Universidade Federal Rural do Semi-Árido
Pró-Reitoria de Pesquisa e Pós-Graduação
https://periodicos.ufersa.edu.br/index.php/caatinga
ISSN 1983-2125 (online)

http://dx.doi.org/10.1590/1983-21252025v3812730rc

Scientific Article

Different biochar: effects on soil fertility and growth of bell pepper

Diferentes biocarvões: efeitos na fertilidade do solo e no crescimento de pimentão

Josely D. Fernandes[1], Laysa G. de Souza Laurentino[1], Lúcia H. G. Chaves[1]*, José N. F. de Andrade[1], Andre A. R. da Silva[2], Gustavo T. M. Kubo[1], Geovani S. de Lima[3], Andrezza M. de Lima[1]

[1]Academic Unit of Agricultural Engineering, Universidade Federal de Campina Grande, Campina Grande, PB, Brazil. [2]Academic Unit of Agronomy, Universidade Federal do Oeste do Pará, Juruti, PA, Brazil. [3]Academic Unit of Agricultural Sciences, Universidade Federal de Campina Grande, Pombal, PB, Brazil.

ABSTRACT - The use of agro-industrial waste as agricultural input is a sustainable alternative to recover soil fertility and increase productivity. The objective of this study was to evaluate the effects of biochars produced from poultry litter, coconut fiber, and rice straw on soil fertility and on the growth of green bell peppers grown in the field, in an Ultisol. Initially, soil samples were incubated with the three biochars at doses of 0.0, 6.0, 9.0, and 12.0 t ha^{-1} for 160 days, with moisture content around 70%. After this period, chemical analyses of the soil were performed. Then, an experiment was conducted in a randomized block design, in a 5 × 3 + 1 factorial scheme (five doses and three types of biochars, plus an additional treatment with mineral fertilizer), with four replicates. Poultry litter biochar promoted the greatest increases in pH, phosphorus (42.04 mg dm^{-3}) and potassium (0.46 $cmol_c$ dm^{-3}). Coconut fiber biochar also increased potassium (0.48 $cmol_c$ dm^{-3}) and promoted greater accumulation of dry matter in the aerial part (33.87 g $plant^{-1}$ with coconut fiber and 34.37 g $plant^{-1}$ with poultry litter), surpassing mineral fertilization. Rice straw biochar did not promote significant improvements. Thus, coconut fiber and poultry litter biochars demonstrated potential as a sustainable alternative to improve soil fertility and bell pepper development.

Keywords: *Capsicum annuum* L.. Agricultural waste. Pyrolysis.

RESUMO - O uso de resíduos agroindustriais como insumo agrícola é uma alternativa sustentável para recuperar a fertilidade dos solos e aumentar a produtividade. Objetivou-se com este trabalho avaliar os efeitos de biocarvões produzidos a partir de cama de aviário, fibra de coco e palha de arroz sobre a fertilidade do solo e o crescimento de pimentão verde cultivado em campo, em um Argissolo. Inicialmente, amostras de solo foram incubadas com os três biocarvões nas doses de 0,0; 6,0; 9,0 e 12,0 t ha^{-1} por 160 dias, com umidade em torno de 70%. Após esse período, realizaram-se análises químicas do solo. Em seguida, foi conduzido experimento em delineamento em blocos casualizados, esquema fatorial 5 × 3 + 1 (cinco doses e três tipos de biocarvões, mais um tratamento adicional com adubação mineral), com quatro repetições. O biocarvão de cama de aviário promoveu os maiores aumentos de pH, fósforo (42,04 mg dm^{-3}) e potássio (0,46 $cmol_c$ dm^{-3}). O de fibra de coco também elevou o potássio (0,48 $cmol_c$ dm^{-3}) e proporcionou maior acúmulo de matéria seca na parte aérea (33,87 g $planta^{-1}$ com fibra de coco e 34,37 g $planta^{-1}$ com cama de aviário), superando a adubação mineral. Já o biocarvão de palha de arroz não promoveu melhorias significativas. Assim, os biocarvões de fibra de coco e cama de aviário demonstraram potencial como alternativa sustentável para melhorar a fertilidade do solo e o desenvolvimento do pimentão.

Palavras-chave: *Capsicum annuum* L.. Resíduos agrícolas. Pirólise.

Conflict of interest: The authors declare no conflict of interest related to the publication of this manuscript.

Received for publication in: June 6, 2024.
Accepted in: May 30, 2025.

Editor in Chief: Aurélio Paes Barros Júnior
Section Editor: Bráulio Luciano Alves Rezende

Data Availability: The data that support the findings of this study can be made available, upon reasonable request, from the corresponding author .

***Corresponding author:**
<lhgarofalo@hotmail.com>

INTRODUCTION

The intensification of agro-industrial activity has resulted in the growing generation of organic waste, whose proper management and disposal represent a significant environmental and logistical challenge. This problem has driven the development of sustainable solutions that reconcile environmental preservation with economic viability, arousing the interest of various sectors of society, including the scientific community (CARNAVAL; JAISWAL; JAISWAL, 2024). In this context, the use of biochars produced from different biomasses, such as poultry litter, coconut fiber, and rice straw, has emerged as a promising alternative for improving soil quality and increasing agricultural productivity. The physical-chemical properties of these materials qualify them as multifunctional soil conditioners, capable of promoting relevant agronomic benefits.

The addition of biochar to the soil can modify essential attributes, such as pH, water retention capacity, cation exchange capacity (CEC), organic carbon, and the availability of macro and micronutrients, such as phosphorus, potassium, calcium, among others (GUARNIERI et al., 2021). In addition to these direct effects on fertility, the use of biochar has been associated with the mitigation of greenhouse gas emissions and the increase of carbon stability in the soil, contributing in a relevant way to biogeochemical cycles (SÁNCHEZ-REINOSO; ÁVILA-PEDRAZA; RESTREPO-DÍAZ, 2020). Scientific evidence shows that the application of this material promotes positive production responses in different agricultural crops, including maize, peanut, and various vegetables, particularly in soils with chemical or physical limitations (REHMAN et al., 2021).

Among the vegetables grown in Brazil, green bell pepper (*Capsicum annuum* L.) stands out, a widely cultivated species of significant commercial relevance. Its agronomic performance is sensitive to nutrient availability and soil quality, and is favored by management practices that promote fertility sustainability. Recent studies indicate that the use of biochar produced from pistachio shells, pyrolyzed at 450 °C, can significantly favor the growth and production of bell peppers, through the improvement of soil chemical attributes, such as pH, electrical conductivity, organic matter content, CEC and total nitrogen. The most significant effects were observed with biochar doses of 1 to 2%, which also resulted in higher chlorophyll content in the leaves and better fruit quality (SANCHEZ et al., 2024). These findings reinforce the importance of seeking alternatives to the intensive use of mineral fertilizers, especially in tropical soils that are naturally impoverished or subject to degradation.

Despite the advances achieved, there is still a lack of studies that evaluate, under field conditions, the combined effects of different types of biomass and doses of biochar, especially in vegetable crops. In view of this gap, the objective of the present study was to evaluate the effects of the application of biochars obtained from regional organic residues: poultry litter, coconut fiber and rice straw, on soil fertility attributes and on the growth of green bell pepper grown in Ultisol, under the edaphoclimatic conditions of the Agreste region of Paraíba, Brazil.

MATERIAL AND METHODS

Biochar production

Biochars from poultry litter, coconut fiber and rice straw were produced in a double-drum furnace, installed at the Center for Agrarian and Environmental Sciences (CCAA), Campus II of the State University of Paraíba (UEPB), Lagoa Seca, PB, Brazil. Pyrolysis was conducted using 20 L iron containers, where each material (poultry litter, coconut fiber and rice straw) was individually stored. Burning was carried out with sabiá (*Mimosa caesalpiniaefolia*) wood, monitoring the temperature with the aid of a thermometer, whose average value during pyrolysis was 492.5 °C. Poultry litter was obtained from CCAA, coconut fiber in the municipality of Mataraca, PB, and rice straw in areas of irrigated cultivation and flood recession farming in the Alto Sertão Paraibano region. After the pyrolysis process, the biochars were chemically characterized according to the Manual of Official Analytical Methods for Fertilizers and Correctives (BRASIL, 2017) (Table 1).

Table 1. Chemical characterization of biochar from poultry litter, rice straw and coconut fiber pyrolyzed in a drum-type furnace.

Types of biochar	pH	Moisture	N	P_2O_5	K_2O	Ca	Mg	C	C/N
		%							
Poultry litter	12.0	1.6	0.4	2.6	1.9	7.3	0.6	12.3	31.5
Rice straw	7.66	3.57	0.65	0.72	0.87	0.29	0.23	35.34	54.37
Coconut fiber	9.45	3.22	0.50	0.33	3.20	0.52	0.35	59.26	118.5

Experiment 1 – Incubation of soil with biochars

The first experiment aimed to evaluate the effects of biochars on soil fertility through the incubation method. The experimental design adopted was completely randomized (CRD), with a 5 × 3 factorial arrangement, corresponding to five doses of biochar: 0.0, 3.0, 6.0, 9.0 and 12.0 t ha^{-1} and three types of biochar (B1 = Coconut fiber; B2 = poultry litter and B3 = rice straw), with four replicates. Soil samples (0.5 kg) were packed in plastic bags and mixed with the treatments. The samples were incubated for 160 days, with moisture maintained at around 70% through the periodic addition of deionized water. At the end of the period, the samples were air-dried and subjected to chemical analyses (pH, phosphorus, calcium, magnesium, sodium, potassium, hydrogen + aluminum, and organic matter), according to the methodologies described by Donagema et al. (2011).

Experiment 2 – Field cultivation of bell pepper

The second experiment was conducted under field conditions in the experimental area of CCAA/UEPB (7º09' S; 35º52' W), in Lagoa Seca, PB, Brazil, using an *Argissolo Vermelho Amarelo eutrófico* (Ultisol). Chemical and physical characteristics of the soil before the experiment were: pH = 6.25; P = 9.3 mg dm^{-3}; organic matter = 12.45 g dm^{-3}; Ca = 2.77; Mg = 1.50; Na = 0.06; K = 0.33; H+Al = 1.33; CEC = 5.99 $cmol_c$ dm^{-3}; and apparent density of 1.3 kg dm^{-3} (DONAGEMA et al., 2011).

The experimental design was randomized blocks (RBD), with a 5 × 3 + 1 factorial arrangement, with five doses of biochar (0, 3, 6, 9 and 12 t ha^{-1}) and three types of biochar (B1 = Coconut fiber; B2 = poultry litter and B3 = rice straw), with four replicates, plus an additional treatment with recommended mineral fertilization (before planting: 30, 120 and 20 kg ha^{-1} of N, P_2O_5 and K_2O, respectively; and at 30 days after planting: 90 and 20 kg ha^{-1} of N and K_2O). In all, there were 64 experimental units, each composed of three plants of the Yolo Wonder bell pepper cultivar.

The seedlings were produced in polystyrene foam trays containing earthworm humus as substrate, with three seeds per cell. Germination was carried out under shade net with manual irrigation twice a day. The seedlings, at 30 days, were transplanted to the field at a spacing of 1.0 m between rows and 0.4 m between plants. Thinning was carried out when the plants had six true leaves, keeping one plant per hole. Staking was performed with a trellis-type system, using plastic rods.

Irrigation was carried out by drip, with Katif drippers (3.75 L h^{-1} per plant), based on readings from the Class A pan and a pan coefficient (Kp) of 0.75. The irrigation depth was applied daily, using 100% of the crop evapotranspiration (ETc), with water obtained from a dam located nearby.

Agronomic evaluations were performed at 111 days after transplanting. The variables analyzed were: plant height, stem diameter, number of leaves, leaf area, and fresh biomass and dry biomass of the aerial part (branches, leaves and stem), with the last-mentioned variable being obtained after drying in an oven at 65 °C.

Statistical analysis

In both experiments, the data were subjected to analysis of variance (F test). When significant, regression analysis was performed for biochar doses and comparison of means by Tukey test for the types of biochar. In addition to these analyses, in the second experiment, orthogonal contrasts were applied to compare the additional treatment (mineral fertilization) *versus* the factors. All statistical analyses were performed using Sisvar software (FERREIRA, 2019).

RESULTS AND DISCUSSION

Experiment 1 – Incubation of soil with biochars

According to the results of the analysis of variance (Table 2), the application of the different types of biochar had a significant effect ($p < 0.01$) on the calcium contents and on the cation exchange capacity (CEC) of the soil. The dose factor, in turn, promoted significant variations in the contents of organic matter ($p < 0.01$) and calcium ($p < 0.05$). In addition, the interaction between the biochar and dose factors was determinant for the other soil chemical attributes evaluated (pH, phosphorus, magnesium, sodium, potassium and potential acidity), showing that the combined effects of the sources and the amounts applied jointly influenced the behavior of these parameters.

Table 2. Analysis of variance table for the chemical parameters of the soil incubated with different biochars and doses.

Source of variation	DF	Mean square								
		pH	P	MO	Ca	Mg	Na	K	H+AL	CEC
Biochar (B)	2	1.097^{**}	12.00^{**}	8.54^{ns}	0.173^{**}	0.22^{**}	0.00711^{**}	0.0405^{**}	0.175^{**}	0.260^{**}
Dose (D)	4	0.221^{**}	2.33^{**}	32.26^{**}	0.089^{*}	0.04^{ns}	0.00162^{**}	0.0114^{**}	0.440^{**}	0.078^{ns}
B x D	8	0.189^{**}	1.39^{**}	1.35^{ns}	0.024^{ns}	0.13^{**}	0.00081^{**}	0.0042^{**}	0.067^{*}	0.092^{ns}
Error	30	0.007	0.18	3.17	0.027	0.03	0.00003	0.0007	0.023	0.048
CV (%)		1.36	27.00	12.51	5.69	12.76	7.66	7.11	15.84	3.73
Overall mean		6.37	1.59 mg $100g^{-1}$	14.25 g dm^{-3}	2.91 $cmol_c$ dm^{-3}	1.55 $cmol_c$ dm^{-3}	0.0783 $cmol_c$ dm^{-3}	0.3751 $cmol_c$ dm^{-3}	0.96126 $cmol_c$ dm^{-3}	5.87 $cmol_c$ dm^{-3}

^{DF}Degrees of freedom, **significant ($p<0.01$), **significant ($p<0.05$), ^{ns}not significant ($p>0.05$).

The application of different doses of biochar promoted an initial increase in the organic matter (OM) content of the soil, reaching a maximum value of 16.22 g dm^{-3} at the estimated dose of 6.06 t ha^{-1}, which represents an increase of 32.97% compared to the control. From this point on, there was a reduction in OM contents, as described by the quadratic model fitted (Figure 1A), indicating that, at low doses, biochar acts as a stabilizer or carbon source, but at high concentrations, it can generate adverse effects on soil carbon dynamics.

This reduction may be associated with the interference of biochar in microbial activity, favoring the mineralization of native OM and, consequently, promoting the release of carbon that was previously stable in the edaphic system. This positive priming effect, as described by Obia et al. (2024), resulted in reductions of 2.8% to 24.5% in soil organic carbon (SOC) stocks, averaging 18.4%. In addition, the high C/N ratio of biochars from coconut fiber and rice straw may have contributed to the immobilization of essential nutrients to the microbiota, limiting OM turnover (LIU et al., 2023a).

Other factors that may have contributed to the reduction of OM include the presence of toxic compounds from incomplete pyrolysis, such as polycyclic aromatic hydrocarbons (PAHs), which tend to inhibit the activity of heterotrophic microorganisms (KRZYSZCZAK; DYBOWSKI; CZECH, 2023), and the high adsorption potential of dissolved organic compounds by biochars with large surface area, which may lead to underestimation of OM in laboratory analyses.

In addition, biochars produced from rice straw and coconut fiber have a high specific surface area and porous structure, characteristics that give them a strong ability to adsorb dissolved organic compounds. This property can interfere with OM laboratory analyses, contributing to a possible underestimation of the actual organic carbon contents in the soil.

The cation exchange capacity (CEC) of the soil, as illustrated in Figure 1B, was influenced by the type of biochar applied, especially the material from rice straw, which promoted a statistically higher increase compared to the others ($p < 0.05$). Such behavior can be attributed to the lignocellulosic nature of this residue, whose pyrolysis results in a structurally more porous and chemically more stable biochar, characteristics that favor the increase of the specific surface area and, consequently, of the cation retention capacity, as demonstrated by previous studies (NAGARAJU et al., 2023).

Also regarding Figure 1B, although the types of biochar influenced this parameter, the average CEC values remained close to those observed in the soil before incubation (5.99 $cmol_c$ dm^{-3}). This modest response may be associated with the surface charge of biochars, which strongly depends on both the raw material used and the thermal conditions of the pyrolysis process. Although the process occurred at intermediate temperature (492.5 °C), this range is recognized for promoting intense aromatization of the carbonaceous matrix, substantially reducing the amount of oxygenated functional groups on the surface of the material (ZHANG et al., 2024a).

Considering that the CEC of biochars is strongly linked to the presence of carboxylic and phenolic groups, among others, which provide variable negative charges, the reduction of these functional groups limits the material's capacity to contribute significantly to the increase of soil CEC, especially in short periods after application (ZHANG et al., 2024b). Thus, although the structural stability of the biochar produced under such conditions is high, its surface reactivity tends to be low (LUSTOSA FILHO et al., 2024), which justifies the slight increments in CEC, even with the use of increasing doses.

The concentration of exchangeable calcium in the soil showed an increasing trend in response to the increase in the biochar doses applied (Figure 1C), reaching a maximum value of 3.02 $cmol_c$ dm^{-3} at the highest dose applied (12 t ha^{-1}), which corresponds to an increase of 8.32% compared to the control treatment. Similar results were reported by Fernandes et al. (2018), who observed an increase in Ca^{2+} contents after the application of biochar produced from poultry litter, evidencing the release of basic cations as an inherent characteristic of the carbonized material.

Regarding the influence of the different raw materials used in the production of biochars (Figure 1D), it was found that those obtained from poultry litter and rice straw provided the highest contents of calcium in the soil. Although coconut fiber biochar led to the lowest absolute value, it did not differ statistically from that obtained with rice straw, indicating that the soil response can be attributed, in part, to the elemental composition of the biomass used in fertilization. Chemical analysis of the raw materials (Table 1) revealed considerably different calcium contents, 7.3% in poultry litter, 0.52% in coconut fiber and 0.29% in rice straw, which corroborates the hypothesis that the contribution of biochar to the supply of Ca^{2+} is strongly conditioned to its original elemental concentration (LIU et al., 2023b).

The soil pH varied as a function of the type of biochar applied, with a significant increase in the samples treated with poultry litter and coconut fiber biochars, showing an alkalizing effect proportional to the doses used (Figure 2A). In contrast, rice straw biochar did not promote the same response, and there was even a slight reduction in pH at higher doses. These differences are related to the composition of the ash and the contents of basic cations of each material, which depend on both the nature of the biomass and the thermal conditions of the pyrolysis process (LUSTOSA FILHO et al., 2024).

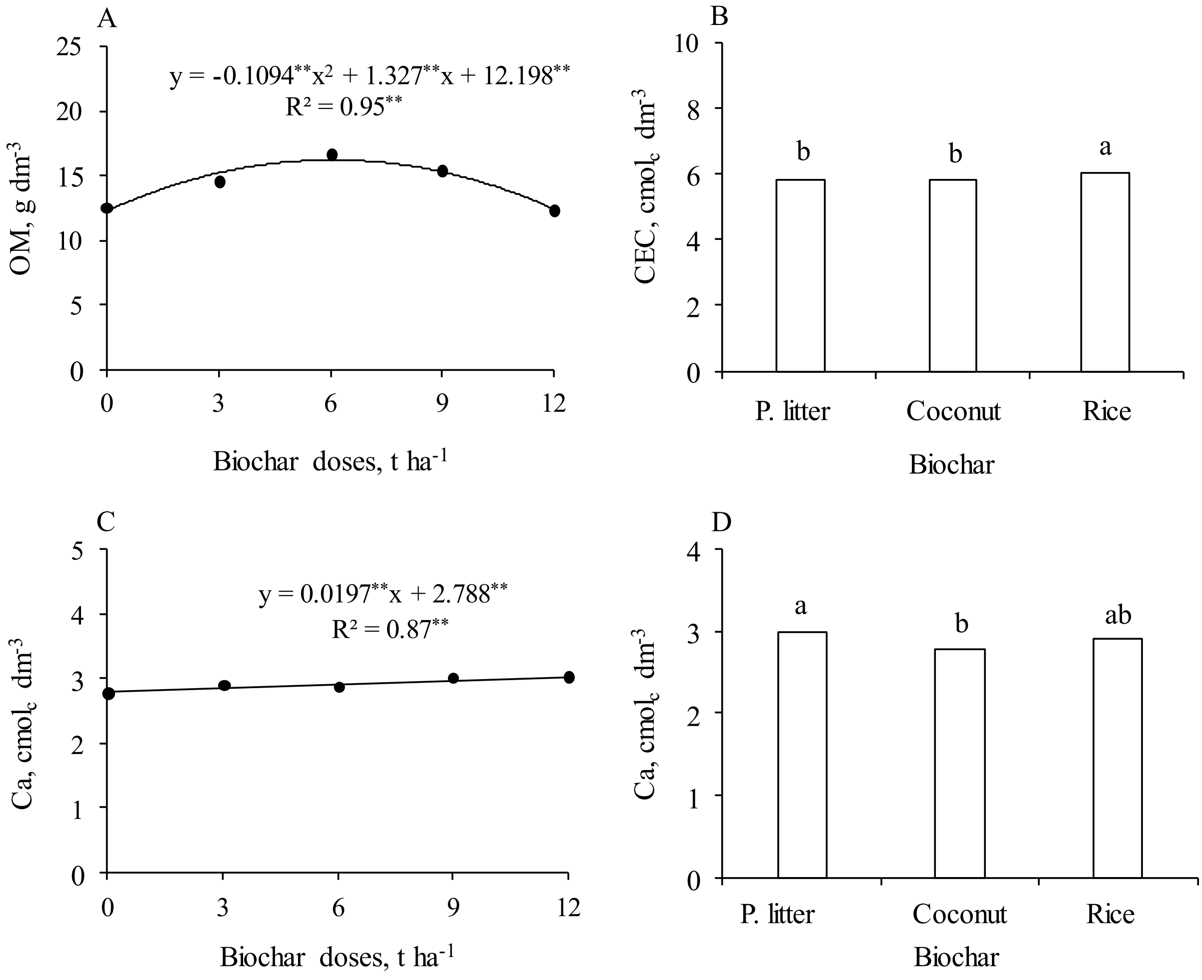

Figure 1. Organic matter (OM), cation exchange capacity (CEC) and calcium (Ca) as a function of the individual effect of different doses and types of biochar.

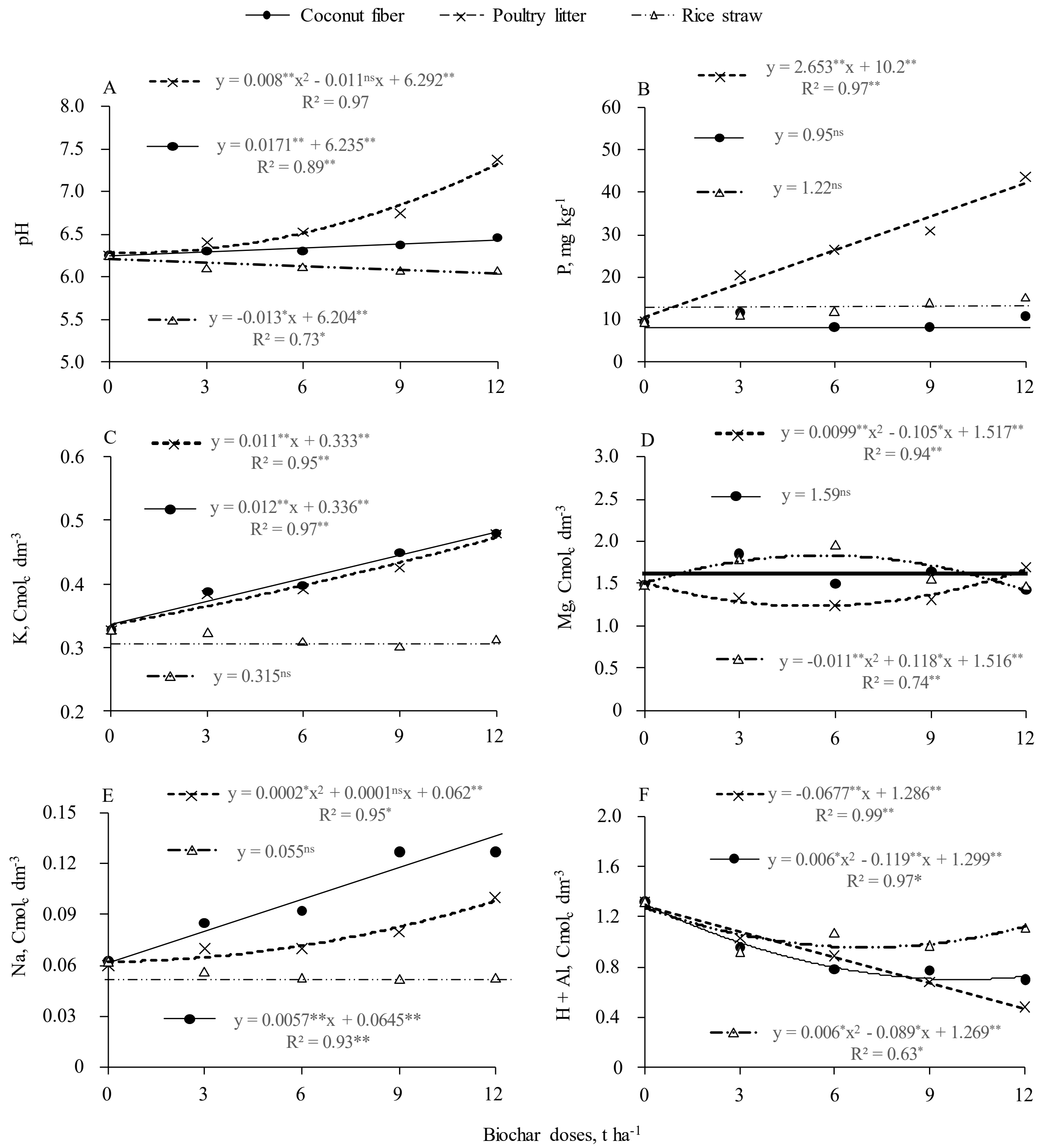

Figure 2. Values of pH, phosphorus, potassium, magnesium, sodium and hydrogen + aluminum as a function of the different doses considering each type of biochar.

Among the materials evaluated, poultry litter biochar showed the most pronounced alkalizing effect, with significant increments in soil pH from the dose of 6 t ha^{-1} (Figure 3A). This behavior is attributed to the high pH of the material (pH 12), as well as its high ash content and the greater presence of basic cations, especially calcium (Ca) (Table 1).

As for the available phosphorus (Figure 2B), only poultry litter biochar showed significant capacity to increase its concentration in the soil. This effect can be attributed to the high nutrient load accumulated in the material, resulting from the presence of excreta, food leftovers, and mineral additives used in feed, especially dicalcium phosphate (FERNANDES et al., 2022). Except for the control, this biochar promoted the highest phosphorus contents at all doses applied, differing statistically from the other materials (Figure 3B). These results show its efficiency in the release of phosphorus, regardless of the amount applied.

In relation to exchangeable potassium (Figure 2C), a linear increase was observed with the use of biochars from poultry litter and coconut fiber, which contain 1.90% and 3.20% of K_2O, respectively (Table 1). This soil enrichment with potassium, in addition to being agronomically relevant, suggests that certain biochars can act as sources of controlled release of the nutrient, with the potential to partially replace conventional potassium fertilizers (BAO et al., 2024). When comparing the biochars, the highest potassium contents (Figure 3C) were recorded with the use of coconut fiber and poultry litter, from the dose of 3 t ha^{-1}, with statistically significant differences compared to rice straw. The superiority of these two materials is directly linked to the higher concentration of K in their composition (Table 1), in addition to their more soluble structure and lower chemical stability, which favors the release of basic cations in the short term. In contrast, rice straw biochar, for having a low K content (Table 1), limited the release of the nutrient into the soil after application.

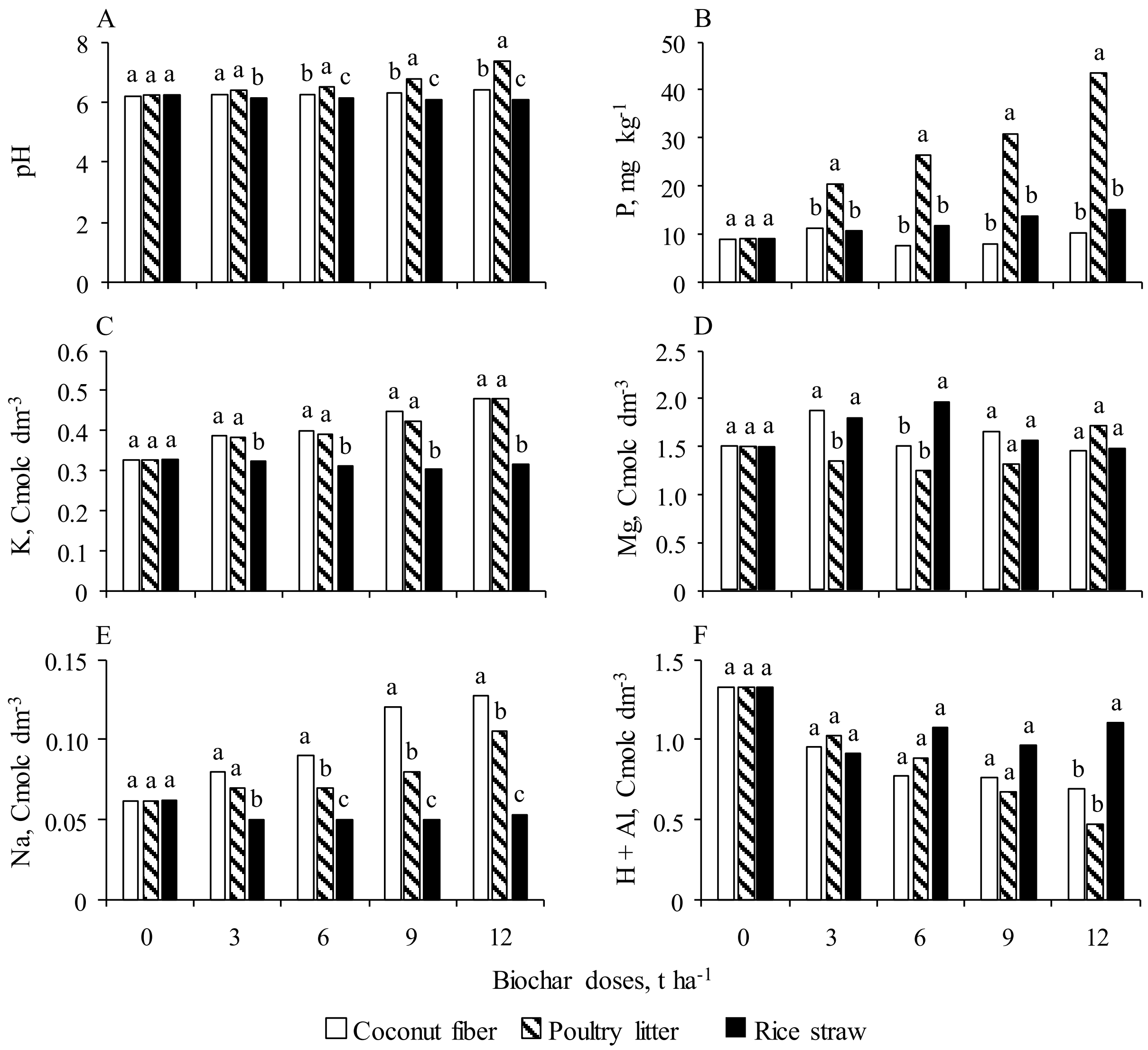

Figure 3. Influence of the types of biochar considering each dose of biochar on pH, phosphorus, potassium, magnesium, sodium and hydrogen + aluminum. Means followed by the same lowercase letter indicate that the biochars do not differ from each other at the same dose.

For exchangeable magnesium (Figure 2D), there was a significant variation due to the interaction between type and dose of biochar. The highest value (1.83 cmol$_c$ dm^{-3}) was achieved with the application of 5.36 t ha^{-1} of rice straw biochar, although it contained only 0.23% of Mg in its composition after pyrolysis. This result indicates that, in addition to the content of the element, characteristics such as porosity, surface reactivity, and kinetics of material release directly influence the availability of Mg^{2+} in the soil (LUSTOSA FILHO et al., 2024). Poultry litter biochar, in turn, showed higher contents of Mg (0.6%) and contributed significantly to the increase of magnesium in the soil only at the highest dose (12 t ha^{-1}), reaching 1.68 cmol$_c$ dm^{-3}.

Coconut fiber biochar, on the other hand, despite containing 0.35% magnesium, did not promote significant variations in soil contents over the tested doses. In general, the differences between the biochars were statistically specific. The highest means were observed with coconut fiber and rice straw at a dose of 3 t ha^{-1}, and with rice straw at a dose of 6 t ha^{-1} (Figure 3D). The absence of a consistent pattern indicates that biochars exhibit similar behavior regarding the release of Mg^{2+}, or that the effects are more significant only in the medium to long term.

In relation to exchangeable sodium (Figure 2E), the contents increased with the doses, especially in the treatments with coconut fiber. This behavior is attributed to the fact that coconut is often grown in areas with some degree of salinity, which leads to the accumulation of Na^+ in plant tissues (SUN et al., 2024). Although sodium is not necessarily toxic to some crops, its elevation in the soil can generate deleterious effects, such as reduced absorption of calcium, magnesium, and potassium, as well as damage to cell expansion and photosynthetic activity. Coconut fiber biochar consistently had the highest contents of Na^+ at each dose, with statistical differences from 6 t ha^{-1}, reinforcing its high content of this element, related to the origin of the biomass. Poultry litter biochar had intermediate values, while rice straw resulted in the lowest sodium contents in the soil (Figure 3E).

Regarding potential acidity ($H^+ + Al^{3+}$) (Figure 2F), there was a reduction with the increase in the doses of poultry litter and coconut fiber biochars, confirming the indirect effect of pH increase on the neutralization of soil acidity. Finally, the potential acidity data (Figure 3F) showed relevant differences only at the highest dose (12 t ha^{-1}), at which rice straw biochar resulted in the highest values, revealing its low efficiency in neutralizing acidity. On the other hand, the lowest values were obtained with the use of poultry litter, which confirms its ability to correct soil acidity.

Experiment 2 – Field cultivation of bell pepper

The results of the analysis of variance (Table 3) indicated, except for the number of branches, that the interaction between type and dose of biochar exerted a significant influence on all the attributes evaluated. This significance shows that the effect of biochars on the growth of bell pepper does not depend only on the type or dose applied alone, but on the specific combination between both, which highlights the complexity of the physiological responses of the plants according to the quality and quantity of the biochar used.

Table 3. Analysis of variance table for the growth parameters of bell pepper as a function of the application of different biochars and doses and the additional treatment (mineral fertilization).

Source of variation	DF	PH	SD	NL	NB	FM	DM	TLA
Treat	15	155.02**	5.36**	957.66**	1.674ns	4993.87**	120.17**	0.0027**
Block	2	76.58ns	2.59**	218.42ns	2.406ns	281.83ns	38.04ns	0.0007ns
Dose (D)	4	50.03ns	1.30ns	518.30*	1.41ns	1892.62*	33.69ns	0.001ns
Biochar (B)	2	442.81**	8.11**	772.02*	0.82ns	4594.32**	202.07*	0.003**
D x B	8	99.82*	6.43**	983.96**	2.12ns	5791.73**	132.72**	0.002**
Factorial x additional	1	441.02**	7.52**	2875.96**	0.80ns	11815.14**	201.98*	0.007**
Residual	30	44.50	0.39	187.21	1.301	598.62	33.30	0.0006
M vs D0B1	1	206.11*	4.92**	1310.2*	-	2904.26*	15.62^{ns}	0.0045*
M vs D0B2	1	14.00ns	0.02ns	18.9ns	-	1222.53ns	46.38^{ns}	0.0016ns
M vs D0B3	1	255.67*	14.65**	3733.3**	-	21231.50**	110.36^{ns}	0.0107**
M vs D3B1	1	489.01**	3.50**	3204.7**	-	5474.41**	175.10*	0.0060**
M vs D3B2	1	436.34**	4.44**	2845.6**	-	7105.38**	379.89**	0.0116**
M vs D3B3	1	141.78ns	1.23ns	979.6*	-	2884.93*	24.13^{ns}	0.0012ns
M vs D6B1	1	453.56**	7.23**	4302.2**	-	13745.96**	171.44*	0.0095**
M vs D6B2	1	563.89**	11.80**	4741.3**	-	10967.59**	500.56**	0.0096**
M vs D6B3	1	81.89ns	1.33ns	224.0ns	-	315.02ns	14.37ns	0.0001ns
M vs D9B1	1	489.01**	10.15**	2153.3**	-	10138.21**	196.23*	0.0069**
M vs D9B2	1	230.23*	8.18**	2802.2**	-	7646.65**	140.97*	0.0058**
M vs D9B3	1	31.13ns	3.18**	188.8ns	-	56.81ns	1.62ns	0.00002ns
M vs D12B1	1	904.47**	21.91**	763.1ns	-	29406.44**	456.63**	0.0016ns
M vs D12B2	1	172.45ns	2.27*	808.8*	-	2509.86*	12.42ns	0.0013ns
M vs D12B3	1	0.78ns	1.80*	675.5ns	-	10458.04**	170.48*	0.0024ns
CV (%)		14.82	7.05	17.16	34.80	22.42	22.82	25.47
Overall mean		45.01	8.96	79.75	3.27	109.12	25.2	0.0991

^{DF}Degrees of freedom, **significant ($p<0.01$), **significant ($p<0.05$), ^{ns}not significant ($p>0.05$). D = dose applied (t ha^{-1}), B1 = Coconut fiber; B2 = poultry litter; and B3 = Rice straw; PH = plant height; SD = stem diameter; NL = number of leaves; NB = number of branches; FM = fresh matter; DM = dry matter; TLA = total leaf area.

Figure 4 shows the effects of the different doses considering each type of biochar, as well as the treatment with mineral fertilization, on the growth variables of bell pepper. Regarding plant height (Figure 4A), coconut fiber biochar promoted the best performance, with an increase of 22.25% between the control (46.1 cm) and the highest dose applied (56.36 cm). These results corroborate Rezende et al. (2022), who observed an 83% increase in the height of bell pepper plants fertilized with vegetable ash, reaching 58.34 cm.

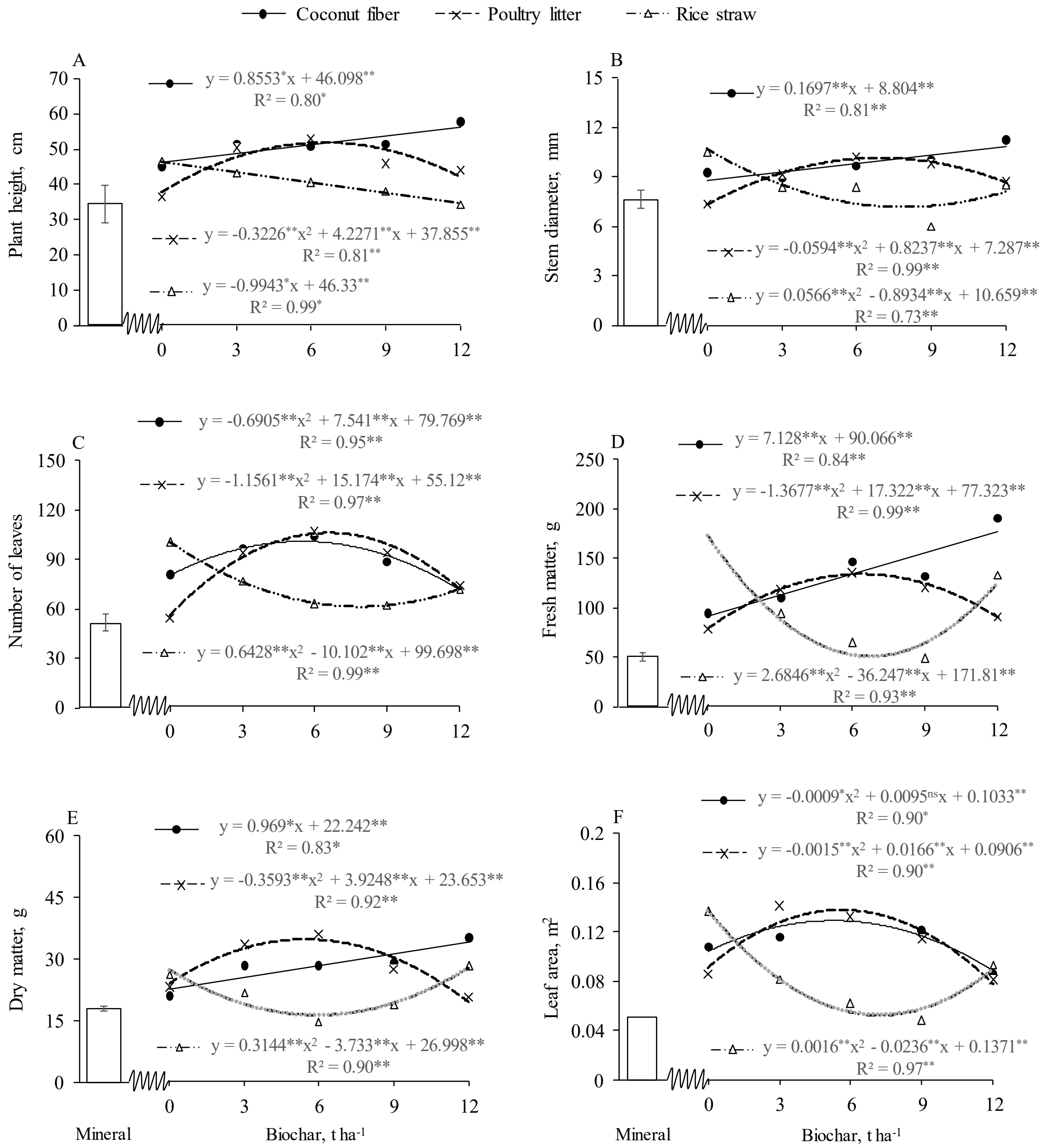

Figure 4. Plant height, stem diameter, number of leaves, fresh matter, dry matter and total leaf area as a function of mineral fertilization and different doses considering each type of biochar.

On the other hand, rice straw biochar showed a decreasing linear trend, with a minimum height of 34.40 cm at a dose of 12 t ha^{-1}, representing a reduction of 25.75% compared to the control (Figure 4A). This result contrasts with the findings of Singh et al. (2018), who reported increases in maize and rice growth, respectively, with the use of rice husk biochar, showing that the effect of biochar strongly depends on the crop and edaphoclimatic conditions.

When analyzing the data in Figure 5A, it can be observed that, at the doses of 0, 3 and 6 t ha^{-1}, the different types of biochar did not promote statistically significant differences in plant height ($p > 0.05$). However, at the highest doses (9 and 12 t ha^{-1}), coconut fiber biochar remained superior, while rice straw biochar had the lowest values, suggesting that the chemical composition of the pyrolyzed material exerts a direct influence on the vertical growth of plants.

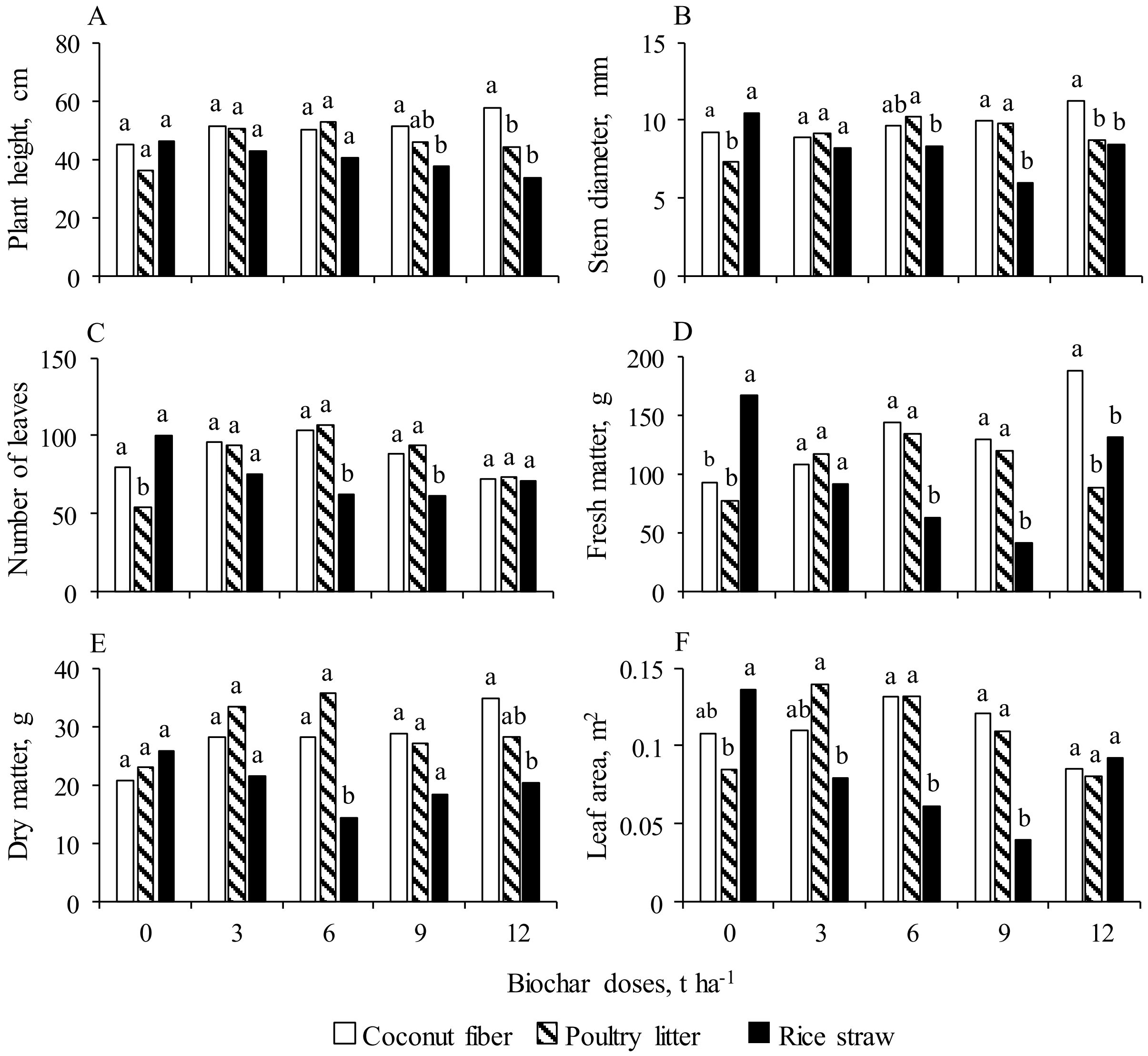

Figure 5. Influence of the types of biochar considering each biochar dose on plant height, stem diameter, number of leaves, fresh matter, dry matter and leaf area. Means followed by the same lowercase letter indicate that the biochars do not differ from each other at the same dose.

Still considering plant height (Figure 4A), the data obtained with poultry litter biochar were described by a quadratic model, with an estimated maximum height of 51.70 cm at a dose of 6.55 t ha^{-1}. From this point on, there was a decline in growth, which may be associated with the high pH of the material (pH 12). As the soil used had an initial pH of 6.25, within the ideal range for bell pepper cultivation (5.5 to 6.8), the application of poultry litter biochar may have caused excessive alkalinization. Data from incubation with the same soil indicated an increase in pH from 6.28 to 7.31 after 160 days of application of this biochar. The increase in soil pH directly interferes with the availability of nutrients, especially phosphorus, whose solubility is reduced in alkaline environments due to the formation of insoluble calcium compounds. Micronutrients such as iron, manganese, zinc, and copper also become less available at high pH, which can compromise essential metabolic functions even in soils with good apparent fertility. In addition, alkalinization may be accompanied by an increase in electrical conductivity and accumulation of soluble salts, favoring the occurrence of salt stress. This condition compromises plant physiology, causing stomatal closure, reduced transpiration and photosynthetic rate, resulting in growth limitation. It is important to highlight that poultry litter biochar has a high ash content compared to other pyrolyzed materials, which contributes to the increase in pH and salt concentration in the soil.

Regarding stem diameter (Figure 4B), coconut fiber biochar, at the highest dose, promoted the best performance, reaching 10.84 mm. For poultry litter biochar, the quadratic fit indicated an optimal value of 10.14 mm at the estimated dose of 6.93 t ha^{-1}. In contrast, with rice straw biochar the data exhibited a decreasing quadratic behavior, with a maximum value observed in the control (10.66 mm) and progressive reduction up to 7.13 mm at the dose of 7.89 t ha^{-1}. These results are compatible with those obtained by Sales (2021), who reported improvements in the morphological characteristics of *Capsicum annuum* in response to organomineral fertilization based on cattle manure and NPK.

According to Taiz and Zeiger (2013), plants with larger stem diameter tend to have a greater capacity for root system regeneration and greater resistance to biotic and abiotic stresses. The superiority observed in the treatment with coconut fiber biochar may be associated with its high potassium content (3.20% of K_2O), an essential element for physiological processes such as meristematic growth, activation of enzymes and control of sap flow.

As evidenced in Figure 5B, the influence of the type of biochar on stem diameter was pronounced, with statistically significant differences ($p < 0.05$) at almost all doses applied, except for the dose of 3 t ha^{-1}. Coconut fiber biochar maintained the highest values under practically all conditions, a result that reinforces the importance of potassium in cell expansion and in the structural strengthening of the stem. On the other hand, rice straw biochar, with the lowest potassium content among the materials evaluated (0.87% of K_2O), showed lower performance, indicating a possible nutritional limitation for this variable.

Regarding the number of leaves (Figure 4C), a quadratic fit was observed for all types of biochar applied. The highest estimated value was obtained with poultry litter biochar, reaching approximately 105 leaves per plant at a dose of 6.56 t ha^{-1}, followed by coconut fiber biochar, with about 101 leaves at a dose of 5.46 t ha^{-1}. On the other hand, rice straw biochar showed a decreasing trend, with a maximum value close to 100 leaves in the control (without application) and progressive reduction to about 60 leaves per plant at a dose of 7.8 t ha^{-1}. These results surpass those obtained by Sales (2021), who observed that bell pepper plants grown under organomineral fertilization had between 51 and 61 leaves per plant.

When evaluating Figure 5C, it was found that poultry litter and coconut fiber biochars promoted the highest values of number of leaves at doses 6 and 9 t ha^{-1}. Rice straw biochar, in turn, maintained lower performance. This pattern may be related to the higher concentration of phosphorus (2.6% of P_2O_5) and calcium (7.3%) present in poultry litter, essential elements for cell differentiation, leaf tissue development and leaf longevity.

The reduction in the number of leaves observed at higher doses, especially with rice straw biochar, may be associated with a set of chemical factors. The first factor is its low potassium content (0.87% of K_2O), which is the lowest among the biochars evaluated. Potassium is a fundamental nutrient for the maintenance of leaf area, regulating processes such as osmoregulation, enzyme activation, photoassimilate transport, and control of stomatal opening (ORTEL; ROBERTS; RUPE, 2024). Its deficiency can result in leaf curling, early senescence and, consequently, a lower number of leaves per plant. In addition, the increase in soil pH promoted by the application of biochars at high doses can reduce the availability of micronutrients such as zinc, manganese and iron, which play essential roles in leaf metabolism and development.

Regarding shoot fresh matter (Figure 4D), coconut fiber biochar promoted the highest accumulation, with an estimated value of 175.60 g at the maximum dose (12 t ha^{-1}), which represents an increase of approximately 94.97% compared to the control treatment. This result can be attributed to the high potassium content present in this material (3.20% of K_2O), an essential nutrient for osmotic regulation, maintenance of cell turgidity, solute transport and enzymatic activation, processes directly related to fresh matter accumulation (ORTEL; ROBERTS; RUPE, 2024). In addition, the high carbon content (59.26%) and the high C/N ratio give coconut fiber biochar a physical structure favorable to soil moisture retention, contributing to plant development (GUARNIERI et al., 2021). In the case of poultry litter biochar, the response was positive up to the dose of 6.33 t ha^{-1}, with an estimated value of 132.17 g. From this dose, there was a decrease in the values, possibly due to the accumulation of soluble salts and the increase in soil pH, which can compromise the absorption of water by the roots. This behavior is compatible with the effects of salt stress, such as reduced cell turgidity and less accumulation of fresh biomass.

Also in relation to Figure 4D, rice straw biochar led to highest value of fresh matter in the absence of application (171.81 g), with a marked reduction from the increasing doses, reaching only 49.46 g at the dose of 6.75 t ha^{-1}. This behavior may be related to its low potassium content (0.87% K_2O).

In Figure 5D, it can be observed that the type of biochar significantly influenced shoot fresh matter, with coconut fiber and poultry litter maintaining the highest values at most doses. Such performance may be related to their capacity to improve water retention and greater water availability to plants. In contrast, rice straw biochar led to the lowest values, suggesting possible nutritional limitation, especially at doses 6 and 9 t ha^{-1}.

Regarding shoot dry matter (Figure 4E), an increasing linear trend was observed for plants fertilized with coconut fiber biochar, with an estimated maximum value of 33.87 g at a dose of 12 t ha^{-1}, which represents an increase of 52.28% compared to the control. This performance shows the efficiency of this material in promoting favorable conditions for photosynthesis and structural growth, both by providing nutrients and by improving the physical properties of the soil, such as moisture retention and aeration. For poultry litter biochar, a quadratic behavior was observed, with an estimated maximum value of 34.37 g at a dose of 5.5 t ha^{-1}. The positive response up to the intermediate dose can be attributed to the significant contents of phosphorus (2.6% of P_2O_5) and calcium (7.3%), fundamental elements for dry matter accumulation. However, at higher doses, the increase in pH and possible salinization of the soil may have compromised the physiological efficiency of the plants, resulting in less biomass accumulation. Also in relation to Figure 4E, plants fertilized with rice straw biochar showed a decreasing quadratic behavior, with the lowest dry matter value (15.92 g) obtained when applying 5.93 t ha^{-1}.

Figure 5E shows that poultry litter and coconut fiber biochars significantly favored the production of dry biomass, reinforcing the role of the supply of nutrients, especially phosphorus and calcium, in the structuring and strengthening of plant tissues. On the other hand, rice straw biochar led to the lowest values, which is in accordance with its less nutritious chemical composition and its limited capacity to provide essential elements for growth.

Regarding total leaf area (Figure 4F), the data related to the three types of biochar were described by the quadratic regression model, with different responses according to the material used. Rice straw biochar exhibited a decreasing quadratic behavior, with the highest leaf area value (0.14 m^2) observed in the absence of application. With the increase in doses, there was a progressive reduction, reaching only 0.06 m^2 at a dose of 7.38 t ha^{-1}. This pattern may be related to the low contents of potassium (0.87% of K_2O) and phosphorus

(0.72% of P_2O_5) in this material, essential elements for leaf growth and expansion.

On the other hand, biochars from poultry litter and coconut fiber showed increasing quadratic behavior. The highest value of total leaf area was estimated at 0.14 m^2 with the use of poultry litter at a dose of 5.53 t ha^{-1}, followed by 0.13 m^2 with coconut fiber at a dose of 5.27 t ha^{-1}. These results indicate that, at intermediate doses, both materials promote edaphic conditions more suitable for leaf development, favoring the accumulation of photosynthetic biomass. In the case of poultry litter, the high phosphorus content (2.6% of P_2O_5) stands out, essential for processes related to vegetative growth. Coconut fiber biochar, in addition to its high potassium content, has physical characteristics that optimize water retention and soil aeration, contributing to the increase of leaf area (NIU et al., 2024).

Analysis of Figure 5F reinforces the influence of the type of biochar on leaf area. The highest values were observed with the application of poultry litter, followed by coconut fiber, both with positive effects on leaf surface expansion. On the other hand, rice straw biochar led to the lowest values, especially at doses 6 and 9 t ha^{-1}.

When comparing the treatments with mineral fertilization with those that used biochars, it is observed that, in several cases, the biochars promoted superior performance, especially the one obtained from coconut fiber. According to the contrasts in Table 3, the treatments with intermediate doses of biochar (especially D6B1 and D6B2) showed significantly higher effects than mineral fertilization for plant height, stem diameter, number of leaves, fresh matter, dry matter and leaf area ($p<0.01$). These findings are in line with Cardoso Júnior et al. (2022), who found that biochar application can significantly increase plant biomass, reaching a 5-fold increase when compared to the absence of this input.

In general, the results of Figures 4 and 5 show that the response of bell pepper plants varied mainly as a function of the type of biochar applied, with coconut fiber and poultry litter being the materials with the best agronomic performance. The inferiority of treatments with rice straw can be explained by its low nutrient contents, as evidenced in Table 1 and Figures 1 and 2. These results reinforce the importance of the chemical characterization of biochar and the careful choice of the material to be applied to the soil, aiming at maximizing the beneficial effects on plant growth.

CONCLUSIONS

Application of poultry litter biochar at a dose of 6 t ha^{-1} was the most efficient for improving soil fertility, promoting an increase in pH, reduction of potential acidity and an increase in the contents of available phosphorus, potassium and calcium;

Coconut fiber biochar, especially at the dose of 12 t ha^{-1}, stood out for favoring the development of bell pepper, resulting in the highest values of plant height, stem diameter, number of leaves, fresh matter, dry matter and leaf area;

Application of rice straw biochar did not promote significant improvements in soil chemical attributes or plant growth, being the least efficient material among those evaluated.

Compared to mineral fertilization, coconut fiber and poultry litter biochars showed superior performance under the conditions evaluated, with potential for use as a sustainable alternative in the cultivation of bell pepper.

REFERENCES

BAO, Z. et al. Long-term biochar application promoted soil aggregate-associated potassium availability and maize potassium uptake. **GCB Bioenergy**, 16: 1-13, 2024.

BRASIL. Ministério da Agricultura, Pecuária e Abastecimento. **Manual de métodos analíticos oficiais para fertilizantes e corretivos** / Ministério da Agricultura, Pecuária e Abastecimento. Secretaria de Defesa Agropecuária. Brasília, DF: MAPA, 2017. 240 p.

CARDOSO JÚNIOR, C. D. et al. Uso agrícola e florestal do biochar: estado da arte e futuras pesquisas. **Research, Society and Development**, 11: e55711225999, 2022.

CARNAVAL, L. D. S. C.; JAISWAL, A. K.; JAISWAL, S. Agro-food waste valorization for sustainable bio-based packaging. **Journal of Composites Science**, 8: 41, 2024.

DONAGEMA, G. K. et al. **Manual de métodos de análise de solos**. Dados eletrônicos. Rio de Janeiro, RJ: Embrapa Solos, 2011. 230 p.

FERNANDES, J. D. et al. Soil chemical amendments and the macronutrients mobility evaluation in oxisol treated with biochar. **Journal of Agricultural Science**, 10: 238-247, 2018.

FERNANDES, J. D. et al. Thermal treatment of poultry litter: part II. Evaluation of structural and morphological characteristics. **Revista Brasileira de Engenharia Agrícola e Ambiental**, 26: 680-687, 2022.

FERREIRA, D. F. Sisvar: a computer statistical analysis system to fixed effects split plot type designs. **Revista Brasileira de Biometria**, 37: 529-535, 2019.

GUARNIERI, S. F. et al. Coconut fiber biochar alters physical and chemical properties in sandy soils. **Acta Scientiarum. Agronomy**, 43: e51801, 2021.

KRZYSZCZAK, A.; DYBOWSKI, M. P.; CZECH, B. Microorganisms and their metabolites affect the content of polycyclic aromatic hydrocarbons and their derivatives in pyrolyzed material. **Science of The Total Environment**, 886: 163966, 2023.

LIU, X. et al. Amending biochar affected enzyme activities and nitrogen turnover in Phaeozem and Luvisol. **GCB Bioenergy**, 15: 954-968, 2023a.

LIU, Z. et al. Effect of Mg-modified waste straw biochar on the chemical and biological properties of acidic soils. **Molecules**, 28: 5225, 2023b.

LUSTOSA FILHO, J. F. et al. Biochars derived from olive mill byproducts: typology, characterization, and eco-efficient application in agriculture - A systematic review. **Sustainability**, 16: 5004, 2024.

NAGARAJU, K. et al. Exploring the benefits of rice husk waste: synthesis and characterization of biochar and nanobiochar for agricultural and environmental sustainability. **International Journal of Environment and Climate Change**, 13: 715-725, 2023.

NIU, M. et al. Biochar effectively promoted growth of *Ardisia crenata* by affecting the soil physicochemical properties. **Plants**, 13: 1736, 2024.

OBIA, A. et al. Biochar dispersion in a tropical soil and its effects on native soil organic carbon. **Plos One**, 19: e0300387, 2024.

ORTEL, C. C.; ROBERTS, T. L.; RUPE, J. C. A review of the interaction between potassium nutrition and plant disease control. **Agrosystems, Geosciences & Environment**, **7**: 1-14, 2024.

REHMAN, I. et al. Evaluating the effects of biochar with farmyard manure under optimal mineral fertilizing on tomato growth, soil organic C and biochemical quality in a low fertility soil. **Sustainability**, 13: 2652, 2021.

REZENDE, J. et al. Adubos orgânicos regionais na produção de mudas de pimentão no semiárido piauiense. **Revista Brasileira de Engenharia e Sustentabilidade**, 10: 8-13, 2022.

SALES, H. A. **Desempenho agronômico de pimentão sob adubação orgânica e mineral**. 2021. 34 f. TCC (Graduação em Licenciatura em Ciências Agrícolas) – Instituto Federal do Espirito Santo, Campus Itabina, Itabina, 2021.

SANCHEZ, E. et al. Assessment of pistachio shell-based biochar application in the sustainable amendment of soil and its performance in enhancing bell pepper (Capsicum annuum L.) growth. **Sustainability**, 16: 4429, 2024.

SÁNCHEZ-REINOSO, A. D.; ÁVILA-PEDRAZA, E. G.; RESTREPO-DÍAZ, H. Use of biochar in agriculture. **Acta Biológica Colombiana**, 25: 327-338, 2020.

SINGH, C. et al. The effect of rice husk biochar on soil nutrient status, microbial biomass and paddy productivity of nutrient poor agriculture soils. **Catena**, 171: 485-493, 2018.

SUN, X. et al. Comparative transcriptome analysis provides insights into the effect of epicuticular wax accumulation on salt stress in coconuts. **Plants**, 13: 141, 2024.

TAIZ, L.; ZEIGER, E. **Fisiologia vegetal**. 5. ed. Porto Alegre, RS: Artmed, 2013. 954 p.

ZHANG, H. et al. Roles of biochars' properties in their water-holding capacity and bound water evaporation: quantitative importance and controlling mechanism. **Biochar**, 6: 1-13, 2024b.

ZHANG, S. et al. Using the conditional process analysis model to characterize the evolution of carbon structure in *Taxodium ascendens* biochar with varied pyrolysis temperature and holding time. **Plants**, 13: 460, 2024a.