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Biochar improved soil salinity, mitigated sodium toxicity, and improved plant growth in salt-affected soils

Biochar melhorou a salinidade do solo, mitigou a toxicidade do sódio e melhorou o crescimento das plantas em solos afetados pelo sal

El biocarbón mejoró la salinidad del suelo, mitigó la toxicidad del sodio y mejoró el crecimiento de las plantas en suelos afectados por la sal

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Kelianne Carolina Targino de Araújo
ORCID: https://orcid.org/0000-0002-3088-5925
Universidade Federal de Sergipe, Brazil
E-mail: kelikarolina@hotmail.com
Wallace Melo dos Santos
ORCID: https://orcid.org/0000-0002-9431-884X
Universidade Federal de Sergipe, Brazil
E-mail: wallacemds@gmail.com
Maria Isidoria Silva Gonzaga
ORCID: https://orcid.org/0000-0002-7884-6386
Universidade Federal de Sergipe, Brazil
E-mail: isidoria@academico.ufs.br
Andreza Nunes Conceição da Silva
ORCID: https://orcid.org/0009-0000-7613-5225
Universidade Federal de Sergipe, Brazil
E-mail: andrezanuneees@academico.ufs
Lafayette Franco Sobral
ORCID: https://orcid.org/0000-0003-0719-5085
Universidade Federal de Sergipe, Brazil
E-mail: lafayette.sobral@embrapa.br

Abstract
In this study, we evaluated the early growth stages of maize plants cultivated in saline-sodic soil treated with various types of biochar. Biochar from sugarcane bagasse, orange bagasse, and corncobs was applied to a clayey saline-sodic soil and transferred to soil columns. After leaching, we measured the electrical conductivity (EC) and the exchangeable sodium percentage. Maize plants were grown in the leached soil. Plant biomass and nutrient concentration were determined. Biochar reduced EC to 3.20 dS m^{-1} and ESP to 2.56%. In the control soil, some seeds barely germinated without biochar, and plant growth was impaired. Conversely, all biochar treatments promoted seed germination and plant development. The CCB treatment not only enhanced plant growth but also achieved the best nutritional balance, as evidenced by plant nutrient concentration, which is similar to values typically found in maize plants during the early growth stages. However, the OBB treatment could not reduce the EC and ESP values to acceptable levels. These findings suggest that SCB and CCB biochar could be a promising solution for improving soil quality and promoting plant growth in salt-affected soils, thereby contributing to the field of sustainable agriculture.
Keywords: Carbon; Soil Remediation; Sustainablewaste Management.

Resumo
Neste estudo, testamos a capacidade do biochar de reduzir o excesso de sais e melhorar o crescimento e a nutrição inicial das plantas. Biochar de bagaço de cana , bagaço de laranja e sabugo de milho foi aplicado em solo argiloso salino-sódico e transferido para colunas de solo. Após a lixiviação, foram medidas a condutividade elétrica (CE) e a porcentagem de sódio trocável.. As plantas de milho foram cultivadas no solo lixiviado. A biomassa vegetal e a concentração de nutrientes foram determinadas. Biochar reduziu CE para 3,20 dSm^{-1} e ESP para 2,56%. No solo controle, algumas sementes mal germinaram sem biochar e o crescimento das plantas foi prejudicado. Por outro lado, todos os tratamentos com biochar promoveram a germinação das sementes e o desenvolvimento das plantas. O tratamento com CCB não só melhorou o crescimento das plantas, mas também alcançou o melhor equilíbrio nutricional, como evidenciado pela concentração de nutrientes nas plantas, que é semelhante aos valores normalmente encontrados nas plantas de milho durante as fases iniciais de crescimento. Entretanto, o tratamento OBB não conseguiu reduzir os valores de CE e ESP a níveis aceitáveis . Estas descobertas sugerem que o biochar SCB e CCB

pode ser uma solução promissora para melhorar a qualidade do solo e promover o crescimento das plantas em solos afetados pelo sal, contribuindo assim para o campo da agricultura sustentável.
Palavras-chave: Carbono; Remediação de Solos; Gestão Sustentável de Resíduos.

Resumen
En este estudio, probamos la capacidad del biocarbón para reducir el exceso de sales y mejorar el crecimiento de las plantas y la nutrición temprana. Se aplicó biocarbón de bagazo de caña de azúcar, bagazo de naranja y mazorca de maíz a suelo arcilloso salino-sódico y se transfirió a columnas de suelo. Después de la lixiviación, se midieron la conductividad eléctrica y el porcentaje de sodio intercambiable. Se cultivaron plantas de maíz en el suelo lixiviado. Se determinó la biomasa vegetal y la concentración de nutrientes. El biocarbón redujo la EC a 3,20 dS m-1 y el ESP a 2,56%. En el suelo de control, algunas semillas apenas germinaron sin biocarbón y el crecimiento de las plantas se atrofió. Por otro lado, todos los tratamientos con biocarbón promovieron la germinación de las semillas y el desarrollo de las plantas. El tratamiento con CCB no solo mejoró el crecimiento de las plantas sino que también logró el mejor equilibrio nutricional, como lo demuestra la concentración de nutrientes en las plantas, que es similar a los valores que normalmente se encuentran en las plantas de maíz durante las fases iniciales de crecimiento. Sin embargo, el tratamiento con OBB no pudo reducir los valores de CE y ESP a niveles aceptables. Estos hallazgos sugieren que el biocarbón SCB y CCB podría ser una solución prometedora para mejorar la calidad del suelo y promover el crecimiento de las plantas en suelos afectados por la sal, contribuyendo así al campo de la agricultura sostenible.
Palabras clave: Carbono; Remediación de Suelos; Gestión Sostenible de Residuos.

1. Introduction

Salt-affected soils, a widespread issue on arable land globally, particularly in irrigated semi-arid regions, significantly hinder plant growth. The physical degradation of these soils limits root expansion, reducing the plant's ability to absorb water and nutrients (Hopmans et al., 2021). Elevated salt concentrations alter the osmotic potential of the soil solution and the impact of specific ions, such as sodium, chlorine, and boron (Wakeel, 2013). The se ions induce plant toxicity and nutritional imbalances by reducing nutrient availability, competing during ion absorption and transport processes, and altering plant nutrient distribution (Wakeel, 2013; Javed et al., 2022).

Maize, a member of the Poaceae family, is a crucial crop in many nations, serving as both a commodity and a source of food and energy security for humans and animals. Accordingto FAO, (2020), maize is the second most-produced cereal globally. As a glycophyte plant, maize is susceptible to saline stress, exhibiting high sensitivety to electrical conductivity above 5 dS m^{-1} (Farooq et al., 2015), a condition that adversely affects seed germination, seedling development, and grain yield. Elevated soil sodium concentrations are the primary cause of toxicity in maize plants grown in salt-affected soils, interfering with potassium uptake.

The cultivation of maize in arid and semi-arid regions is of significant economic and societal importance. Therefore, remediating salt-affected soils in these areas is crucial for enhancing agricultural productivity and the sustainability of agroecosystems.

Countless studies have explored the potential of biochar derived from organic waste to enhance soil quality (Carvalho Junior et al., 2019) and remediate salt-affected soils (Chaganti et al., 2015; Bhaduri et al., 2016; Zhang et al., 2020; Xiao & Meng, 2020; Sun et al., 2022; Wang et al., 2022; Wang et al., 2023; Yuan et al., 2023; Yue et al., 2016). These studies underscore the high potential of biochar for this purpose, offering a promising avenue for the future of agriculture in salt-affected soils. The significant variability among different types of precursor biomass leads to varying degrees of effectiveness in biochar, as consistently observed in studies conducted by our research group. Therefore, it is crucial to investigate the impact of each pyrolyzed residue on soil salinity treatment.

The adaptability of biochar to different soil types is a crucial feature, with its action mechanism varying with the texture and mineralogy of the soil (Fanqi et al., 2022). This adaptability makes biochar a versatile tool in soil management. For example, in soils with a low percentage of clay, a predominance of secondary minerals with a Si: Al ratio of 1:1, a high proportion of Fe and Al oxides, and a high percentage of sand, adding biochar will reduce drainage and increase water retention. This scenario is desirable when the objective is to increase the retention of ions in the soil. In soils with a high content of high-activityclay (2:1), biochar facilitates water flow in the soil and, consequently, favors the removal of ions by leaching (Obia et al., 2018; Khan et al., 2024). This effect of biochar qualifies it for use in clayey soils with high salinity and sodicity since, in these soils, there are frequent drainage problems due to compaction caused by the dispersion of particles and clogging of pores.

Therefore, adding biochar to fine-textured salt-affected soils reduces particle cohesion, enhances soil porosity, and significantly increases soil permeability and water flow (Wong et al., 2022), which facilitates the leaching of excess salts (Chaganti et al., 2015). Yue et al. (2016) applied biochar with lignocellulosic characteristics to salinized soil and observed improved soil quality and maize plant development. This promising result suggests that biochar can mitigate the adverse effects of salt-affected soils. However, it is essential to note that without subsequent nutrient supply and monitoring, this approach may induce nutritional imbalances in plants, mainly maize, due to their high nutrient demand. This caution underscores the need for careful planning and management when using biochar in agriculture.

In this study, we evaluated the early growth stages of maize plants cultivated in saline-sodic soil treated with various types of biochar. Specifically, we investigated i) plant growth and development, ii) concentrations of N, P, K, and Na in shoots and roots, and iii) the Na: K ratio in shoots and roots. Our objective was to determine the most effective type of biochar for reducing the negative effect of excess salts and promoting maize growth and nutrition.

2. Methodology

In this work, a mixed research was carried out, part in the field and part in the laboratory, of a quantitative nature, according to Pereira et al. (2018).

Soil and biochar preparation and characterization

The salt-affected, saline-sodic Luvisol was collected in the 0-0.20 m layer at an abandoned agricultural field in Northeast Brazil. The soil was air dried, sieved to pass a 2 mm mesh screen, and analyzed for the main characteristics: pH (7.73), EC (69.5 dS m^{-1}), total organic carbon (0.85%), concentrations of K (156.4 mg kg^{-1}), Na (6600 mg kg^{-1}), P (32.6 mg kg^{-1}), Exchangeable Sodium Percentage (32.7%), textural class: clay loam.

All biochar were produced in a retort kiln at temperatures varying from 500 to 600o C and analyzed for specific characteristics: particle distribution (> 2mm and< 2mm), total porosity (Zhang et al., 2011), water holding capacity, EC, pH (Gasking et al., 2008), concentration of extractable K, and Na, total concentration of N and P (Table 1).

Table 1 - Biochar characteristics. Santos, (2024).

C.haracteristic	Biochar		
	Sugarcane bagasse	Orange bagasse	Corncobs
P* (mg kg^{-1})	496	318	433
K*(mg kg^{-1})	3401	15952	10948
Na*(mgkg^{-1})	92.0	230	92.0
EC** (dS m^{-1})	0.98	4.16	1.90
Total P (g kg^{-1})	2.91	5.73	2.44
Total N (g kg^{-1})	5.20	18.5	6.46
Size> 2.00 (mm)	19.7	13.6	20.9
Size< 2.00 (mm)	80.2	86.4	79.1
WHC (%)	692	271	465
Total porosity (Å)	184	847	180

* Mehlich 1 extract. ** biochar:waterratioof 1:20. Fonte: Autores.

Soil column and pot experimente

The experimente was set up as a completely randomized design with three types of biochar: sugarcane bagasse (SCB), orange bagasse (OBB), corncobs (CCB), and control soil without biochar. All treatments were performed in four replicates. Biochar was applied at rates of 60 t ha^{-1}.

After the preparation of the treatments, they were transferred to PVC columns, according to Yue et al. (2016), wet at field capacity, and incubated for a week before the leaching procedure the soil in each column was air-dried and transferred to black polyethylene pots that had a total height of 13.0 cm, bottom diameter of 9.0 cm, and top diameter of 15.0 cm, comprising a total volume of 1500 cm3. The soil was added up to a height of 8.0 cm to replicate a soil bulk density of 1.38 g cm-3. Each pot contained 1 kg of soil. Samples of the soil of each treatment were used to determine the electrical conductivity [23] (Richards, 1954) and the exchangeable sodium percentage. The exchangeable sodium percentage (ESP) was calculated according to the Equation:

$$ESP = Na^{+}/CTC \times 100$$

Soil moisture was adjusted to 70% of field capacity, and base fertilization was added as 30 kg ha^{-1} of N and 20 kg ha^{-1} of P in the form of urea and triple superphosphate, respectively. On the same day, three maize seeds (*Zea mays* L.) were sown in each pot, approximately 4 cm deep. The pots were randomly distributed and kept in a greenhouse with an internal temperature of 26-28º C. During the experiment, soil moisture was maintained at 70% of field capacity by weighing the pots daily and considering the daily evaporative demand of the crop. When the second genuine leaf (V2) was emitted, thinning was performed, keeping only the plant with the best vegetative development or the one that first reached the V2 stage. When the fourth leaf was emitted, topdressing fertilization was applied via fertigation at 35 kg ha^{-1} of N.

At 45 days after sowing, the plants were harvested, shoots were separated from roots, washed with distilled water, transferred to paper bags, oven-dried at 65º C, and ground to a powder. Plant growth was determined primarily as the dry weight of shoot and root at harvest. Plant samples were ground, sieved, and acid-digested to determine the concentration of nitrogen, phosphorus, sodium, and potassium (Silva, 2009). Soil samples were analyzed for pH, electrical conductivity (EC), and exchangeable sodium percentage (ESP) (Silva, 2009).

Statistic alanalysis

The results are presented as the mean values of four replicates. Data were analyzed using Analysis of Variance (ANOVA) to evaluate significant differences in the variables, with the statistical software Sisvar [25] (Ferreira, 2007). Multiple comparisons between treatments were performed using Tukey's test at a significance level of $P < 0.0$

3. Results and Discussion

Soil salinity indicators following biochar treatment

The effective remediation of saline-sodic soils, a crucial aspect of soil management, involves reducing the salt content and the concentration of exchangeable sodium, thereby improving soil quality and facilitating plant growth and development (Endo et al., 2021). In this study, we determined electrical conductivity (EC) and exchangeable sodium percentage (ESP) as primary indicators to assess the impact of biochar on mitigating salt-affected Luvisol.

All biochar treatments significantly decreased the electrical conductivity of soil extracts compared to treatments without biochar, with CCB (92.0%) = SCB (90.2%) > OBB (53.0%) (Figure 1A). Therefore, the most effective treatments were SCB and CCB, which reduced the EC values from 69.5 dS m^{-1} to 3.80 dS m^{-1} and 3.20 dS m^{-1}, respectively. These values fall below the threshold limit of 4 dS m^{-1} proposed by Richards (1954), which is considered restrictive for most crop plants. Considering the initial soil EC of 69.5 dS m^{-1}, the treatment without biochar (39.0 dS m^{-1}) reduced the EC by only 43%, leaving a high salt concentration. This result confirms the physical barrier to water movement and salt leaching from saline soils.

Besides reducing the EC values, biochar was effective in reducing the exchangeable sodium percentage in the order CCB (85.8%) > SCB (72.9%) > OBB (11.0%) as compared to the control soil (Figure 1B). According to Richards (1954), ESP values above 15% are high. They can cause clay dispersion, low aggregate stability, and reduced macropore spaces, impairing soil water movement when the soil hydraulic conductivity falls below 100 mm h^{-1}.

Yuan et al. (2023) conducted a comprehensive review of the effect of biochar on mitigating soils affected by salts. They showed that the improvement in the soil's physical, chemical, and biological quality due to the presence of biochar contributes to facilitating the removal of excess sodium, reducing its deleterious effect on soil structure. The characteristics of biochar such as high porosity, low density, presence of many functional groups, high CEC and specific surface, and presence of polyvalent ions such as Ca^{+2} and Mg^{+2} favor the growth and activity of microorganisms in saline soils, which, in turn, produce aggregating organic substances that contribute to the formation of aggregates and increased soil porosity.

In addition to creating additional pores in the soil by interacting with mineral particles (interpores), a significant proportion of pores are created in the soil due to the pores present in the biochar structure (intrapores) that are not filled with clay minerals from the soil (Williams et al., 2020). A study by Zong et al. (2014) had already demonstrated that biochar of varied particle assortment caused a reduction in soil cohesiveness with high clay content. In our study, sugarcane and corncob biochar treatments contributed to the reduction of cohesion between soil particles due to their particle size distribution and reduced density.

Plant mass

The results of shoot and root biomass are detailed in Figure 2D. Plant growth was impaired in the control treatment, reflecting the effect of the elevated salt concentration (EC: 39 dS m-1), especially Na (ESP: 18%). Salt stress negatively affects seed germination, nutrient uptake, and root and shoot development, reducing plant productivity (Yuan et al., 2023). Excess salts in the soil are widely known to cause oxidative stress in plants, influencing several metabolic processes. Therefore, the reduction in plant development occurs not only due to the deleterious effect of salinity on soil quality but also due to its direct effect on plants (Vasconcelos, 2020).

Applying biochar to the salt-affected soil facilitated the leaching of salts, effectively reducing the osmotic stress and promoting seed germination and plant growth. However, there were significant differences among biochar treatments. The SCB and CCB treatments increased the shoot biomass approximately 12.8 times, whereas the OBB treatment increased shoot mass 11 times compared to the control. The reduced plant growth in the OBB treatment was due to this biochar's lower performance in reducing the soil salinity indicators.

Despite OBB biochar not showing the same positive effect as SCB and CCB on maize plant development, it still holds significant potential for use in salt-affected soils. This is because it can promote seed germination and plant growth in an environment with high electrical conductivity (EC: 18 dS m^{-1}) and exchangeable sodium percentage (ESP: 16%), both of which exceed the reference limits set by Richards (1954). The less pronounced effect of OBB on plant development is not due to its ability to effectively improve soil drainage conditions, a trait shared by the other two biochar treatments (SCB and CCB). Instead, it is likely due to OBB's unique characteristics, such as its higher K (1.6%), N (1.85%), and CEC (63 cmolc kg^{-1}) content, which could have helped to regulate the Na/K homeostasis (Ali et al., 2017).

Our findings validate the potential of these three biochars to enhance the quality of degraded soil, enabling maize plants to flourish in otherwise challenging conditions.

Concentration of N, P, and K in plant tissues

The concentrations of nitrogen (N) in maize plants are depicted in Figure 2. Shoot and root N concentrations ranged from 13.7 to 19.0 g kg^{-1} and 6.5 to 9.1 g kg^{-1}, respectively. Typically, maize plants in their early growth stages exhibit N concentrations between 17-30 g kg^{-1} in shoots and 13-16 g kg^{-1} in roots (Dong et al., 2020), placing our results at the lower end of the range for plant N content. In the early stages, maize plants need more N to support rapid leaf and stem development; therefore, N management in biochar-treated soils should be a matter of close attention.

There was no significant difference in the plant N content across biochar treatments, even though the N content in the OBB was much higher than the other two biochars.

In addition, excessive salt levels hinder N absorption, particularly in the form of nitrate, due to ionic competition and reduced assimilation caused by decreased xylem sap flow to the aerial parts. The application of N fertilizers at sowing and during the V4 phase may have mitigated residual salt effects, even in soils with high electrical conductivity (EC). Despite this, N translocation to the aerial parts of the plant appeared unaffected, as indicated by higher N concentrations in shoots compared to roots across all treatments, a typical pattern for this element in plants.

Rajkovich et al. (2012) observed reduced N concentrations in maize plants 46 days after sowing when testing biochars derived from eight different feedstocks and produced at various temperatures and application rates. They suggested that although biochar is highly stable, a small fraction can mineralize rapidly, inducing microbial nitrogen immobilization. Additionally, increasing pyrolysis temperature elevates the carbon-to-nitrogen (C:N) ratio, contributing to low N concentrations in plants.

In contrast to N concentrations, phosphorus (P) concentrations were significantly influenced by biochar treatments (Figure 2). P concentrations ranged from 0.44 mg kg^{-1} to 0.58 mg kg^{-1} in shoots and from 0.20 mg kg^{-1} to 0.38 mg kg^{-1} in roots across treatments.

Although the total P concentration in the biochars was high, only a tiny fraction was extractable or available to plants (5.5% in the OBB - 18.0% in the SCB and CCB) (Table 1), which explains the low P concentration (0.44-0.58 g kg-1) in shoot tissue (Figure 2), below the adequate range of 2.2 g kg^{-1}. This disparity indicates that elevated soil P levels did not correspond to increased P uptake by the plants, especially in the OBB treatment where the available P concentration was 5% ofthe total P concentration.

In alkaline soils (pH > 7.0), phosphorus may be immobilized due to fixation by silicate clays and calcium carbonate (Jindo et al., 2020). In addition, the alkaline nature of the three biochars used in our study may have contributed to the reduced availability of P, as biochars also present Ca in their composition. An adequate level of P in the plants is required in the early growth stage, especially to promote root development, preparing the plant for the flowering stage where P is much needed. Therefore, adequate P management is required When using biochar in salt-affectedsoils.

Furthermore, the use of the Mehlich-1 extraction method in semi-arid soils may result in an overestimation of available P, as this technique is sensitive to calcium-bound phosphorus. Despite this, the study opens promising avenues for further investigation into alternative methods for assessing labile phosphorus fractions in salt-affected soils. This could facilitate more accurate phosphorus management, enhancing both crop productivity and environmental sustainability.

The N/P ratio in the shoots and roots of the plants was different between the biochar types (Figure 2C), being significantly higher in SCB, which reflects the lower P concentration in the plants of this treatment. However, there does not appear to be a relationship between biomass and the plants' concentration of N and P. The N/P ratio in maize plants is vital for balancing vegetative and reproductive growth, improving yields, and optimizing nutrient use. For the vegetative growth phase, the N/P ratio is generally in the range of 5:1 to 15:1 (Zhang et al., 2021), but there is significant variation according to the different stages of plant growth. The values found for the N/P ratio in maize plants in our study are high (33:1 to 41:1 in the shoots and 22:1 to 37:1 in the roots), showing a significant nutritional imbalance in the plants.

Potassium (K) concentrations varied 39.3 mg kg^{-1} to 46.0 mg kg^{-1} in shoots and from 4.90 mg kg-1 to 12.2 mg kg^{-1} in roots (Figure 3A). The optimal shoot K concentration for maize plants typically falls between 17.5 to 22.5 g kg^{-1} (Magalhaes et al., 2016); therefore, our results indicate higher K accumulation during the first 45 days of plant growth in the biochar treated soils. Given potassium's mobility within plants and its role in regulating stomatal movement, there were no apparent disruptions in K translocation to the shoot. In fact, high K levels increased plant tolerance to abiotic stress. For example, maize plants accumulate K in roots and shoots under high soil salinity conditions while reducing Na concentration to alleviate Na stress (Zhang et al., 2023).

A more significant amount of biomass was also observed in the aerial part, suggesting that K may have contributed to this result. The intrinsic characteristics of biochar may also have helped mitigate salinity's effects, promoting an increase in water availability in plants and consequently reducing their osmotic effect and ionic toxicity of salts (Thomas et al., 2013).

In the present study, the three biochars promoted similar K concentrations in shoots but different root K levels in the order CCB > SCB > OBB. The lower K concentration in the roots of plants in the OBB treatment may be related to the lower performance of this treatment in reducing soil salinity, which was reflected in the lower shoot and root biomass (Figure 1D) when compared to the other two biochars. Jaffar et al. (2024) confirmed the positive effect of sugarcane bagasse biochar (SCB) in alleviating salt stress and promoting the growth of maize plants. The authors applied 2% SCB in soil with EC of 8d S m^{-1}. They observed significant plant growth, mainly attributed to the increased activity of enzymes such as acid phosphatase, alkaline phosphatase, and urease.

Generally, biochar from plant material is rich in K, with concentrations ranging from 0.7-116 g kg^{-1} (Ippolito et al., 2014). This statement is corroborated by the results observed by Costa et al. (2018) when applying *Prosopis juliflora* biochar to an Ultisol, observing a higher concentration of K not only in the biochar but also in the aerial part of the maize plants, obtaining a higher biomass. In the present study, biochars presented available K concentrations ranging from 3.4-16 g kg^{-1} (Table 1).

Concentration of Na in planttissueandNa:Kratio

Sodium is a mobile plant element, with concentrations typically ranging from 0.01 to 35 g kg^{-1} in sensitive, tolerant, hyperaccumulator plants. However, in plants of the Poaceae family, such as maize, Na concentration ranges from 0.127 to 2.825 g kg^{-1}, with an average of 0.326 g kg^{-1} (Malavolta, 2006). Our study obtained Na concentration considerably higher than the average for most plants, with variation between biochar types, both in the shoots (0.24 - 4.45 g kg^{-1}) and in the roots (3.17 - 7.68 g kg^{-1}) (Figure 3B).

Higher Na concentrations were found in roots than in shoots, a pattern observed in all treatments, with a Na shoot/Na root ratio of 0.07 (SCB) < 0.35 (CCB) < 0.58 (OBB) (Figure 3D). This distribution of Na between shoots and roots is consistent with the distribution of toxic elements in plants, which use this strategy to reduce the negative effect of high concentrations of undesirable elements in the shoots. Some plants have as a mechanism the extrusion of Na, expelling it from vital tissues such as the xylem, preventing the accumulation of cations in the aerial part and, consequently, its harmful effects on both leaf metabolism and the photosynthetic process (Munss et al., 2002; Schossler et al., 2012). This process can be called osmotic adjustment, whereby the plant favors the entry of K into the xylem and prevents the entry of Na, causing it to accumulate in the root. Therefore, this could probably have happened in the present study.

Among the three treatments, SCB was the only one that sustained a low sodium concentration in maize shoots, likely attributable to its higher potassium release into the soil, facilitated by the greater hydration capacity of this biochar (Table 1). The high water retention capacity of SCB (692%) associated with its high K concentration should play an essential role in the ion exchange process in the soil (Santos et al., 2022) and in the uptake of K and Na by plants. Sugarcane bagasse biochar effectively improves soils affected by salts, with multiple benefits for soil microbiota and plants (Jaffer et al., 2024).

An increase in soil solution Na content is known to elevate Na concentration in plants, particularly in roots (Freitas et al., 2022). This pattern explains the higher Na concentration in the roots and shoots of maize plants in the OBB treatment. Although this biochar has excellent attributes in correcting soil acidity, carbon sequestration, and substrate components (Feitosa et al., 2020), the present study demonstrated that it is not as efficient in remediating soils affected by salts. The results suggest that the drainage time and water infiltration capacity into the soil were inefficient in reducing EC and sodium concentration. According to Santos et al. (2022), this inefficiency may be related to the low value of the surface area, which was lower when compared to other biochars, contributing to low soil aggregation resulting in high density, decreased porosity, and consequently less infiltration of water into the soil.

Sodium ions passively penetrate roots, accumulating in salt glands of halophytic plants such as *Atriplex* sp. In contrast, in salt-sensitive plants like maize, roots prevent Na transport to shoot and leaf meristems by accumulating Na ions in root cell vacuoles or extruding them into the soil solution (Taiz and Zeiger, 2013). Despite elevated tissue Na concentrations in the OBB treatment, no salt stress symptoms were observed in the plants.

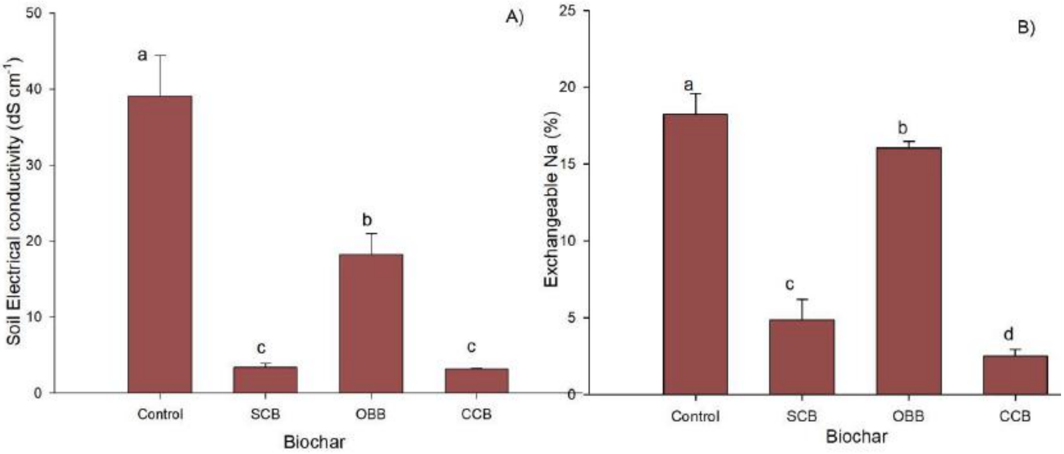
The Na/K ratio, a crucial indicator in plant nutrition, ranged from 0.005 to 0.11 in the shoot and 0.26 to 1.58 in the root (Figure 3C). This ratio serves as an index for Na toxicity in plants, providing valuable insights for agricultural practices (Zhang et al., 2019). Maintaining low Na concentration and adequate Na/K ratio in plant cells is essential for the survival and development of plants in soils with high salt concentrations (Zhang et al., 2022). Maintaining the ratio below 0.6 is crucial as it ensures optimal metabolic efficiency in plants, while higher values can indicate excess Na ions, leading to plant damage. In our study, all biochar treatments kept the Na/K ratio below the threshold value except the OBB.

The low values of the Na/K ratio indicate an efficient reduction of Na translocation to photosynthetic tissues and high soil K concentration favoring absorption. An inversion of the Na/K ratio is observed in roots, as sodium accumulates in root tissues to prevent aerial part toxicity and promote Na ion extrusion into the soil. Increased soil salinity exacerbates this relationship due to membrane integrity loss in root tissues, reducing K ion selectivity and potentially causing nutritional imbalances, which reduce vegetative growth and dry matter accumulation (Freitas et al., 2022).

Reducing some macronutrients, such as K, is common in plantssubjectedto some salinity stress. In studies carried out by Cruz et al. (2006), the authors observed a reduction in K in all parts of the plant when subjected to salinity conditions. Similar results were also observed by Barbosa et al. (2010). Therefore, based on the results of the present study and the works mentioned, it is possible to state that the plant adopted the accumulation of Na in its roots in order to avoid toxicity of the aerial part.

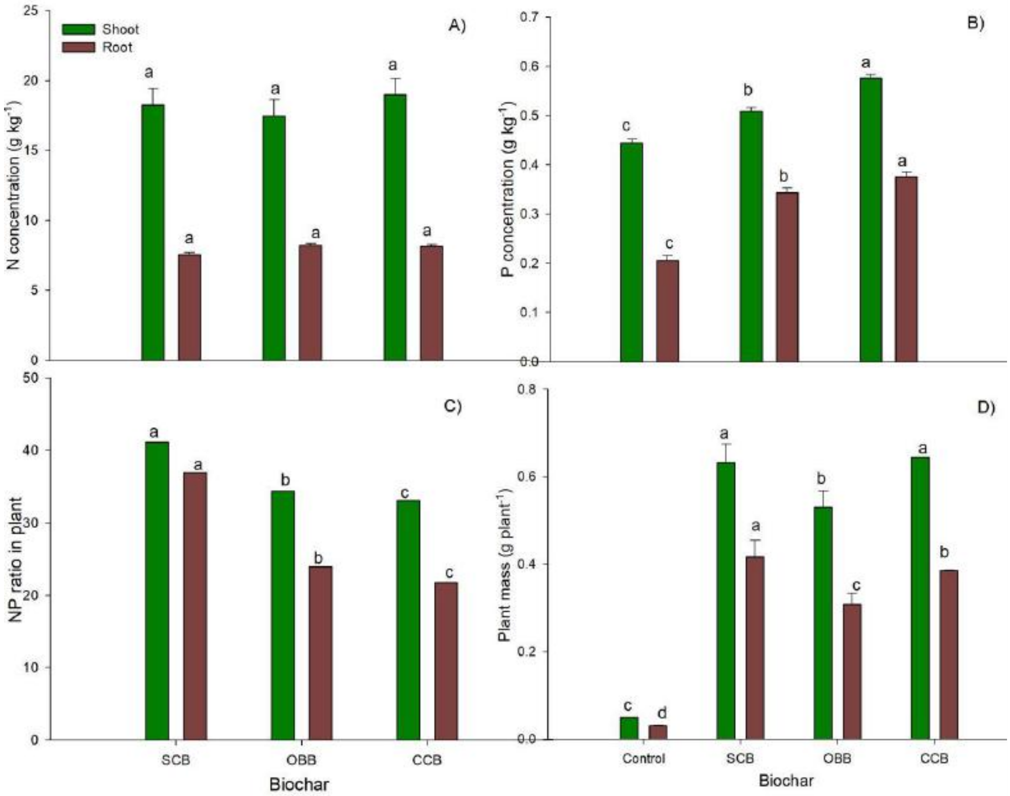
Maize plants have specific ion transporters that control the entry and exit of K and Na, regulating the flow in the xylem cells and promoting the exclusion of Na from the leaves to maintain an adequate Na/K ratio in the cells. These processes are involved in mechanisms that increase tolerance to salt stress (Zhang et al., 2019). Therefore, using K-rich biochar can significantly increase plant resistance in saline soils.

Figure 1 - Soil electrical conductivity (A) and exchangeable Na percentage (B) in the salt-affected soil after the application of biochar from sugar cane bagasse (SCB), orange bagasse (OBB) and corn cobs (CCB), and leaching procedure. Means followed by the same letter are not significantly different according to the Tukey test ($P < 0.05$).



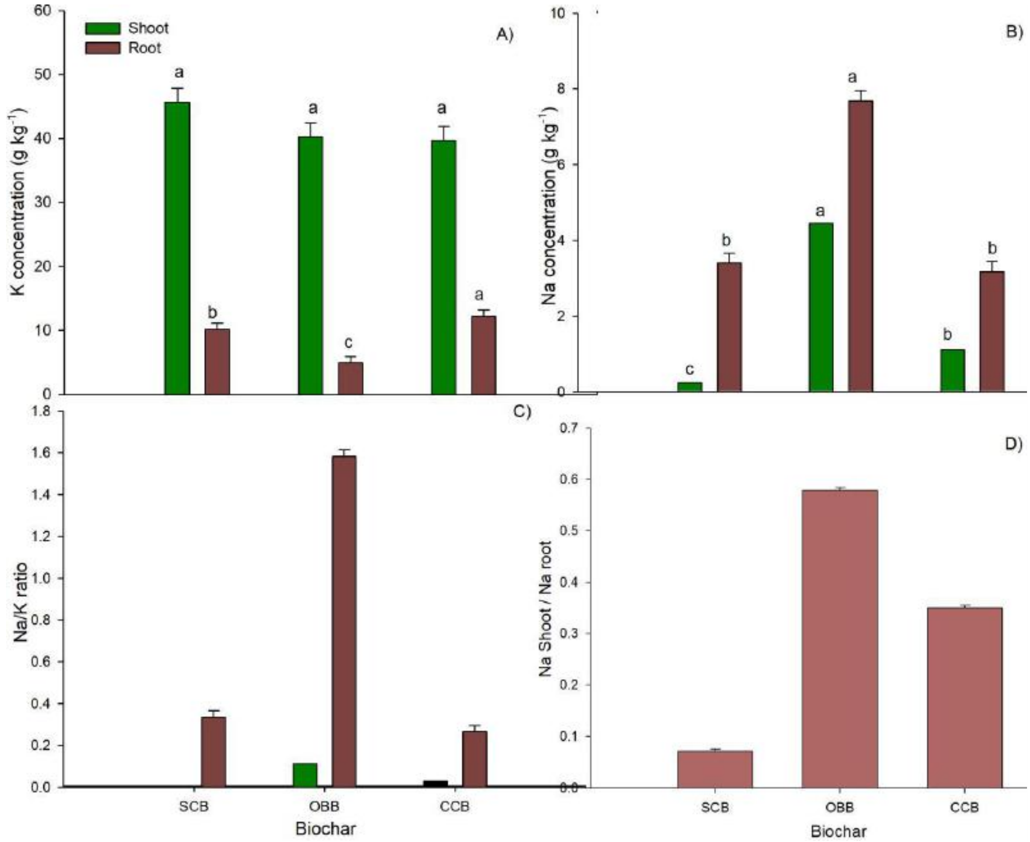
Fonte: Autores.

Figure 2 - Nitrogen (A) and P (B) concentration, N/P ratio, and Plant biomass dry weight (D) in the shoot and root of young maize plants grown in a remediated saline-sodic soil treated with biochar from sugar cane bagasse (SCB), orange bagasse (OBB) and corn cobs (CCB), and leaching procedure. *Means followed by the same lowercase letter do not differ statistically from each other by the Tukey test ($p<0.05$) in the same plant part.



Fonte: Autores.

Figure 3 - Potassium (A) and sodium concentration (B), and Na/K ratio (C) in the shoot and root of young maize plants grown in a remediated saline-sodic soil treated with biochar from sugar cane bagasse (SCB), orange bagasse (OBB) and corn cobs (CCB), and leaching procedure. *Means followed by the same lowercase letter do not differ statistically from each other by the Tukey test ($p<0.05$) in the same plant part.



Fonte: Autores.

4. Conclusion

The leaching procedure applied to the soil without amendment could not decrease the EC and ESP to below threshold levels, which impaired plant growth. On the contrary, all biochar treatments reduced the soil salinity levels and allowed plant germination and development. While applying biochar enhanced the growth of maize plants in salt-affected soil, the concentrations of N and P fell below typical levels observed in plants during their early growth stages. Conversely, K concentrations were notably high in plant tissues, possibly due to excess Na alleviation through soil leaching. Biochar from sugar cane bagasse and corn cobs performed better and had higher plant growth than the orange bagasse biochar, likely due to the reduced concentration of Na in the shoot and root. Therefore, the sugarcane bagasse and corncob biochars emerged as the most promising in reducing soil salinity, improving plant nutrient balance, reducing plant Na concentration, and allowing proper plant growth.

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