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Research Article

Effects of biochar on corn yield[1]

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ABSTRACT

Biochar has been widely used as a soil conditioner to enhance the growth and yield of short-cycle crops; however, its effects on soils degraded by mining and logging remain insufficiently studied. This study aimed to evaluate the impact of seven biochar formulations on maize (*Zea mays* L.) yield in two localities characterized by highly degraded soils. Residues of branches, coastal slabs, leaves, and stumps were pyrolyzed and applied at doses of 1 and 2 kg m^{-2}, in a randomized complete block factorial design. Germination, growth, biomass, and ear production were analyzed using linear mixed models. The biochar significantly increased germination, with values exceeding 79 % in all active treatments, when compared to 41.7 % in the control. Consistent increases in plant height and total dry biomass were also observed, especially in treatments derived from mixed residue formulations, which exhibited greater water-holding capacity, higher pH, and increased nutrient contents. Although stem diameter did not exhibit overall statistical differences, higher doses indicated a positive trend. Ear production increased with biochar application, although absolute yields remained below the national average, due to the severe soil degradation and high rainfall of the region. Biochar, particularly when applied in mixed formulations, has a strong potential to improve maize yield in degraded tropical soils, although its effectiveness depends on edaphoclimatic conditions and duration of soil incorporation.

KEYWORDS: *Zea mays* L., degraded soils, soil conditioner.

RESUMO

Efeitos de biocarvão na produtividade de milho

O biocarvão tem sido amplamente utilizado como condicionador de solo para melhorar o crescimento e a produtividade de culturas de ciclo curto; entretanto, seus efeitos em solos degradados por mineração e exploração madeireira permanecem pouco estudados. Objetivou-se avaliar o impacto de sete formulações de biocarvão sobre a produtividade de milho (*Zea mays* L.) em duas localidades caracterizadas por solos altamente degradados. Resíduos de galhos, costaneiras, folhas e tocos foram pirolisados e aplicados em doses de 1 e 2 kg m^{-2}, utilizando-se delineamento fatorial em blocos ao acaso. A germinação, crescimento, biomassa e produção de espigas foram analisados por modelos lineares mistos. O biocarvão aumentou significativamente a germinação, com valores superiores a 79 % em todos os tratamentos ativos, em comparação a 41,7 % no controle. Também foram observados aumentos consistentes na altura das plantas e na biomassa seca total, especialmente nos tratamentos derivados de misturas de resíduos, que apresentaram maior capacidade de retenção de água, pH mais alto e maiores teores de nutrientes. Embora o crescimento em diâmetro não tenha apresentado diferenças estatísticas globais, doses mais elevadas indicaram tendência positiva. A produção de espigas aumentou com o uso de biocarvão, embora os rendimentos absolutos tenham permanecido inferiores à média nacional, devido à forte degradação do solo e à elevada pluviosidade da região. O biocarvão (particularmente em formulações mistas) tem elevado potencial para melhorar a produtividade de milho em solos tropicais degradados, embora sua eficácia dependa das condições edafoclimáticas e do tempo de incorporação.

PALAVRAS-CHAVE: *Zea mays* L., solos degradados, condicionador de solo.

INTRODUCTION

Logging and gold mining are two of the dominant economic activities in the Colombian Pacific region, providing livelihoods for local and migrant populations (Ramírez et al. 2019, Torres-Torres et al. 2019). However, these activities have generated extensive deforestation, severe soil disturbance, and long-term degradation of ecosystem functioning (Hallaj et al. 2024). Mining-derived substrates, in particular, are characterized by coarse texture, low organic matter, reduced cation exchange

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capacity, and high aluminum saturation, all of which drastically diminish soil fertility (Quinto et al. 2022, Torres-Torres et al. 2023). As a consequence, agricultural production (especially of staple crops) is often limited by poor seedling establishment, reduced nutrient availability, and overall low yields (Cong et al. 2023).

Maize (*Zea mays* L.), one of the grains most widely cultivated worldwide, is highly sensitive to nutrient-poor or structurally degraded soils (Erenstein et al. 2022, Yan et al. 2022). Under such conditions, soil amendments are required to restore fertility and support crop development.

Biochar, a carbon-rich material produced by pyrolysis of organic residues, has been widely recognized for its ability to improve soil physical, chemical, and biological properties (Kammann et al. 2015, Lehmann & Joseph 2015, Hussain et al. 2017). Several studies have demonstrated that biochar can enhance soil structure, increase water-holding capacity, reduce bulk density, and retain nutrients against leaching, a key advantage in high-rainfall tropical environments (Kapoor et al. 2022, Kabir et al. 2023, Ighalo et al. 2025).

In agronomic systems, biochar has shown variable but often positive effects on plant metabolic activity, chlorophyll content, nutrient uptake, root development, and yield components (Minhas et al. 2020, Khan et al. 2024). However, biochar responses are highly context-dependent and influenced by pyrolysis conditions, feedstock type, soil properties, and climatic regime (Jeffery et al. 2016, Agegnehu et al. 2017). This leads to inconsistent findings across studies, especially under tropical conditions where excessive rainfall accelerates nutrient leaching and alters soil-plant interactions.

Despite the global interest in biochar, research evaluating its effects on soils degraded by long-term mining and logging remains limited, particularly in highly weathered tropical environments (Ighalo et al. 2025). Moreover, the physiological mechanisms underlying maize growth responses to biochar in hyper-humid tropical environments remain poorly understood, particularly regarding germination dynamics, early vegetative growth, and biomass partitioning.

Given that degraded soils in the Colombian Pacific exhibit extremely low nutrient availability (Quinto et al. 2022), and that biochar is rich in stable carbon, basic cations, and functional groups capable of enhancing soil fertility (Kammann et al. 2015, Hussain et al. 2017), we hypothesized that incorporating biochar into degraded soils would enhance overall maize yield by improving germination, stimulating vegetative growth, increasing biomass accumulation, and boosting ear production. Therefore, this study aimed to evaluate the effect of eight treatments (seven biochar formulations derived from mixed forest residues and one untreated control) on maize yield in two localities strongly affected by mining and logging activities.

MATERIAL AND METHODS

The study was carried out in April 2023, in the municipality of Quibdó, Colombia, specifically in the villages of Tutunendo (5º48’N and 76º35’W) and San Francisco de Ichó (5º46’N and 76º30’W; Figure 1), which are located in the tropical rainforest (bp-T) life zone, characterized by average temperature of 28 ºC and annual rainfall of more than 7,000 mm (IIAP 2001). The main economic activities in the area include agriculture, gold mining, and timber extraction, with agriculture being the predominant activity.

Forest residues were collected from a timber harvest area in San Francisco de Ichó and air-dried for one month. Eight active treatments were formulated from these residues: branch biochar (B); coastal/butt plate biochar (BT); leaf + stump biochar (LT); branch + coastal biochar (BBP); branch + leaf + stump biochar (BLS); coastal + leaf + stump biochar (BTS); branch + coastal + leaf + stump biochar (MIX); and control (additional treatment without biochar, managed with the traditional practice of slash-and-burn).

Pyrolysis was performed in a double-chamber retort furnace. The internal chamber consisted of a 15-kg metallic tank hermetically sealed with high-temperature silicone, whereas the external chamber corresponded to a 55-gallon drum with an upper chimney. Combustion took place in the lower part of the equipment, using firewood, and was monitored through a thermocouple (Zcebox) that registered temperature during the 3-hour pyrolysis process.

Representative samples of 500 g were collected from each formulation, stored in hermetically sealed plastic bags and sent to the laboratory for physical-chemical characterization. Analyses included pH, electrical conductivity, nutrient content (N, P, K, Ca, Mg, S, B, Cu, Mn, Fe, Zn, Na), organic matter, and organic carbon.

Composite soil samples were taken (15 cm depth) before planting and after harvest, at five points per location. The samples were sent to the same laboratory to evaluate physical-chemical properties: texture (Bouyoucos); pH (potentiometer; 1:2 ratio); organic matter (Walkley & Black); available phosphorus (L-ascorbic acid; UV-VIS spectrophotometry); total nitrogen (micro-Kjeldahl); aluminum (KCl 1M; volumetry); and nutrients (Ca, Mg, K) by atomic absorption. The procedures recommended by Osorio (2018) were followed.

A randomized complete block factorial design, with two fixed factors, was used: biochar type, with eight levels corresponding to the treatments (B, BT, LT, BBP, BLS, BTS, MIX, and control); and application rate (1 and 2 kg m^{-2}). Because local edaphoclimatic conditions were expected to differ substantially (notably rainfall, soil texture, and nutrient availability), location was modeled as a random effect. Each combination of biochar type x dose was replicated twice in each location, resulting in 64 experimental plots (8 treatments x 2 doses x 2 replicates x 2 sites). Plots measured 2 m^2 and contained six *Z. mays* plants. Biochar was incorporated at one week before planting at 15 cm depth. The evaluated variables included germination percentage, plant height, stem diameter, total dry biomass, and ear yield.

Data were analyzed using linear mixed-effects models to account for the factorial structure and the random effect of location. For each response variable (germination, height, diameter, biomass, and ear yield), the following model was fitted: $Y_{ijkl} = \mu + T_i + D_j + (T \times D)_{ij} + L_k + \varepsilon_{ijkl}$, where: Y_{ijkl} is the observed value of the response variable; μ the overall mean; T_i the fixed effect of the i-th biochar treatment (8 levels); D_j the fixed effect of the dose (1 or 2 kg m^{-2}); $(T \times D)_{ij}$ the interaction; L_k the random effect of location [$L_k \sim N(0, \sigma^2_L)$]; and ε_{ijkl} the residual error [$\sim N(0, \sigma^2)$].

The models were fitted by restricted maximum likelihood, using the lmer() function of the lme4 package (Bates et al. 2015) in R (R Core Team 2023). Normality of residuals was evaluated using Shapiro-Wilk tests and skewness/kurtosis inspection. Homogeneity of residual variances was assessed using Bartlett and Levene tests (Hoshmand 1998). No variable required transformation. Significance of treatment, dose, and their interaction was assessed using Type-III Anova, with Satterthwaite's approximation for degrees of freedom (lmerTest package).

The comparisons were adjusted using the Tukey method to control the family-wise error rate. In addition, compact letter displays were generated to group treatment-by-dose combinations according to statistical similarity (Lenth 2025). These groupings were used to summarize differences among factor levels in tables.

RESULTS AND DISCUSSION

The physical-chemical characterization of the seven biochar formulations demonstrated marked differences associated with the type of feedstock used (Table 1). All biochars showed alkaline pH values (8.04-10.07), which is consistent with the literature on wood-derived biochars produced at moderate-high pyrolysis temperatures. The highest pH was recorded in LT (leaf + stump; pH 10.07), suggesting a greater concentration of basic cations and ash-forming minerals.

Bulk density ranged from 160 to 280 kg m^{-3}, values typical of porous carbonized materials. Electrical conductivity (EC) showed a strong variation among formulations, with BT (coastal/butt plate biochar) presenting the highest EC (1.25 mS cm^{-1}), being consistent with its elevated concentrations of Ca, Fe, Mn, and Na. This suggests a higher ionic load and exchangeable cation availability, which may partially explain the stronger effects of BT-based treatments on maize germination and early growth.

Nutrient content followed distinct patterns depending on feedstock. BLS (branches + leaves + stump) and BT displayed the highest total N values (0.45 and 0.42 %, respectively), whereas LT had the highest K (0.31 %) and ash (103,000 mg kg^{-1}) contents. Effective cation exchange capacity (ECEC) ranged from 26.03 to 47.08 $cmol_c$ kg^{-1}, with BT and BLS showing the highest values, indicating a greater cation retention capacity and potential to improve soil nutrient-holding properties.

The organic carbon content varied between 3.59 and 7.48 %, with BT again ranking highest. The C/N ratio (13.6-18.1) suggests a moderate recalcitrance and a balance between structural carbon and more labile components. The moisture

Table 1. Physical-chemical properties of biochar formulations and soil before and after planting.

Parameter	Unit	B	BT	LT	BBP	BLS	BTS	MIX
Bulk density	kg m^{-3}	160	280	260	280	270	230	280
pH (10 %)	-	9.47	8.04	10.07	9.70	9.71	9.84	9.86
Electrical conductivity	mS cm^{-1}	0.17	1.25	0.36	0.14	0.20	0.21	0.21
Moisture	mg kg^{-1}	38.6	11.82	451.2	341.4	197.9	297.8	296.8
Ashes	mg kg^{-1}	69,700	40,600	103,000	80,200	54,400	60,200	62,200
Acid insoluble residue	mg kg^{-1}	11,300	4,700	3,800	8,900	10,000	6,000	7,000
ECEC	cmol$_c$ kg^{-1}	36.32	47.08	26.03	29.62	46.16	39.18	43.16
Total N	%	0.25	0.42	0.26	0.26	0.45	0.28	0.42
Total K	%	0.26	0.18	0.31	0.20	0.39	0.25	0.27
Total Ca	%	0.94	0.97	0.94	0.47	0.60	0.62	0.62
Total Mg	%	0.09	0.06	0.13	0.06	0.12	0.07	0.08
Total P	%	0.07	0.09	0.08	0.07	0.09	0.11	0.10
Total Si	%	0.04	0.005	0.003	0.004	0.005	0.004	0.004
S	%	0.006	0.009	0.005	0.007	0.008	0.007	0.007
B	%	0.006	0.009	0.005	0.007	0.008	0.007	0.007
Cu	%	0.001	0.004	0.001	0.002	0.002	0.001	0.002
Mn	%	0.006	0.009	0.016	0.001	0.008	0.007	0.007
Fe	%	0.020	0.090	0.012	0.030	0.050	0.100	0.054
Zn	%	0.012	0.0002	0.22	0.003	0.001	0.04	0.002
Na	%	0.01	0.02	0.01	0.01	0.02	0.04	0.002
Organic C	%	4.15	7.48	3.59	3.60	6.34	5.08	6.23
C/N ratio	-	16.9	17.67	13.65	13.65	14.13	18.08	16.12
Moisture retention	%	89.26	131.13	63.64	80.58	91.05	79.62	82.04

* B: branch biochar; BT: coastal/butt plate biochar; LT: leaf + stump biochar; BBP: branch + coastal biochar; BLS: branch + leaf + stump biochar; BTS: coastal + leaf + stump biochar; MIX: branch + coastal + leaf + stump biochar. ECEC: effective cation exchange capacity.

retention capacity was particularly high in BT (131 %), reflecting its greater porosity and surface area.

Overall, the combined formulation (MIX: branch + coastal + leaf + stump biochar) integrated the favorable attributes of individual feedstocks, including high pH, moderate EC, balanced nutrient concentration, and high ECEC. These properties help to explain the strong agronomic response of maize in treatments where mixtures of residues were applied.

The treatments B (branch biochar) and MIX (leaf and stump biochar) presented improvements in soil physical-chemical parameters, showing a positive effect on potential fertility. However, only some nutrients, such as nitrogen (N), potassium (K), sulfur (S) and boron (B), increased after the biochar application (Table 2). This behavior has been previously described by Chan et al. (2007), who pointed out that biochar can improve the availability of mobile nutrients in the short term, but that other nutrients, such as phosphorus or calcium, require more time to express significant changes.

The few responses in some soil nutrients to the addition of biochar may be related to two reasons, the first with the short period of biochar addition, since it has been observed that, after supplying the soil with plant amendments, significant changes tend to be reflected in the medium and long term (Osorio 2018), and more in soils with mining background (Tutunendo case), in which ecosystems are deforested, soil is removed and mounds are formed with notable characteristics: coarse texture, low moisture retention capacity and limited proportions of silt, clay and organic matter (Ramírez et al. 2019). The second explanation is related to the recalcitrant nature of biochar and the need for humification processes to release retained nutrients (Ighalo et al. 2025). In addition, the climatic conditions of Quibdó, characterized by rainfall in excess of 7,000 mm year^{-1}, can cause nutrient leaching, especially in soils with loose structure and low cation exchange capacity, as in areas of recent mining (Quinto et al. 2022, Torres-Torres et al. 2024).

The mixed model showed that the treatment factor had a highly significant effect on maize seed germination ($p < 0.001$), whereas dose showed a marginal trend ($p = 0.090$), and the treatment x dose interaction was not significant ($p = 0.743$; Table 3).

This indicates that the germination response was primarily driven by the type of biochar used rather than the amount applied.

Adjusted means revealed that all active biochar treatments achieved markedly higher germination percentages (79.2-100 %), when compared with the control (41.7 %), which exhibited a statistically significant reduction in germination capacity ($p < 0.05$; Table 4). Although some active treatments shared statistical groupings, they all consistently outperformed the untreated soil, confirming the positive effect of biochar on early seed development.

Biochar influences germination through several soil-plant mechanisms. First, biochar improves the soil physical structure, reducing bulk density, increasing porosity, and enhancing

Table 2. Main physical-chemical parameters of the soil before and after the biochar application.

Parameter	Unit	Before	After	Interpretation*
Potassium	$cmol_c\ kg^{-1}$	0.01	0.02	D
Calcium	$cmol_c\ kg^{-1}$	0.19	0.17	D
Magnesium	$cmol_c\ kg^{-1}$	0.12	0.11	D
Sodium	$mmol_c\ kg^{-1}$	0.11	0.30	D
Aluminum	$cmol_c\ kg^{-1}$	4.89	4.27	E
ECEC	$cmol_c\ kg^{-1}$	5.24	4.67	B
Phosphorus	$mg\ kg^{-1}$	4	2	D
$N\text{-}NO_3$	$mg\ kg^{-1}$	5	10	D
Sulfur	$mg\ kg^{-1}$	1	3	D
Iron	$mg\ kg^{-1}$	67	121	B
Manganese	$mg\ kg^{-1}$	1	1	D
Copper	$mg\ kg^{-1}$	0.7	0.7	M
Zinc	$mg\ kg^{-1}$	0.9	0.7	D
Boron	$mg\ kg^{-1}$	0.6	0.19	D
pH	-	4.5	4.53	B
Electrical conductivity	$mS\ cm^{-1}$	0.07	0.10	D
Organic matter	%	3.07	3.34	-
Organic C	%	1.78	1.94	B
Moisture saturation	%	74	64	A
Base saturation	%	6.65	8	-
Bulk density	kg/m^3	460	530	-

* D: deficient; B: low; M: medium; A: high. ECEC: effective cation exchange capacity.

Table 3. Mixed model results for the evaluated variables.

Variable	Effect	F-value	gl (effect , error)	p-value	Significance
Germination	Treatment	5.9	7 , 16	< 0.001	***
	Dose	3.01	1 , 16	0.09	.
	Treatment x dose	0.61	7 , 16	0.743	ns
Growth in height	Treatment	4.46	7 , 16	0.0002	***
	Dose	0.54	1 , 16	0.467	ns
	Treatment x dose	2	7 , 16	0.082	ns
Diameter growth	Treatment	1.16	7 , 16	0.346	ns
	Dose	0.89	1 , 16	0.348	ns
	Treatment x dose	0.93	7 , 16	0.467	ns
Dry biomass	Treatment	9.88	7 , 16	< 0.001	***
	Dose	2.81	1 , 16	0.101	ns
	Treatment x dose	0.88	7 , 16	0.528	ns
Ear production	Treatment	10.93	7 , 16	< 0.001	***
	Dose	1.97	1 , 16	0.168	ns
	Treatment x dose	0.49	7 , 16	0.84	ns

*** $p < 0.001$; .: trend; ns: not significant. N = 32; df_error = 16; df_total = 31.

Table 4. Effects of biochar on maize seed germination.

Treatment	Dose	Germination (%)*	SE	Df	LCL (95 %)	UCL (95 %)
Control	1	41.7 a	16.3	2.24	-185	269
Control	2	41.7 a	16.3	2.24	-185	269
B	2	79.2 ab	14.9	1.54	-441	599
LT	1	79.2 ab	14.9	1.54	-441	599
LT	2	79.2 ab	14.9	1.54	-441	599
BT	2	79.2 ab	14.9	1.54	-441	599
MIX	1	83.3 ab	14.9	1.54	-437	604
BLS	2	83.3 ab	14.9	1.54	-437	604
MIX	2	83.3 ab	14.9	1.54	-437	604
BBP	2	83.3 ab	14.9	1.54	-437	604
BTS	2	83.3 ab	14.9	1.54	-437	604
BLS	1	83.3 ab	14.9	1.54	-437	604
BBP	1	91.7 b	14.9	1.54	-429	612
B	1	91.7 b	14.9	1.54	-429	612
BTS	1	91.7 b	14.9	1.54	-429	612
BT	1	100.0 b	14.9	1.54	-420	620

* Different letters within the same dose indicate significant differences (Tukey; $p < 0.05$). B: branch biochar; BT: coastal/butt plate biochar; LT: leaf + stump biochar; BBP: branch + coastal biochar; BLS: branch + leaf + stump biochar; BTS: coastal + leaf + stump biochar; MIX: branch + coastal + leaf + stump biochar; LCL: lower control limit; UCL: upper control limit; SE: standard error.

aeration, key conditions for radicle emergence and oxygen diffusion (Murtaza et al. 2023). These structural changes also promote water retention in the germination zone, preventing seed desiccation and supporting uniform imbibition (Hussain et al. 2017, Bo et al. 2023). In the context of the Quibdó's high rainfall (> 7,000 mm year^{-1}), increased porosity may further facilitate infiltration and reduce waterlogging stress, which is known to inhibit germination by limiting oxygen availability (Xuan et al. 2023). This suggests that biochar may buffer both extremes (drought and excess moisture), what is particularly important in tropical climates with intense rainfall variability. Second, biochar can enhance early rhizospheric biochemical activity, including increases in soil enzyme activity (β-glucosidase, urease) and shifts in microbial populations that support the early metabolic activation of seeds (Khan et al. 2022). These processes facilitate nutrient mobilization during the early stages of seedling establishment and may contribute to the higher germination rates observed. Finally, the increased germination observed with all biochar treatments may be partially attributed to increases in nutrient availability, particularly N and K (Table 2), which are essential for early metabolic activation and radicle elongation.

The treatment BT (coastal/butt plate biochar) showed the highest germination percentage (100 %). This may be due to the fact that coastal residues often contain bark, twigs, and cambial tissues, which are known to accumulate higher concentrations of nutrients such as K, Ca, Mg, and micronutrients (Briedis et al. 2011). The carbonization of these tissues produces biochar with higher ash content and electrical conductivity, properties associated with increased nutrient availability and improved soil chemical environment during germination.

Mixtures of residues (e.g., MIX, BTS, BBP) tended to perform better than single-source biochars, supporting the hypothesis that biochar derived from heterogeneous feedstocks may deliver a broader spectrum of nutrients and functional groups, enhancing both soil cation exchange capacity and early availability of mobile nutrients (Freitas et al. 2020, Kapoor et al. 2022). Although these effects were not statistically distinguishable among active treatments, the trend suggests potential synergistic interactions that merit future investigation.

In regions with extreme rainfall, such as the study area, germination may be negatively affected by nutrient dilution and leaching (Quinto et al. 2022). Biochar's high surface area and charge density help to retain nitrate, ammonium, and potassium through electrostatic interactions and micropore entrapment, reducing nutrient loss during heavy rainfall events (Zhang et al. 2021). This buffering capacity likely contributed to the superior germination observed in biochar-amended plots.

The moisture retention capacity was especially high in BT (131 %), B (89 %), and BLS (91 %). These properties help to maintain adequate matric potential around seeds, supporting the hydration process that activates the metabolic pathways required for germination (Gholami et al. 2019, Ali et al. 2021).

The higher water retention capacity of BT biochar may explain why this treatment reached the highest germination (100 %), as hydrated seeds experience faster enzyme activation, mobilization of starch reserves, and radicle protrusion (Nonogaki 2019).

These results are consistent with Hussain et al. (2017) and Minhas et al. (2020), who found that biochar enhances germination by improving soil aggregation, lowering bulk density, and stabilizing moisture availability during the early developmental stages.

The mixed-model analysis showed that biochar treatments significantly affected maize height ($p < 0.05$), whereas the dose factor did not ($p = 0.467$). The treatment x dose interaction exhibited a marginal trend ($p = 0.082$) (Table 3), suggesting that the height response was largely consistent across doses, but certain treatment and dose combinations produced slightly stronger effects. The control treatment achieved the lowest height values, highlighting the limitations imposed by the unamended soil, a typical constraint in post-mining substrates characterized by low organic matter, limited moisture retention, and poor nutrient availability (Ramírez et al. 2019, Quinto et al. 2024).

In contrast, all active biochar treatments improved plant height, with the greatest adjusted mean observed for branch biochar (B) at the dose 1 (176.7 cm). Other treatments, such as LT, BT, BLS and BTS, consistently formed part of the top statistical groups, reflecting their strong contribution to early vegetative growth. Multiple comparisons indicated that coastal-derived biochar (BT) and mixed formulations containing leaf and stump residues (BLS and BTS) exhibited robust effects even at the dose 1, whereas the dose 2 tended to enhance height marginally for some treatments (e.g., BT and BTS), although not significantly (Table 5).

These improvements in plant height reflect several mechanistic pathways supported by the characterization of the used biochar. First, biochar displayed a high pH (8.0-10.1), which can partially neutralize soil acidity and reduce soluble aluminum (Table 2), improving root elongation and nutrient uptake (Agegnehu et al. 2016). Second, their effective cation exchange capacity (ECEC) was markedly elevated (26-47 $cmol_c$ kg^{-1}), particularly in BT and BLS biochars, favoring nutrient retention and reducing losses through leaching, an important aspect in the Quibdó's extremely high rainfall environment (~7,000 mm $year^{-1}$). Enhanced ECEC is a well-documented mechanism through which biochar improves nutrient availability and promotes shoot growth (Agegnehu et al. 2017).

The moisture retention capacity of the biochars was generally high (63-131 %), particularly in BT,

Table 5. Effects of biochar on plant height growth of *Zea mays*.

Treatment	Dose	Height (cm)*	SE	Df	LCL (95 %)	UCL (95 %)
Control	2	30.2 a	48.5	1.89	-938	999
Control	1	45.4 ab	48.5	1.89	-923	1,014
B	2	103.3 abc	44.9	1.40	-2,059	2,266
LT	1	104.8 abc	44.9	1.40	-2,058	2,267
LT	2	131.8 abc	44.9	1.40	-2,031	2,294
BBP	2	126.2 abc	44.9	1.40	-2,036	2,289
BTS	1	128.7 abc	44.9	1.40	-2,034	2,291
BTS	2	163.5 c	44.9	1.40	-1,999	2,326
BLS	1	145.8 bc	44.9	1.40	-2,017	2,308
B	1	176.7 c	44.9	1.40	-1,986	2,339
BT	1	148.4 bc	44.9	1.40	-2,014	2,311
BT	2	165.3 c	44.9	1.40	-1,997	2,328
MIX	1	149.8 abc	44.9	1.40	-2,013	2,312
MIX	2	158.7 bc	44.9	1.40	-2,004	2,321

* Different letters within the same dose indicate significant differences (Tukey; $p < 0.05$). B: branch biochar; BT: coastal/butt plate biochar; LT: leaf + stump biochar; BBP: branch + coastal biochar; BLS: branch + leaf + stump biochar; BTS: coastal + leaf + stump biochar; MIX: branch + coastal + leaf + stump biochar; LCL: lower control limit; UCL: upper control limit; SE: standard error.

BLS and MIX, supporting a better water availability in this coarse-textured post-mining soil. Improved water retention and soil physical structure promote faster shoot expansion by reducing hydric stress during early vegetative development (Kammann et al. 2015, Hussain et al. 2017).

Beyond physical improvements, nutrient contents of biochar also explain the observed differences. Coastal biochar residue (BT) and mixed biochar residue (BLS, BTS, MIX) presented high concentrations of N, Ca, K and micronutrients such as Fe and Mn, and organic carbon levels above 5 % (Table 1). After soil incorporation, increases in N, K and S were observed (Table 2), reinforcing the role of biochar in enhancing the nutrient environment of the rhizosphere. Nitrogen, in particular, is a critical driver of plant height, because it supports high rates of photosynthesis, leaf area expansion and biomass allocation to structural tissues (Li et al. 2019, Yan et al. 2019). This aligns with the strong performance of BT and BTS biochar, which contained the highest N concentrations (0.42-0.45 %).

The slight but consistent height increment at the dose 2 for several treatments may reflect increased nutrient availability and higher water retention at greater biochar rates, although the non-significant dose effect suggests that even the lower dose was sufficient to trigger substantial physiological responses. Similar findings were reported by Cong et al. (2023), who observed, beyond a certain threshold, the effect of biochar on height growth plateaus, particularly in soils with initially low fertility.

Overall, the combined evidence indicates that biochar enhances plant height through synergistic improvements in soil fertility, water retention, and nutrient dynamics, with coastal-derived and mixed-residue biochar providing the most pronounced benefits under the edaphoclimatic conditions of post-mining soils in Quibdó.

The mixed-model analysis indicated no significant main effects of treatment ($p = 0.346$), dose ($p = 0.348$), or their interaction ($p = 0.467$) on stem-diameter growth (Table 3). However, the adjusted means reveal notable patterns that provide biological insight. In particular, a comparatively high mean diameter was observed in the treatment B under the dose 2 (29.77 mm), whose confidence interval remained above zero (3.66-55.90 mm), suggesting a potential positive response to higher biochar application rates.

Although these differences were not statistically significant across all treatments (Table 6), the pattern suggests that stem diameter may be more responsive to the quantity of biochar applied rather than to biochar type. This aligns with previous findings indicating that increased biochar doses can enhance stem thickness by improving soil water retention, increasing nutrient availability and reducing

Table 6. Effects of biochar on plant diameter growth of *Zea mays*.

Treatment	Dose	Diameter growth (mm)*	SE	Df	LCL (95 %)	UCL (95 %)
Control	2	2.98 a	8.29	18.73	-25.02	31.00
Control	1	5.20 a	8.29	18.73	-22.80	33.20
LT	2	5.89 a	6.33	8.15	-20.22	32.00
LT	1	7.53 a	6.33	8.15	-18.58	33.60
BT	1	8.55 a	6.33	8.15	-17.55	34.70
BLS	1	8.68 a	6.33	8.15	-17.43	34.80
BT	2	8.75 a	6.33	8.15	-17.36	34.90
B	1	8.75 a	6.33	8.15	-17.36	34.90
BBP	2	9.47 a	6.33	8.15	-16.64	35.60
MIX	1	9.49 a	6.33	8.15	-16.62	35.60
BTS	1	9.84 a	6.33	8.15	-16.27	35.90
BBP	1	9.94 a	6.33	8.15	-16.17	36.10
BLS	2	10.76 a	6.33	8.15	-15.35	36.90
MIX	2	10.79 a	6.33	8.15	-15.32	36.90
BTS	2	11.07 a	6.33	8.15	-15.03	37.20
B	2	29.77 a	6.33	8.15	3.66	55.90

* Different letters within the same dose indicate significant differences (Tukey; $p < 0.05$). B: branch biochar; BT: coastal/butt plate biochar; LT: leaf + stump biochar; BBP: branch + coastal biochar; BLS: branch + leaf + stump biochar; BTS: coastal + leaf + stump biochar; MIX: branch + coastal + leaf + stump biochar; LCL: lower control limit; UCL: upper control limit; SE: standard error.

mechanical resistance of the soil matrix (Dai et al. 2020).

Biochar with higher moisture-retention capacity [particularly B (89.26 %), BLS (91.05 %), and BT (131.13 %)] likely contributed to sustained water availability during early stem thickening. Stem diameter is highly sensitive to soil water status because turgor-mediated cell expansion depends on adequate hydration (Gallardo et al. 2006). This is consistent with the observations of Dai et al. (2020), who demonstrated that biochar increases stem diameter by improving water retention and reducing soil compaction.

Moreover, the measured increase in soil organic carbon after biochar addition (from 1.78 to 1.94 %; Table 2) may have improved soil structure and aeration, reducing mechanical resistance to root growth. A better root proliferation enhances water uptake and supports secondary growth in stems (Strock & Lynch 2020).

Recent studies have demonstrated that biochar amendments can strengthen stem tissue, increasing stem-breaking force by up to 52 %, which reflects improved mechanical support and potential tolerance to stress (Zwart & Kim 2012, Chi et al. 2024, Zhou et al. 2024). These structural effects are agronomically relevant, because thicker stems are associated with improved drought tolerance, greater mechanical stability, and enhanced translocation of water and nutrients (Hazman & Kabil 2022).

Therefore, while no strong statistical evidence was detected in the present experiment, the observed diameter responses under higher doses (particularly in the B treatment) indicate a possible positive trend. This suggests that biochar additions, especially at higher application rates, may contribute to stem thickening in maize. Nevertheless, these findings should be interpreted cautiously, and further experiments with larger sample sizes or refined dose levels are necessary to confirm these effects.

The mixed-effects model showed a highly significant effect of the biochar treatment on total dry biomass ($p < 0.001$), whereas the dose ($p = 0.101$) and the treatment x dose interaction ($p = 0.528$) were not statistically significant (Table 3). This indicates that biomass accumulation in maize was primarily driven by the type of biochar applied rather than by the amount used.

The combined branch + coastal biochar (BBP) produced one of the strongest responses, significantly increasing the total dry biomass, when compared to the control ($p = 0.0028$), with an adjusted mean of 481 g plant^{-1}, representing a gain of more than 330 g relative to untreated soil. Similarly, the treatments composed of branch + coastal + leaf + stump biochar (BLS; $p = 0.019$) and coastal + leaf + stump biochar (BTS; $p = 0.037$) also significantly outperformed the control (Table 7). These increases align with previous studies reporting substantial biomass improvements in maize when biochar is

Table 7. Effects of biochar on biomass content of *Zea mays* plants.

Treatment	Dose	Biomass (g)*	SE	Df	LCL (95 %)	UCL (95 %)
Control	2	125 a	152	1.51	-5,511	5,761
Control	1	150 ab	152	1.51	-5,486	5,786
B	1	269 abc	144	1.23	-10,766	11,304
B	2	282 abcd	144	1.23	-10,753	11,318
BT	2	306 abcd	144	1.23	-10,729	11,341
BT	1	338 abcde	144	1.23	-10,698	11,373
LT	1	362 abcde	144	1.23	-10,673	11,398
LT	2	397 abcde	144	1.23	-10,638	11,432
BTS	1	412 abcde	144	1.23	-10,623	11,448
MIX	1	431 bcde	144	1.23	-10,604	11,466
BTS	2	459 cde	144	1.23	-10,576	11,494
BBP	1	481 cde	144	1.23	-10,554	11,516
BBP	2	501 cde	144	1.23	-10,534	11,536
LT	2	512 de	144	1.23	-10,523	11,548
MIX	2	572 e	144	1.23	-10,463	11,607

* Different letters within the same dose indicate significant differences (Tukey; $p < 0.05$). B: branch biochar; BT: coastal/butt plate biochar; LT: leaf + stump biochar; BBP: branch + coastal biochar; BLS: branch + leaf + stump biochar; BTS: coastal + leaf + stump biochar; MIX: branch + coastal + leaf + stump biochar; LCL: lower control limit; UCL: upper control limit; SE: standard error.

applied at moderate rates (2-4 t ha^{-1}), attributed to enhanced nutrient retention, greater aeration, and improved soil moisture dynamics (Hussain et al. 2017, Minhas et al. 2020).

A higher biomass production is commonly associated with improved nutrient use efficiency, enhanced photosynthetic capacity, and greater vegetative vigor (Semida et al. 2019). In particular, biochar-rich in base cations and surface functional groups can enhance nutrient availability and microbial activity, promoting root expansion and plant productivity (Lehmann & Joseph 2024, Oke et al. 2025).

Random-effects estimates also revealed substantial variability associated with locality ($\sigma^2 = 37,194$), indicating that site-specific conditions strongly influenced biomass outcomes. This is consistent with the findings of Jeffery et al. (2016), who emphasized that biochar performance is context-dependent, particularly under contrasting edaphoclimatic conditions. Such variability reinforces the importance of locally adapted management approaches in tropical high-rainfall environments like the Chocó region.

Biomass responses in maize can also interact with rainfall dynamics. Park et al. (2023) documented higher biomass accumulation when biochar was applied during rainy periods, likely due to increased nutrient mobility and reduced water stress. Given the extremely high rainfall in the study area (~7,000 mm $year^{-1}$), biochar may enhance biomass production by improving soil structure and reducing nutrient leaching. However, excessive rainfall may also limit final crop yield through impaired pollination or prolonged waterlogging (Kumar et al. 2024). Therefore, future research should investigate maize-biochar interactions under controlled water-stress conditions to develop more precise agronomic recommendations.

In general, these results indicate that biochar derived from mixed woody residues (particularly those including coastal material) has strong potential to enhance biomass accumulation and carbon storage in maize systems in hyper-humid tropical regions.

The mixed-effects model revealed a highly significant effect of biochar treatments on ear weight ($p < 0.001$), whereas neither dose ($p = 0.168$) nor the treatment x dose interaction ($p = 0.840$) influenced this variable (Table 3). As expected, the control treatment exhibited the lowest cob weight (0.070 kg $plant^{-1}$) (Table 8), reflecting the severe soil fertility limitations documented for the study site: very low base saturation, low P concentration (2 mg kg^{-1} after planting), high Al saturation, low cation exchange capacity (ECEC), and acidic pH (4.5) (Table 2). These conditions are known to restrict maize reproductive development due to impaired nutrient uptake, root growth inhibition, and reduced

Table 8. Effects of biochar on ear production.

Treatment	Dose	Cob weight (kg)*	SE	Df	LCL (95 %)	UCL (95 %)
Control	1	0.070 a	0.168	1.44	-7.33	7.47
Control	2	0.085 ab	0.168	1.44	-7.31	7.48
LT	2	0.365 abc	0.161	1.20	-13.40	14.13
LT	1	0.378 abc	0.161	1.20	-13.39	14.14
BBP	2	0.388 bc	0.161	1.20	-13.38	14.15
B	2	0.400 c	0.161	1.20	-13.36	14.16
BBP	1	0.405 c	0.161	1.20	-13.36	14.17
BLS	2	0.412 c	0.161	1.20	-13.35	14.18
BT	2	0.435 c	0.161	1.20	-13.33	14.20
BTS	2	0.438 c	0.161	1.20	-13.33	14.20
BT	1	0.448 c	0.161	1.20	-13.32	14.21
BLS	1	0.470 c	0.161	1.20	-13.29	14.23
BTS	1	0.487 c	0.161	1.20	-13.28	14.25
B	1	0.547 c	0.161	1.20	-13.22	14.31
MIX	2	0.575 c	0.161	1.20	-13.19	14.34
MIX	1	0.585 c	0.161	1.20	-13.18	14.35

* Different letters within the same dose indicate significant differences (Tukey; $p < 0.05$). B: branch biochar; BT: coastal/butt plate biochar; LT: leaf + stump biochar; BBP: branch + coastal biochar; BLS: branch + leaf + stump biochar; BTS: coastal + leaf + stump biochar; MIX: branch + coastal + leaf + stump biochar; LCL: lower control limit; UCL: upper control limit; SE: standard error.

transport of assimilates toward developing kernels (Fageria 2009).

Among the active treatments, branch + coastal biochar (BBP) produced a significantly lower cob weight, when compared to the control ($p = 0.046$). This unexpected reduction may be associated with the lower nutrient availability or possible immobilization effects observed in mixed woody feedstocks when pyrolysis conditions do not fully stabilize organic fractions, an effect already reported in a study using heterogeneous residues (Laird et al. 2009).

Conversely, the highest cob weight was achieved in the treatment combining branch, coastal, leaf, and stump residues (MIX), with an adjusted mean of 0.585 kg plant^{-1} (Table 8). Although these differences were not statistically significant, if compared to other active treatments, the trend suggests a potential synergistic effect among diverse feedstocks, likely resulting in a broader supply of nutrients, higher cation exchange capacity, and improved moisture retention. Similar patterns have been reported in biochar derived from mixed biomass inputs, which tend to enhance translocation of photoassimilates to reproductive organs, thereby increasing cob formation and grain filling (Zhang et al. 2024).

The positive response of ear weight to most biochar treatments highlights the role of biochar as a soil amendment capable of enhancing reproductive performance, particularly in degraded tropical soils. Several mechanisms may explain this improvement: enhanced nutrient availability: biochar increases soil pH, reduces Al toxicity, and improves P accessibility, key factors for reproductive processes in maize. Long-term studies report marked increases in P uptake and grain yield when biochar is applied repeatedly (Cao et al. 2020); improved soil water regulation: the study area receives > 7,000 mm year^{-1} of rainfall, which can promote leaching of essential nutrients. Biochar's porous structure helps to retain nutrients and water, moderating extreme moisture fluctuations. Park et al. (2023) showed that biochar enhanced maize yield under heavy rainfall conditions due to increased water-holding capacity and reduced N losses; stimulation of carbon metabolism: biochar can stimulate root function, increase photosynthesis, and improve the partitioning of carbon toward reproductive tissues (Zhang et al. 2024).

Despite these improvements, cob weights remained well below the Colombia's national average yield for maize (≈1.8 t ha^{-1}; MADR 2021). Several factors may explain these reduced values: legacy of soil degradation: the study site had a long history of extraction and burning cycles, which likely reduced soil biological activity and organic matter, limiting the short-term impact of biochar; short time frame of application: biochar effects on yield often increase over time as the material ages and interacts with soil biota. Hu et al. (2021) demonstrated that a single biochar application can enhance maize and wheat yields for up to four years due to gradual improvements in soil structure and nutrient dynamics; excess rainfall and pollination constraints: extremely high rainfall may disrupt tassel formation, pollen viability, and grain filling. Carr et al. (2016) observed a reduced maize yield in high-rainfall environments due to impaired pollination, corroborated by Novak et al. (2019), who reported that prolonged rainfall reduces kernel set by limiting pollen dispersal and silk receptivity.

Taken together, the results indicate that, while biochar substantially improves cob weight, when compared to unamended soil, yields are constrained by environmental and historical soil factors beyond the scope of the amendment. Longer-term studies and complementary agronomic practices (e.g., mulching, drainage improvement) may help to fully realize the potential of biochar for maize production in these hyper-humid tropical regions.

CONCLUSIONS

1. The seven biochar formulations exhibited clear physical-chemical differences determined by feedstock type, with coastal/butt plate biochar (BT) and branch + leaf + stump biochar (BLS) showing the highest nutrient concentrations, effective cation exchange capacity (ECEC), moisture retention, and organic carbon, indicating their superior potential to improve degraded soils;
2. Biochar application produced short-term improvements in selected soil parameters, particularly N, K, S, and B, whereas limited changes in other nutrients reflected the short evaluation period and the inherent recalcitrance of biochar in recently mined, coarse-textured soils;
3. All biochar treatments significantly increased maize seed germination, when compared with the control, demonstrating that biochar effectively improves early seed establishment under high-rainfall tropical conditions through enhanced structure, moisture retention, and nutrient availability;

4. The BT treatment produced the highest germination rate (100 %), likely due to its elevated ash content, electrical conductivity, and nutrient concentration, confirming its greater capacity to enhance early soil-seed conditions;
5. Mixed-residue biochars [branch + coastal + leaf + stump biochar; BLS; coastal + leaf + stump biochar (BTS); branch + coastal biochar] performed consistently well across variables, supporting the hypothesis that heterogeneous feedstock combinations provide more balanced nutrient profiles and improved functional properties relative to single-source biochars;
6. Biochar significantly increased plant height across treatments, with branch biochar, BTS, BT, and BLS showing the greatest improvements. This response was linked to increases in nutrient retention (higher ECEC), reduced aluminum toxicity, and enhanced water availability in the amended soil;
7. Dose did not significantly affect any measured variable, indicating that even the lower biochar rate was sufficient to improve germination and early growth in this post-mining soil.
8. Biochar derived from forestry residues, particularly BT and mixed formulations, is a promising amendment for restoring nutrient-poor, acidic, and highly leached post-mining soils in tropical high-rainfall environments.

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