Cao and Harris (2010) indicate that the pyrolysis of plant waste, e.g., cotton seed hulls, results in biochar with a low specific surface area (SSA) value (4.7 m2/g), and that of animal manure with a higher SSA value (13 m2/g). In turn, the SSA value of biochar is related to several other properties, such as CEC and WHC. In the developed world, corn (*Zea mays L.*) is an important source of carbohydrates for human diet in developing countries and for animal feed (Ngoune-Tandzi and Mutengwa, 2020). Colombia is well-known for its high good-quality coffee productivity, where numerous residues that derive from this activity are produced. One solution to them is biochar production because it represents a potential way of transforming residue into valuable products by reducing their waste management problem (Trujillo-González et al., 2024).

Studies carried out recently in the Colombian Orinoquia reveal the strongly acid character (therefore with abundant Al exchange and low base saturation) in response to high rainfall and temperature values. Values close to 6,000 mm of rain per year are cited (Trujillo-Gónzález et al. 2022). Thus, very poor soils are generated with hardly any nutrients. Under these conditions, strong fertilisation is needed if the aim is to obtain good crop results. Consequently, biochar addition may be a factor to consider. In light of all the above, the objective of this research is to precisely evaluate the effect of applying biochar from coffee agricultural residues on corn crop development and yields in soils from where the Piedmont begins and on the high plains of the Orinoquia region in Colombia.

2. Materials and methods

2.1. Study site

The study was carried out in 2021 in an experimental unit in Villavicencio in the Department of Meta (Colombia). Its geographical location lies at coordinates 4º4'37.68" north latitude and 73º34'54.94" west longitude (Figs 1 and 2), and at an altitude of 340 m a.s.l. Its climate is tropical, and its average temperature is 26 °C, with variations between 21.7 ºC and 30.6 ºC throughout the year. The average rainfall is 3,368 mm, with a rainy period between March and November, and a dry period between December and February. The average relative humidity is 80%, dropping in the months when temperature rises (January to February) up to 66%.

2.2. Experimental design and sampling

"Soil samples were collected from two native soil areas in the Orinoquia region of Colombia: one from the high plains and another from the Piedmont. Samples were taken at depths of 0 to 30 cm in the field and transported to the soil laboratory. These are Oxisols and Alfisols (Soil Survey Staff 2022), respectively, which correspond to Ferrosols and Lixisols, according to IUSS Group (2015). Before being used for the experiment, they were analysed in the laboratory. The results in Table 1 were obtained. The soil from the high plains was strongly acidic, with low organic matter (OM) content and a very low content of available forms of phosphorus, total N, and very low ECEC.

The soil from the Piedmont was very slightly acidic, and contained more OM, phosphorus, total N and ECEC, but their values were not so different.

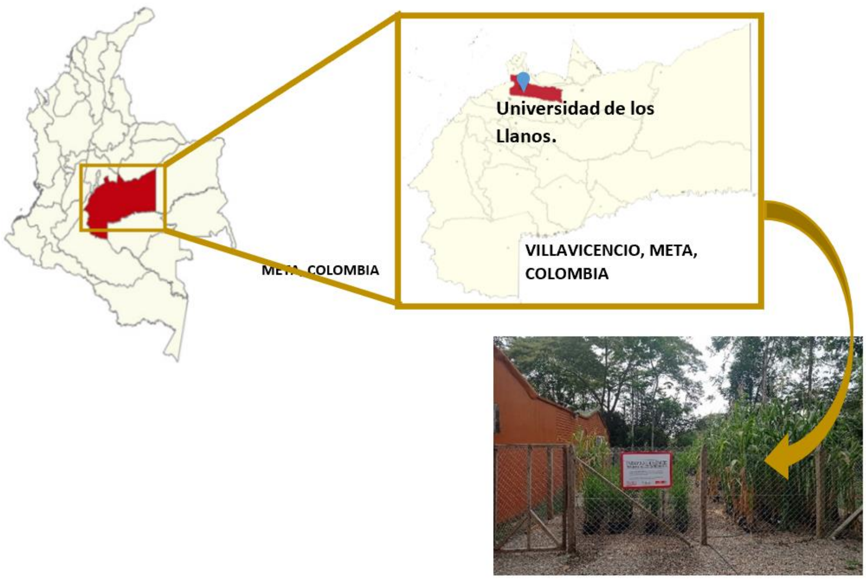

Figure 1. Study area, Universidad de los Llanos, Barcelona campus, Villavicencio, Meta (Colombia)

2.3. Experimental design

An experimental design was established using randomized complete blocks with five replications and a factorial arrangement of treatments as follows: biochar was mixed with soils in containers to simulate field trial practices." For corn cultivation (The maize hybrid DK 7088RR (DEKALB®, Bayer Crop Science) was used. It is a single-cross variety with strong stalk and root architecture, high lodging resistance, and good adaptation to tropical environments. It carries the Roundup Ready® trait for glyphosate tolerance and has a medium-to-full maturity cycle (130–150 days). The hybrid produces uniform ears with 20–22 kernel rows and yellow-orange semi-flinty grains, suitable for both grain and silage), 40 experimental units were prepared due to soil origin is 2 (High plains and Piedmont) Biochar rate is 4 (0, 1, 2, 10%) and 1 variety (corn hybrid DK7088RR) and 5 replicates (2x 4 x 1 x 5 = 40). (Table 2). Pots were fertilised with 5.1 g of urea per container 15 days after emergence and with 2 g of urea per container 55 days after emergence to represent the field fertiliser

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application rates. According to Haider et al., (2017) and Ramlow et al., (2019), considering increased soil moisture content that did not affect corn yields, a decision was made to not water plants, especially if the weather was very humid.

Maize plants were individually cultivated in polypropylene bags with dimensions of 30 cm in diameter and 40 cm in height for the agronomic trial, resulting in an approximate volume of 28 litres. Before sowing, the soil substrate was uniformly incorporated with biochar to ensure a uniform distribution and to evaluate its impact on early vegetative growth and root development.

2.4. Biochar characterisation

In Colombia, and particularly in the study area, as abundant pruning residues are produced and coffee-growing processes take place, the biochar used in the present study comes from these waste types and has the following properties (Table 3). The pyrolysis temperature of biochar is 450°C and the feedstock is coffee industry waste. Before the experiment, the biochar was previously passed through a 4 mm sieve.

Figure 2. Distribution of treatments in the experimental area, Universidad de los Llanos, Barcelona campus, Villavicencio, Meta (Colombia). Detail of the experimental area

Table 1. Results of the analysis of native soils before the experiment began

Parameter	Units	Native Soils	
		High plains	Piedmont
pH (1:2.5) (H_2O)	Unit	5.01	4.69
Electrical conductivity	dS/m	0.13	0.26
Soil organic carbon (soc)	%	1.02	2.08
Phosphorus	mg/kg	1.9	7.52
Total nitrogen	%	0.09	0.18
Available K	Cmol (+)/kg	0.29	0.78
eCEC	Cmol (+)/kg	1.93	5.05
Exchangeable acidity	Cmol (+)/kg	0.93	3.24

2.5. Agronomic management, planting, maintenance and harvest of the experiment

The experiment was carried out in a plot covering approximately 70 m2 without a roof; that is, in the open air. Gravel was laid at the base. Experimental units were prepared in black high-density polyethylene bags (weighing 10 kg). Prior to the planting process, treatments were prepared with different soils and biochar. For greater experimental control, daily monitoring was carried out. Establishing an irrigation system was not necessary because the study area is very rainy (3,368 mm/year on average). As pests and diseases were sometimes detected, adequate handling with chemicals was required. The fertilisation plan was established from the results previously obtained from laboratory analysis.

Table 2. The experimental design treatments, percentages of carbonaceous material and soil origins

Treatment	Description		
	Factor 1	Factor 2	Factor 3
	Soil origin	% Biochar	Crop
1	High plains	0	Corn (hybrid DK 7088RR)
2	High plains	1	Corn (hybrid DK 7088RR)
3	High plains	2	Corn (hybrid DK 7088RR)
4	High plains	10	Corn (hybrid DK 7088RR)
5	Piedmont	0	Corn (hybrid DK 7088RR)
6	Piedmont	1	Corn (hybrid DK 7088RR)
7	Piedmont	2	Corn (hybrid DK 7088RR)
8	Piedmont	10	Corn (hybrid DK 7088RR)

The applied mineral fertilisers contained nitrogen NH_4NO_3 and $CO(NH_2)_2$ (urea), phosphorus as P_2O_5, potassium as K_2O and calcium as CaO. In addition, there were minor elements such as magnesium, sulphur, boron, copper, molybdenum, and zinc, which were added in two surface applications. Corn seeds (local seeds) were sown at a depth of approximately 2.5 cm in pots, in March 2021. Pots were fertilised with 5.5 g of urea 10 days after emergence, and with 2 g of urea per container 30 days after emergence, to simulate the field fertiliser application rates. Corn crop development was monitored with the following variables: corn plant height, stem diameter, ear length and kernel weight (Fig. 3).

Table 3. Physico-chemical characteristics of the biochar used in the experiment

Parameter	Unit	Value
pH	Unit	9.05
Electrical conductivity	(dS/m)	3.58
Humidity	(%)	4.68
Organic carbon (%)	(%)	14.5
Moisture retention (%)	(%)	177
C/N	-	> 80
CEC	(cmol(+)/kg)	41.6
Ashes	(%)	13.3
Density	(g/cc)	0.3

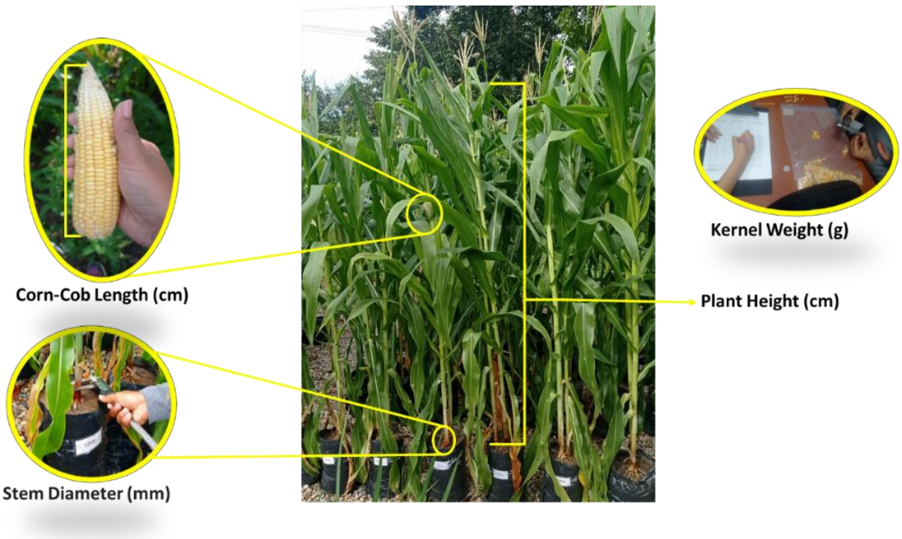

Figure 3. Image of the phenological and yield variables measured in corn (*Zea mays L.*) crops

2.6. Test performed on the soil samples of the experimental design

The experiment ended after 135 days. To evaluate the influence of biochar on the soils in which the experiment was carried out, the soil of each treatment repetition was homogenised when the experiment finished. In this way, three samples composed of each treatment were obtained. The following analysis types were carried out on these samples:

soil pH potentiometer: water is (1:2.5); electrical conductivity (EC) (1:5) organic carbon (OC) Walkey & Black; available phosphorus by Bray II; ECEC was for calculations bases and changeable acidity (Al+H).

Table 4. Descriptive statistics and the ANOVA of the variables measured in corn treatments

Treatment	Descriptive statistics	Plant height (cm)	Stem diameter (mm)	Corn-Cob length (cm)	Kernel weight (g)
T1	Mean	0^{d}	0^{b}	0^{c}	0^{b}
	SD	0	0	0	0
	CV%	0	0	0	0
T2	Mean	82.88^{c}	14.95^{a}	12.73^{ab}	24.97^{a}
	SD	13.58	1.44	2.23	3.77
	CV%	16.39	9.62	17.52	15.11
T3	Mean	105.38^{abc}	14.83^{a}	12.90^{ab}	28.10^{a}
	SD	13.27	0.93	1.57	5.97
	CV%	12.59	6.26	12.19	21.24
T4	Mean	122.28^{ab}	20.58^{a}	15.73^{a}	28.78^{a}
	SD	18.87	8.21	3.07	5.42
	CV%	15.43	39.89	19.53	18.82
T5	Mean	77.33^{c}	13.89^{a}	12.83^{ab}	30.28^{a}
	SD	10.10	0.66	0.59	3.48
	CV%	13.06	4.76	4.61	11.50
T6	Mean	96.98^{bc}	13.75^{a}	11.85^{ab}	32.30^{a}
	SD	9.49	0.59	1.55	5.15
	CV%	9.79	4.30	13.12	15.95
T7	Mean	109.88^{abc}	14.46^{a}	10.33^{b}	28.03^{a}
	SD	4.66	0.54	1.81	5.34
	CV%	4.24	3.74	17.57	19.05
T8	Mean	130.63^{a}	15.95^{a}	13.88^{ab}	33.75^{a}
	SD	26.35	2.52	2.14	1.38
	CV%	20.17	15.78	15.44	4.09

In columns, the means with the same letters do not present a significant difference P>0.05

2.7. Statistical analysis

The physico-chemical results of the soil and the phenological and yield variables of corn plants were expressed as means ± standard deviations. Statistical analyses were performed by an analysis of variance (ANOVA) at a 5% significance and the mean comparison test followed by Tukey's multiple comparison test (also at 5% significance) using the free infostat software. Any differences between the mean values in $p < 0.05$ were considered statistically significant.

3. Results and discussion

3.1. Phenological variables

The descriptive statistics of the plant development variables are presented in Table 4. The corn plants in treatment T1 (High land + 0% biochar) did not develop;

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leaves showed chlorosis and stopped growing 15 days after germination. According to the mean values taken 65 days after germination, the plant height showed this behaviour in descending order: T8>T4>T7>T3>T6>T2>T5. This indicates that the contribution of biochar influenced this variable. However, no significant differences in plant height were detected between soil origins at P>0.05% as detailed in Table 4. These results are consistent with those found by Butnan et al. (2015), who demonstrated that biochar reduces the phytotoxicity of Al in Ultisol- and Oxisol-type soils, which could have positively influenced the height of the corn plants, similarly to those studied herein.

Stem diameter and Kernel weight (g) exhibited similar trends across treatments, with higher values associated with higher biochar concentrations (10%). However, no significant differences were observed among treatments ($P > 0.05$). The mean values for Corn-Cob length (cm) at 65 days post-germination indicated that treatment 7 (10.33 cm) yielded the shortest cobs, with significant differences ($P < 0.05$) compared to treatment 4, whose average Corn-cob length was 15.73 cm. The plant height variable exhibited significant differences ($P > 0.05$) in treatments 4 and 8, whose biochar concentrations and mean values were the highest. No significant differences were observed in stem circumference ($P = 0.5$). Therefore, biochar improved the soil microenvironment by enhancing its quality, which resulted in taller corn plant height, greater stem thickness and more biomass accumulation (Table 4). These findings are consistent with Borchard et al. (2014), who applied biochar at a rate of 15 g/kg of soil and observed increased corn yields, as well as higher N and calcium (Ca) levels in corn leaves.

3.2. Soil variables

Addition of biochar led to an increase in some soil parameters (pH, P, and eCEC) because the amount of added biochar was higher. Variables like OM and nitrogen (N) also slightly increased (Table 5), with maximum values observed in the treatments with 10% biochar addition. EC increased in the treatments with higher biochar concentrations, showing significant differences ($P < 0.05$) compared to treatments with lower concentrations. This aligns with previous findings that indicate biochar's ability to alter soil water content and pH (Guo et al., 2020). Although biochar may have various effects on soil pH (Haque et al., 2021), it tends to induce alkalinity by reducing acidity (Jeffery et al., 2017).

Soil nutrients are essential for enhancing crop yield and increasing food production (Choudhary et al., 2021). Biochar has the capacity to retain and provide bioavailable nutrients for plant uptake (Gao et al., 2019). Biochar addition increases available phosphorus (P) for plant growth, likely due to enhanced phosphatase activity, while the potassium (K) present in biochar becomes available for plant uptake (Joseph et al., 2010).

A substantial body of literature has examined the effects of biochar on soil and plants, particularly for acidic or infertile soils (Ippolito et al., 2012; Indrawati, 2024), because biochar is a good soil amendment that improves soil quality, plant growth and crop yield by increasing soil pH, CEC, porosity and WHC, as pointed out by Duku et al., (2011). Other authors like Paz-Ferreiro et al., (2014) have noted retaining nutrients that, according to Asai et al. (2009), enhance fertiliser efficiency (Asai et al., 2009). The soils in both the Altillanura and Piedemont regions are considered poor and may be classified as "problematic soils", characterised by deficient (biological, physical or chemical) properties that hinder long-term plant growth and health. Our study focuses on soils exposed to a high degree of weathering, as documented by Trujillo et al. (2022), where nutrient retention is particularly problematic due to low eCEC, which results from the reduced mineral component present in these soils (Glaser et al., 2002). Previous research has demonstrated that biochar application to soil yields various agronomic benefits. Studies by Melo et al. (2019) indicate that it enhances nutrient supply and crop yields, while research by Yu et al. (2017) suggests that it can improve soil texture and physico-chemical properties. Biochar has also been observed to reduce nutrient loss in soil and to enhance fertiliser efficiency for plant uptake (Kim et al., 2017). Khan et al. (2015) reports a significant increase in soil nutrients after biochard applications. However, it is important to note that variations in crop yield may be attributed to differences in biochar quality related to feedstock, production conditions and native soil characteristics (Ronsse et al., 2013).

The present results indicate the notion that biochar application increased native soil pH (Table 5), which is consistent with previous studies that demonstrate biochar's potential to raise soil pH (Rutigliano et al., 2014; Alling et al., 2014). Although this effect is attributed to the neutral to alkaline nature of biochar, its impact may vary depending on feedstock, soil type and application rate (Jeffery et al., 2011). Biochar has also been shown to improve nutrient retention in soil by contributing to increased nutrients availability for plants. Lehmann et al. (2006) and Blackwell et al. (2015) have noted that biochar effects are more pronounced in low-fertility and low-productivity soils. Their findings are supported by our results. However, discrepancies in biochar effects on crop yield exist, as indicated by Haider et al. (2017) and Ramlow et al. (2019), especially concerning corn crops. According to Majeed et al. (2018), the effectiveness of biochar combined with N fertiliser may be influenced by

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various factors, such as biochar type, biochar dose and fertiliser dose, which impact soil fertility and corn growth. Other authors suggest that biochar has not always resulted in consistenly increased yields, as indicated by Haider et al. (2017) or Ramlow et al. (2019), especially for corn (*Zea mays L.*) crops.

Table 5. Descriptive statistics and the ANOVA of the soil variables measured in the corn treatments

Treatment	Descriptive statistics	pH	EC dS/m	Organic carbon g/100g	P mg/kg	Total N g/100g	eCEC cmol (+)/kg	Acidity cmol (+)/kg
	Mean	4.91^{f}	0.53^{ab}	1.12^{cd}	23.04^{e}	0.09^{b}	1.84^{e}	0.60^{c}
T1	SD	0.12	0.14	0.26	6.66	0.01	0.19	0.10
	CV%	2.44	26.82	23.66	28.91	9.84	10.21	16.12
	Mean	5.71^{d}	0.37^{cd}	1.25^{cd}	38.18^{cd}	0.08^{b}	2.71^{de}	0
T2	SD	0.2	0.0	0.1	11.2	0.0	0.1	0
	CV%	2.9	13.2	11.2	29.2	38.3	4.3	0
	Mean	6.37^{c}	0.33^{d}	1.07^{d}	30.82^{de}	0.08^{b}	3.22^{d}	0
T3	SD	0.08	0.01	0.20	2.69	0.01	0.22	0
	CV%	1.20	3.16	18.81	8.72	13.47	6.91	0
	Mean	8.30 ^{a}	0.59^{a}	1.45^{c}	78.51^{a}	0.08^{b}	11.26^{b}	0
T4	SD	0.06	0.02	0.08	8.22	0.01	1.25	0
	CV%	0.76	3.34	5.56	10.47	11.18	11.06	0
	Mean	4.82^{f}	0.62^{a}	2.18^{b}	41.81^{c}	0.20^{a}	7.29^{c}	2.0^{a}
T5	SD	0.08	0.03	0.08	15.86	0.01	0.22	0
	CV%	1.56	5.46	3.60	37.39	7.07	2.98	0
	Mean	5.26^{e}	0.43^{c}	2.44^{ab}	29.84^{de}	0.19^{a}	6.83^{c}	1.03^{b}
T6	SD	0.04	0.06	0.25	5.27	0.02	0.38	0.09
	CV%	0.81	14.65	10.16	17.68	8.88	5.63	8.72
	Mean	5.76^{d}	0.46^{bc}	2.27^{ab}	25.64^{e}	0.19^{a}	7.14^{c}	0
T7	SD	0.09	0.04	0.14	3.61	0.05	0.50	0
	CV%	1.55	9.56	6.11	14.07	28.28	7.06	0
	Mean	7.34^{b}	0.61^{a}	2.45^{a}	60.07^{b}	0.23^{a}	14.55^{a}	0
T8	SD	0.08	0.11	0.32	10.73	0.02	0.39	0.08
	CV%	1.12	17.44	12.76	17.87	8.80	2.66	1.12

The present study demonstrates that biochar application can significantly enhance maize growth parameters under tropical acidic soil conditions. Treatments with higher biochar concentrations (notably 10% in both Piedmont and High Plains soils) showed increased plant height, stem diameter, and kernel weight, as observed in treatments T4 and T8, which reached 122.28 cm and 130.63 cm in height and 28.78 g and 33.75 g in kernel weight, respectively. These findings are consistent with previous reports by Butnan et al. (2015), who found that biochar can alleviate aluminum phytotoxicity in highly weathered soils such as Ultisols and Oxisols. Similarly, Borchard et al. (2014) observed improved corn performance and nutrient content with biochar applications in sandy and silty soils. Although microbial interactions were not assessed in the current study, it is widely acknowledged that biochar enhances plant–microbe interactions, potentially contributing to higher crop yields (Quilliam et al., 2013; Man et al., 2021). Blackwell et al. (2010) also noted that even low, concentrated applications of biochar can modify the rhizosphere microenvironment, thereby improving seedling development. In our trial, these effects translated into improved biomass accumulation and better vegetative growth compared to control treatments. Overall, these results support the hypothesis that biochar acts as a beneficial soil amendment by improving root-zone conditions, buffering soil acidity, and enhancing the availability of key nutrients, as also reported by Kim et al. (2007), Basiri Jahromi et al. (2020), and Lehmann et al. (2011).

4. Conclusion

This study presents compelling evidence that the utilization of biochar derived from coffee pruning residues markedly improves plant growth and soil fertility in acidic tropical soils, particularly in the High Plains and Piedmont regions of Colombia. The addition of biochar at varying concentrations (1%, 2%, and 10%) resulted in significant improvements in essential growth metrics of maize, such as plant height, stem diameter, ear length, and kernel weight. The most notable responses were recorded in the 10% biochar treatments, particularly in the T4 and T8 treatments, where both biomass accumulation and yield potential significantly increased relative to the control. The favourable agronomic responses are directly associated with improvements in soil chemical properties. The incorporation of biochar elevated soil pH, thereby mitigating the severity of acidity, a significant limitation n these areas. It also improved effective cation exchange capacity (eCEC), base saturation, and the availability of vital nutrients, including phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg), particularly in Piedmont soil. In the High Plains, although some responses were more moderate, nutrient retention and increased pH facilitated superior early vegetative growth. The results indicate that biochar functions as a carbon-rich amendment and soil conditioner, enhancing nutrient use efficiency, alleviating aluminium toxicity, and promoting healthier root development.

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Authors Contribution

JMTG, ASP, MATM, MSG and EFCM conceived and designed the research; JDMP, JMTG and AMAC performed sample collection and statistical analysis, and employed the software; JMTG; JDMP, AMAC and MATM contributed to the data analysis of this work; JMTG, FJGN and RJB writing prepared the original draft; JMTG and RJB reviewed and edited the manuscript. All authors have read and approved the published version of the manuscript.

Availability of data and materials:

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of 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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