



# Biochar from Co-pyrolysis of Sewage Sludge Improves Plant Eco-physiology in Degraded Soils?

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## Abstract

**Purpose** A pot experiment was conducted under greenhouse conditions using a completely randomized design in a  $3 \times 4 + 1$  factorial arrangement. Three organic residue sources were evaluated: sewage sludge (SS), a mixture of sewage sludge and cashew pruning residues (SSCP), and the co-pyrolyzed biochar derived from these materials (BSSCP), applied at four phosphorus-equivalent rates, in addition to an untreated control. *Mimosa caesalpiniiifolia* Benth. was used as the model plant species.

**Methods** A pot experiment was conducted in a greenhouse in a completely randomized design ( $3 \times 4 + 1$  factorial), with three organic residue sources: sewage sludge (SS), a sludge–cashew pruning mixture (SSCP), and their co-pyrolysis biochar (BSSCP) at four phosphorus-equivalent doses, plus a control.

**Results** BSSCP at moderate doses (5 and 10 Mg ha<sup>-1</sup>) enhanced photosynthetic efficiency and water use, while non-carbonized residues promoted greater biomass accumulation, likely due to faster nutrient release. BSSCP raised soil pH and stabilized carbon but reduced short-term nitrogen availability.

**Conclusion** BSSCP is a potential alternative for degraded soil management and improving plant ecophysiology, provided application rates are properly adjusted.

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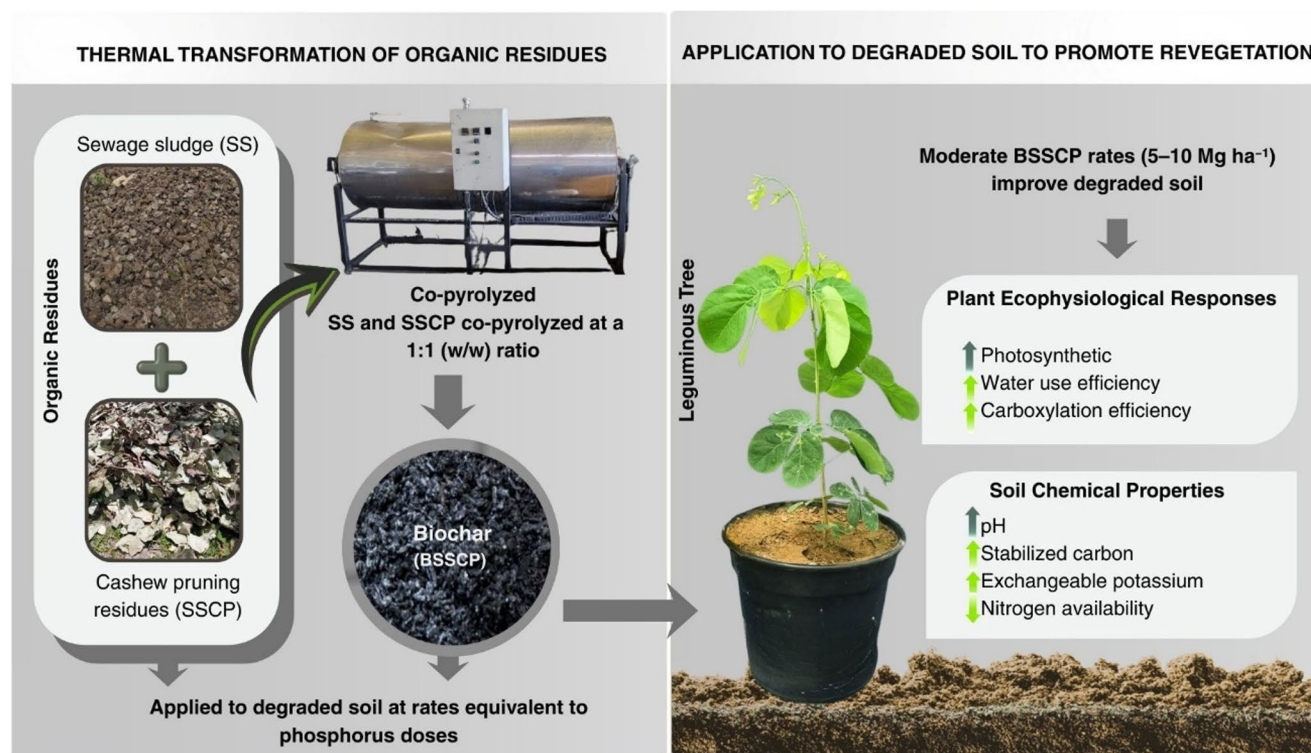
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## Graphical abstract



**Keywords** soil conditioner · *Mimosa caesalpinifolia* Benth · morphophysiology · pyrolysis · soil quality · waste treatment

## 1 Introduction

The effective management of the substantial volume of SS produced globally is one of the greatest challenges to sustainable development, especially in countries with large populations and high rates of urbanization and industrialization, where waste generation is massive (Fan et al. 2023). Global dry SS production is estimated to reach 127.5 million tonnes by 2030 (Cao et al. 2024).

Conventional SS treatment options, such as incineration and landfill disposal, have been increasingly discouraged due to their high operational costs and associated environmental risks, including groundwater contamination and secondary pollution (Rehman et al. 2018). As an alternative, SS can be used in agriculture and forest recovery as a soil conditioner and fertilizer, due to its high concentrations of organic matter and essential plant nutrients, such as phosphorus (P), in addition to improving the physical, chemical, and biological properties of the soil (Chang et al. 2023; Xu et al. 2024).

Nevertheless, the direct application of SS to soils remains a matter of concern, as this material may contain elevated concentrations of potentially toxic elements, pathogens, microplastics, and pesticide residues—classified as emerging

contaminants that constrain its safe agricultural use (Hassan et al. 2023; Xu et al. 2024 b). Without appropriate treatment, SS application can impair plant growth and pose risks to human health and environmental integrity, highlighting the need for strategies that mitigate these hazards while enabling resource recovery (Gonçalves et al. 2026).

A promising strategy to recover valuable resources from SS and minimize its environmental and health risks is its conversion into biochar—a stable, carbon-rich material with high surface area, porosity, and oxygenated functional groups (Chen et al. 2023; El-Desouki et al. 2024). SS biochar can be obtained through pyrolysis or co-pyrolysis, processes carried out under oxygen-limited or oxygen-free environments (Cao et al. 2024; Fan et al. 2023).

Co-pyrolysis, which involves blending SS with other biomass feedstocks such as agricultural or agro-industrial residues, has been shown to further improve biochar properties, including increased specific surface area, porosity, and nutrient bioavailability, while reducing ash content and potential toxicity compared with biochar produced solely from SS (Chen et al. 2020). The agronomic relevance of this approach is particularly evident when SS is co-processed with regionally abundant residues, such as cashew pruning waste. This strategy enables the integrated

management of multiple waste streams and yields a biochar with enhanced functionality for soil amendment applications (Penido et al. 2019). Such materials have demonstrated potential to improve soil fertility, increase cation exchange capacity (CEC), enhance water retention, and promote nutrient use efficiency—attributes that are especially critical in degraded soils and water-limited environments (Antonangelo et al. 2024; Hasnain et al. 2023). However, its effects vary depending on the feedstock, soil type, crop, and application rate.

Although numerous studies report beneficial effects of SS-derived and co-pyrolysis biochars on soil properties and plant productivity, most have focused on crops and short-term chemical responses. In contrast, comparatively little attention has been given to forest species used in the restoration of degraded lands, or to plant ecophysiological responses under environmental stress conditions (Brtnicky et al. 2021; Gale and Thomas 2019). This gap in knowledge is particularly critical in semi-arid regions, where soil degradation, nutrient limitations, and water scarcity severely constrain vegetation establishment and ecosystem recovery.

*Mimosa caesalpiniiifolia* Benth., a native leguminous tree species widely distributed in northeastern Brazil, is especially relevant within this framework. This species is commonly found in degraded environments and in areas at different stages of ecological succession (Antas et al. 2024). It forms a specific symbiosis with rhizobia, nitrogen-fixing bacteria, responsible for biological N<sub>2</sub> fixation, and independently establishes associations with arbuscular mycorrhizal fungi, which enhance the uptake of nutrients, particularly, phosphorus and water (De Oliveira et al. 2019; Garcia et al. 2025). Together, these interactions support nutrient cycling, biological soil recovery, and increased plant resilience under nutrient-limited conditions (Pessoa et al. 2025). In addition, its high tolerance to water deficit makes this species particularly suitable for studies in semi-arid regions, where drought resistance is a fundamental requirement for successful revegetation and ecological restoration.

Against this background, the present study evaluated the effects of applying biochar produced by the co-pyrolysis of sewage sludge and cashew pruning residues, as well as the corresponding uncarbonized organic materials, to degraded soils, comparing their impacts on the ecophysiological performance of *Mimosa caesalpiniiifolia* Benth. We hypothesized that, relative to the uncarbonized feedstocks (sewage sludge, cashew pruning residues, and their mixture), the co-pyrolysis-derived biochar, despite its greater recalcitrance, would improve soil chemical properties in ways that translate into enhanced plant ecophysiological performance, with responses dependent on the applied dose.

Overall, this study advances an integrated and innovative framework that combines the valorization of environmental

liabilities with soil remediation and plant ecophysiological assessment, using native species adapted to environmentally limiting conditions. By aligning waste management with soil restoration and circular economy principles, the findings provide scientific support for the development of sustainable, scalable, and nature-based solutions with relevance at both regional and global scales.

## 2 Materials and Methods

### 2.1 Soil and Organic Residues

The soil was collected in Irauçuba, Ceará, Brazil, in an area affected by degradation/desertification processes, mainly due to overgrazing (Fig. 1). The soil is classified as Planosol (IUSS Working Group WRB 2022). Samples were collected from the 0–0.10 m layer.

After air-drying and homogenization, the soil was sieved through a 4 mm mesh and classified as sandy loam (761, 174, and 65 g kg<sup>-1</sup> of sand, silt, and clay, respectively). Chemical characterization is presented in the supplementary file (Table S1).

The SS was obtained from a domestic wastewater treatment plant in Fortaleza (Ceará, Brazil), using a UASB (Upflow Anaerobic Sludge Blanket) reactor. After discharge and 20 days of drying, a sample was collected for characterization (Table S1).

Biomass from cashew pruning residues (SSCP) was also collected from the same site. The SS and pruning residues were dried, stored, and then mixed at a 1:1 (w/w) ratio. The mixture was characterized (Table S1).

The biochar (BSSCP) was produced via co-pyrolysis of the SS and SSCP (1w/w) in a sealed metallic reactor heated to 500±4.3 °C for 97 min under a moderate nitrogen flow to ensure inert conditions. Biochar physicochemical properties are detailed in Table S1 of Supplementary File 1.

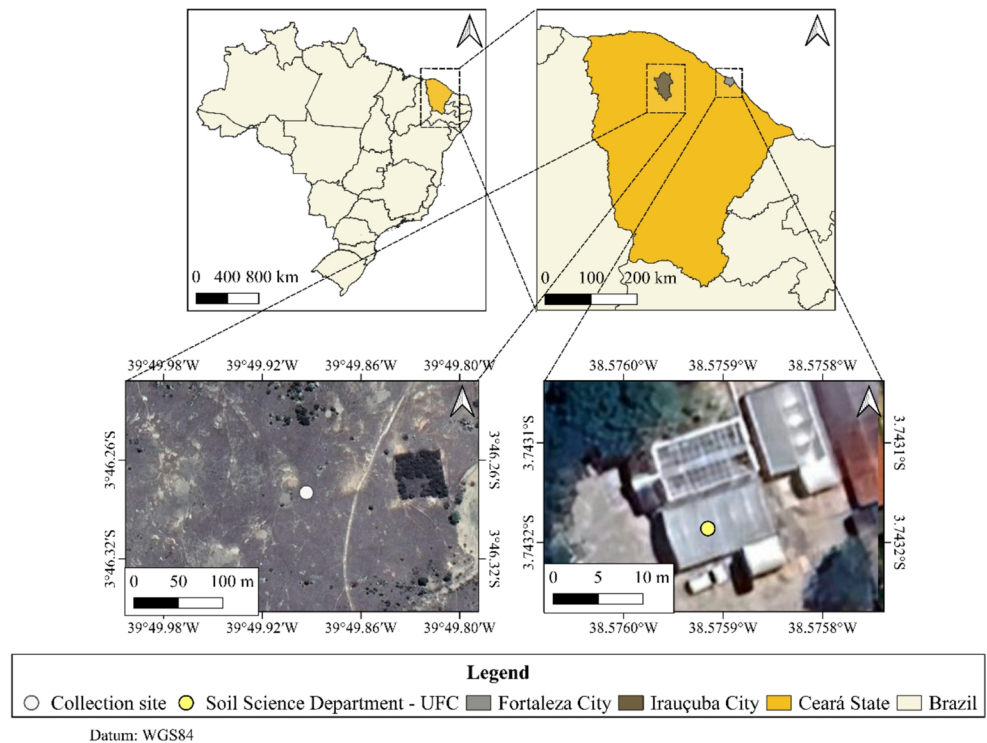
### 2.2 Experimental Design

The experiment was conducted under greenhouse conditions (27–35 °C and ~80% relative humidity) for 76 days at the Federal University of Ceará, Fortaleza, Brazil.

The design was completely randomized in a factorial arrangement (3×4+1). Three organic residue sources were tested: two uncarbonized residues: SS, SSCP, and BSSCP. These residues were applied at four rates, along with a control treatment without any organic residue.

The application rates for BSSCP were 5, 10, 20, and 40 Mg ha<sup>-1</sup>, within the 2% (w w<sup>-1</sup>) limit recommended for biochar soil application (Novotny et al. 2015). Since phosphorus (P) is considered the most limiting nutrient for plant growth

**Fig. 1** Sequence of maps (WGS84) showing Brazil, Ceará State, Fortaleza, and the desertification hotspot of Irauçuba. The white circle marks the overgrazed soil sampling site (0–10 cm, Planosol), and the red circle indicates the Soil Science Department (UFC), Fortaleza. Coordinates are in degrees



(Rehman et al. 2018), the rates of the uncarbonized residues (SS and SSCP) were adjusted to match the P content of BSSCP, resulting in: 10.4, 20.8, 41.5, and 83.1 Mg ha<sup>-1</sup> for SS; and 17.5, 35.1, 70.2, and 140.3 Mg ha<sup>-1</sup> for SSCP. To standardize data presentation, doses were named D1, D2, D3, and D4. No base fertilization was carried out. Each treatment had four replicates, totaling 52 experimental units in 2.2-liter plastic pots. The quantities applied per pot are shown in Supplementary File 1 (Table S2).

Each residue was incorporated into the soil, and the mixture was adjusted to 70% of field capacity with distilled water. The pots were covered with plastic sheeting to avoid evaporation and incubated for 18 days to allow residue-soil interaction. Daily weighing ensures constant moisture by replenishing lost water.

To evaluate the effects of carbonized and non-carbonized residues on plant ecophysiology, the forest species *Mimosa caesalpiniiifolia* Benth. was used within the framework of an alternative strategy for the recovery of degraded soils. The selection of this species was based on its functional and ecological traits, which make it particularly suitable for studies focused on soil quality restoration, as well as on the fact that it is not included in the list of invasive plant species in the state of Ceará, Brazil. This species is a pioneer arboreal legume with rapid growth, adapted to low-fertility soils and to conditions of pronounced water limitation, features commonly associated with degraded environments. Moreover, its presence enhances soil microbiota and nutrient cycling due to its ability to establish symbiotic associations

with both nitrogen-fixing bacteria and arbuscular mycorrhizal fungi (Antas et al. 2024; Garcia et al. 2025). These interactions enhance nutrient uptake, particularly phosphorus, and water acquisition, promoting improvements in soil fertility, structure, and quality over time, while increasing plant resilience in degraded environments.

Moisture control followed the same procedure as during incubation, with daily weighing and water replenishment to maintain 70% field capacity. The first watering occurred at snowing. No additional fertilization was applied.

## 2.3 Plant Analysis

### 2.3.1 Gas exchange and Plant Growth

Gas exchange was measured using an infrared gas analyzer (IRGA, LCI BioScientific). In each pot, one recently expanded leaf was selected for measurements of transpiration rate ( $T_r$ ,  $\mu\text{mol H}_2\text{O m}^{-2} \text{s}^{-1}$ ), photosynthetic rate ( $A_n$ ,  $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$ ), intercellular  $\text{CO}_2$  concentration ( $C_i$ ,  $\mu\text{mol CO}_2 \text{mol}^{-1}$ ), and stomatal conductance ( $g_s$ ,  $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$ ). Readings were taken between 9:00 and 11:00 a.m., under artificial light in  $1800 \mu\text{mol m}^{-2} \text{s}^{-1}$ .

Water use efficiency and carboxylation efficiency were calculated based on gas exchange parameters as follows: water use efficiency (WUE), expressed as the ratio between net  $\text{CO}_2$  assimilation rate ( $A$ ) and transpiration rate ( $T_r$ ) ( $A/T_r$ ); intrinsic water use efficiency (iWUE), calculated as the ratio between net  $\text{CO}_2$  assimilation rate ( $A$ ) and

stomatal conductance (gs) (A/g<sub>s</sub>); and instantaneous carboxylation efficiency (EiC), determined as the ratio between net CO<sub>2</sub> assimilation rate (A) and internal CO<sub>2</sub> concentration (C<sub>i</sub>) (A/C<sub>i</sub>).

Total chlorophyll content was measured on the same leaves using a SPAD chlorophyll meter (SPAD 502, Minolta Co., Ltd., Osaka, Japan), based on the average of three readings per plant. At the end of the experiment, plant height (Ph) and stem diameter (SD) were determined using a measuring tape and a digital caliper, respectively.

Plants were then separated into shoots and roots. Leaf area was measured with an area meter (LI-3100, Li-Cor Inc., Lincoln, NE, USA). Roots were separated using a 2 mm mesh sieve, washed with tap and distilled water.

All plant parts were weighed and oven-dried at 65 °C to constant weight. Shoot dry mass (SDM), root dry mass (RDM), and total dry mass (TDM) were recorded.

Allometric ratios were calculated as the proportion of biomass allocated to each part: SAR (shoot allocation ratio) = shoot/TDM; RAR (root allocation ratio) = root/TDM.

## 2.4 Soil Chemical Attributes

To evaluate changes in soil chemical properties resulting from residue addition, pH and electrical conductivity (EC) were measured in 1:2.5 and 1:1 soil: water ratios using appropriate probes.

Total organic carbon (TOC) was measured by acid dichromate digestion followed by titration with ferrous ammonium sulfate (Mendonça and Matos 2017). Total nitrogen (N) was determined according to Raij et al. (2001), involving sulfuric acid extraction, Kjeldahl distillation with sodium hydroxide, and boric acid titration. P, K, Ca, and Mg were extracted using Mehlich-1 solution. P was quantified by the molybdovanadophosphoric acid method, Ca and Mg by atomic absorption spectrophotometry, and K by flame photometry.

## 2.5 Data Analysis

Data were tested for normality using the Shapiro-Wilk test and for homogeneity of variances using the Bartlett test. When normality was not met, Box-Cox transformation was applied. SAS® OnDemand for Academics was used. ANOVA (F test) and mean comparison tests were then conducted: Tukey for qualitative factors (residue type) and Dunnett for comparing treatments with the control, both at 5% significance ( $p < 0.05$ ). For quantitative factors (residue doses), linear and quadratic regression analyses were performed. The best-fitting model was selected based on R<sup>2</sup> and significance. All analyses were conducted in R using RStudio with the packages Tratamentos.ad (mean comparisons) and ExpDes.pt (regression analysis).

## 3 Results

The internal CO<sub>2</sub> concentration (C<sub>i</sub>), photosynthetic rate (A<sub>r</sub>), water use efficiency (WUE), intrinsic water use efficiency (iWUE), instantaneous carboxylation efficiency (EiC), and SPAD index responded to the interaction between organic residues (OR) and dose (D) (Fig. 2; Table S2). Stomatal conductance (gs) and transpiration (Tr) varied independently with OR and D (Table S3).

The internal CO<sub>2</sub> concentration (C<sub>i</sub>) was statistically similar at doses D1 and D2 for all organic residues (Fig. 2a). However, at dose D4, the organic residues resulted in a significant difference in mean, with the treatment containing BSSCP showing the highest intracellular CO<sub>2</sub> concentration compared to SS and SSCP (Fig. 2a).

Plants grown in soil amended with BSSCP at doses D1 and D2, especially at D2, maintained a higher photosynthetic rate (A<sub>n</sub>) (Fig. 2b). On average, the A value increased by 82–102% at D1 and 294–391% at D2 compared to SSCP. This advantage declined at D3 and D4 (Fig. 2b).

Regarding the SPAD index, it was observed that, except at D2, significant differences between organic residues were observed (Fig. 2c).

At D1, the BSSCP treatment resulted in the highest total chlorophyll content. At D3 and D4, SSCP stood out, with an 83% increase at D4 compared to BSSCP, which had the lowest mean value (Fig. 2c). WUE was highest for BSSCP at D2 (10 Mg/ha). However, increasing the dose to 20 and 40 Mg ha<sup>-1</sup> (D3 and D4) resulted in reductions of 1.8 and 2.6 times compared to SSCP and SS, respectively (Fig. 2d). A similar pattern was observed for EiC at dose treatments D1 and D2, where BSSCP showed higher values than other residues and the control (Fig. 2e).

The addition of SS and SSCP – residues not thermally treated, especially at D3, resulted in higher iWUE means, surpassing the BSSCP values (Fig. 2f). At dose D4, SSCP produced the highest means. The increases compared to the control were 57% for SSCP, 52% for SS, and 116% for BSSCP (Fig. 2f).

The interactions for C<sub>i</sub>, A<sub>n</sub>, and SPAD were described by quadratic models (Table 1). SSCP at D3/D4 had the lowest C<sub>i</sub>, with reductions of 4–9% from the maximum.

Although the highest dose of BSSCP increased the internal mesophyll CO<sub>2</sub> concentration compared to the other treatments (Fig. 2a), the mean data did not fit well to linear or quadratic models, which also applied to SS (Table 1).

Regression models for plant photosynthetic rate indicated a decrease in A with increasing dose treatments for SSCP and SS. For SSCP, the minimum rate was 1.7 μmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup> at a dose of 1.6 (28.4 Mg ha<sup>-1</sup>), while for SS, the minimum was 1.9 μmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup> at a dose of 1.3 (14.32 Mg ha<sup>-1</sup>). In contrast, BSSCP showed a parabolic

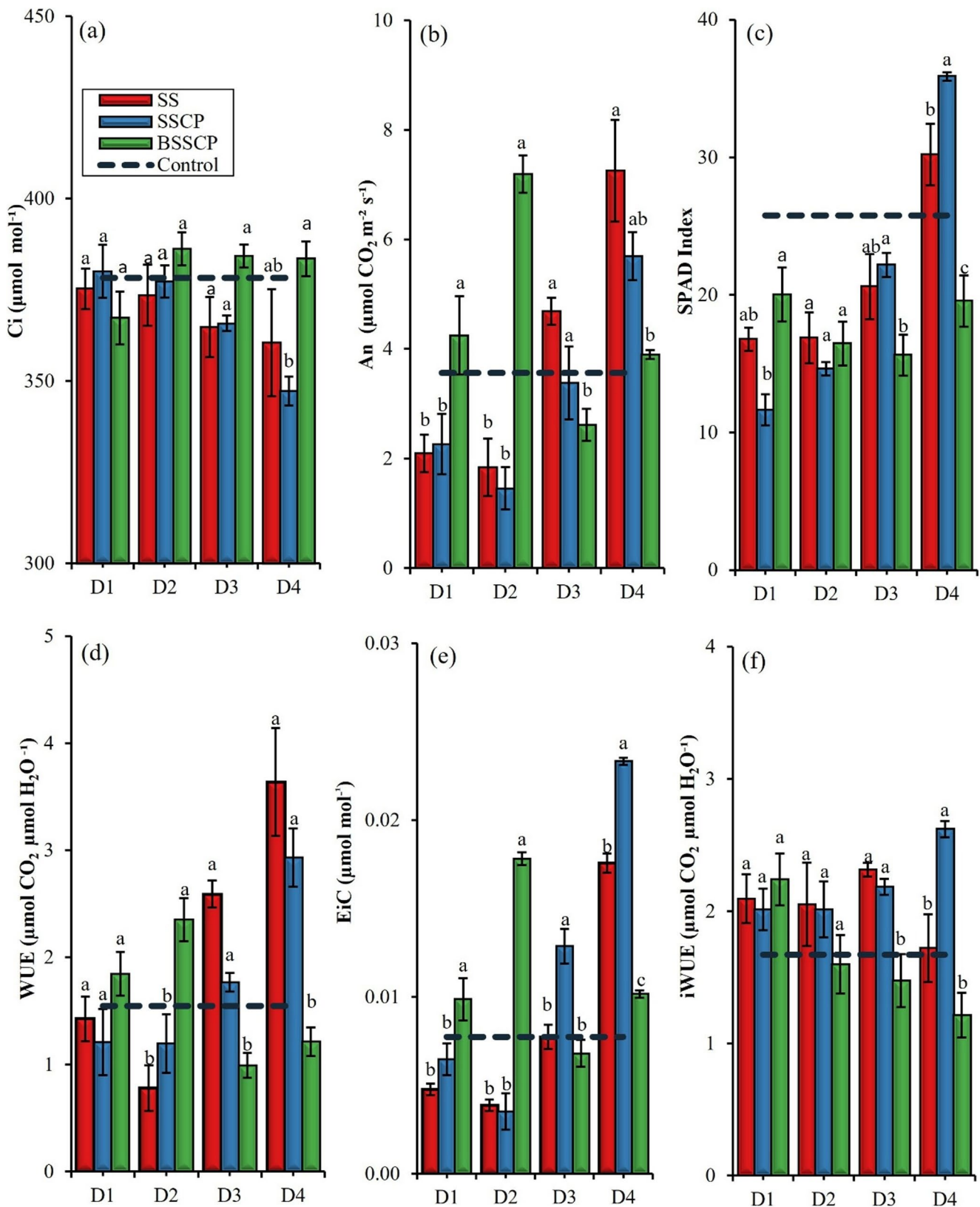


**Fig. 2** Gas exchange parameters: internal CO<sub>2</sub> concentration (a), photosynthetic rate (b), SPAD index (c), instantaneous water use efficiency (d), instantaneous carboxylation efficiency (e), and intrinsic water use efficiency (f). D1 to D4 correspond to the applied doses of organic residues:

sewage sludge – SS: 10.4, 20.8, 41.5, 83.1 Mg ha<sup>-1</sup>; sewage sludge with cashew pruning – SSCP: 17.5, 35.1, 70.2, 140.3 Mg ha<sup>-1</sup>; and biochar from sewage sludge with added cashew pruning – BSSCP: 5; 10; 20; 40 Mg ha<sup>-1</sup>. Lowercase letters indicate significant differences ( $p < 0.05$ )

**Table 1** Regression models adjusted for the relationship between ecophysiological parameters and application rates of organic residues (OR): sewage sludge (SS), a mixture of sewage sludge and cashew pruning residues (SSCP), and the co-pyrolysis-derived biochar from this mixture (BSSCP). The evaluated parameters included intercellular CO<sub>2</sub> concentration (Ci), net photosynthetic rate (An), SPAD index, water use efficiency (WUE), instantaneous carboxylation efficiency (EiC), and intrinsic water use efficiency (iWUE)

| Variable   | OR    | Models    | Equation <sup>(1)</sup>                | R <sup>2</sup><br>(%) | P-value |
|------------|-------|-----------|----------------------------------------|-----------------------|---------|
| Ci         | SS    | Ns        | -                                      | -                     | -       |
|            | SSCP  | Quadratic | $\hat{Y} = -3.52x^2 + 6.45x + 377.9$   | 99                    | <0.0001 |
|            | BSSCP | ns        | -                                      | -                     | -       |
| An         | SS    | Quadratic | $\hat{Y} = 0.79x^2 - 2.20x + 3.49$     | 97                    | <0.0001 |
|            | SSCP  | Quadratic | $\hat{Y} = 0.71x^2 - 2.31x + 3.62$     | 97                    | <0.0001 |
|            | BSSCP | Quadratic | $\hat{Y} = -0.45x^2 + 1.71x + 3.6$     | 25                    | <0.0001 |
| SPAD Index | SS    | Quadratic | $\hat{Y} = 2.92x^2 - 10.39x + 25.34$   | 99                    | <0.0001 |
|            | SSCP  | Quadratic | $\hat{Y} = 4.3x^2 - 14.11x + 24.47$    | 96                    | <0.0001 |
|            | BSSCP | Quadratic | $\hat{Y} = 1.58x^2 - 8.0x + 26.01$     | 99                    | <0.0001 |
| WUE        | SS    | Quadratic | $\hat{Y} = 0.34x^2 - 0.84x + 1.61$     | 89                    | <0.0001 |
|            | SSCP  | Quadratic | $\hat{Y} = 0.26x^2 - 0.69x + 1.58$     | 100                   | <0.0001 |
|            | BSSCP | Quadratic | $\hat{Y} = -0.14x^2 + 0.42x + 1.61$    | 45                    | <0.0001 |
| EiC        | SS    | Quadratic | $\hat{Y} = 0.002x^2 - 0.006x + 0.008$  | 96                    | <0.0001 |
|            | SSCP  | Quadratic | $\hat{Y} = 0.002x^2 - 0.006x + 0.008$  | 99                    | <0.0001 |
|            | BSSCP | Quadratic | $\hat{Y} = -0.001x^2 + 0.004x + 0.007$ | 26                    | <0.0001 |
| iWUE       | SS    | ns        | -                                      | -                     | -       |
|            | SSCP  | Linear    | $\hat{Y} = 0.21x + 1.69$               | 90                    | <0.0001 |
|            | BSSCP | Linear    | $\hat{Y} = -0.17x + 1.98$              | 49                    | <0.0001 |

<sup>(1)</sup> $\hat{Y}$ : Responses (%) estimated by the models for each organic residue. The gs data were transformed using  $x^{-0.2}$ . (\*) (\*\*) Angular coefficient (linear regression) or dominant coefficient (quadratic regression) significant at 1 and 5% probability, (ns) not significant

relationship with a dominant coefficient  $a < 0$ , reaching a maximum at a dose of 1.9 (9.5 Mg ha<sup>-1</sup>) (Table 1).

The SPAD index for SSCP and SS showed a decreasing quadratic pattern (Table 1). In contrast, BSSCP fits a quadratic model with a dominant coefficient  $a > 0$  (Table 1), differing from the regression model for BSSCP in photosynthesis (An), which showed  $a < 0$  (Table 1).

For gs, the isolated effect of dose fit well to a quadratic regression model ( $\hat{Y} = -0.05x^2 + 0.17x + 1.13$ ;  $R^2 = 0.80$ ;  $P < 0.001$ ), with the maximum dose estimated at 1.8,

equivalent to 32, 19, and 9 Mg ha<sup>-1</sup> for SSCP, SS, and BSSCP, respectively, corresponding to a stomatal conductance of 1.3  $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ . For E, the regression equation was ( $\hat{Y} = 0.125x^2 - 0.404x + 2.246$ ;  $R^2 = 0.84$ ;  $P < 0.001$ ), indicating the highest transpiration rate occurred at dose treatment 2, peaking at 2.66  $\mu\text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}$  at dose 4 (40, 83.1, and 140.3 Mg ha<sup>-1</sup> for SSCP, SS, and BSSCP, respectively), 16% higher than at dose 0.

WUE and EiC showed quadratic relationships in response to organic residue doses (Table 1). For WUE, increasing SSCP and SS in the soil resulted in a significant dominant coefficient  $a > 0$  (Table 1), with gains observed only at higher doses. For BSSCP, the generated regression equation indicated that maximum carbon assimilation per transpired water was 1.91 at a dose of 1.46 (7.3 Mg ha<sup>-1</sup>), with a sharp reduction beyond that.

For EiC, SSCP, and SS showed quadratic responses (Table 1) with minima at intermediate doses. BSSCP explained only 26% of the variation.

There was significant interaction between organic residues and applied dose treatments for all analyzed variables (Table S3, Fig. S3, 4, and 5). The greatest plant height (Ph) was observed in SSCP and LE, with values higher than the control (Fig. 3a).

Stem diameter growth (SD) was greater with SSCP and SS at D1, D2, and D3, exceeding the control and BSSCP by an average of 20% (Fig. 3b). At D4, only SSCP resulted in a significant diameter increase.

Leaf area (LA) of plants was greater with SS at dose treatments D1, D2, and D3, especially at D3 (4366 cm<sup>2</sup>) (Fig. 3c). At D4, only SSCP sustained the increase, with a leaf area four times greater than the control. Although BSSCP did not significantly differ from the control, it resulted in the lowest leaf area growth compared to SSCP and SS across all doses (Fig. 3c).

The interaction between organic residues and applied doses on total dry mass, shoot dry mass, and root dry mass (TDM, SDM, RDM) (Fig. 4) revealed that B-LP did not significantly increase biomass production, showing results like the control. SDM and RDM were lower in B-LP than LE and LP at all doses. At D4, SDM with LP was four times higher than with B-LP, and RDM was twice as high (Fig. 4b, c).

The allocation of biomass to shoots and roots (Shoot Allocation Ratio – SAR and Root Allocation Ratio – RAR) varied significantly in plants treated with SSCP and SS at dose treatments D2, D3, and D4 (Fig. 5). Plants grown in soil amended with SSCP and SS allocated more resources to the shoot biomass (leaves and petioles) (Fig. 4a). In contrast, RMR was lower with SSCP and SS compared to BSSCP and the control, especially at doses D3 and D4 (Fig. 5b). At dose D4, RMR decreased by 51% and 44% for SSCP and by 42% and 34% for SS, compared to BSSCP and the control, respectively.

**Fig. 3** Plant height (a), stem diameter (b), leaf area (c). D1 to D4 correspond to the applied doses of organic residues: sewage sludge – SS: 10.4, 20.8, 41.5, 83.1 Mg ha<sup>-1</sup>; sewage sludge with cashew pruning – SSCP: 17.5, 35.1, 70.2, 140.3 Mg ha<sup>-1</sup>; and biochar from sewage sludge with added cashew pruning – BSSCP: 5; 10; 20; 40 Mg ha<sup>-1</sup>. Lowercase letters indicate significant differences ( $p < 0.05$ )

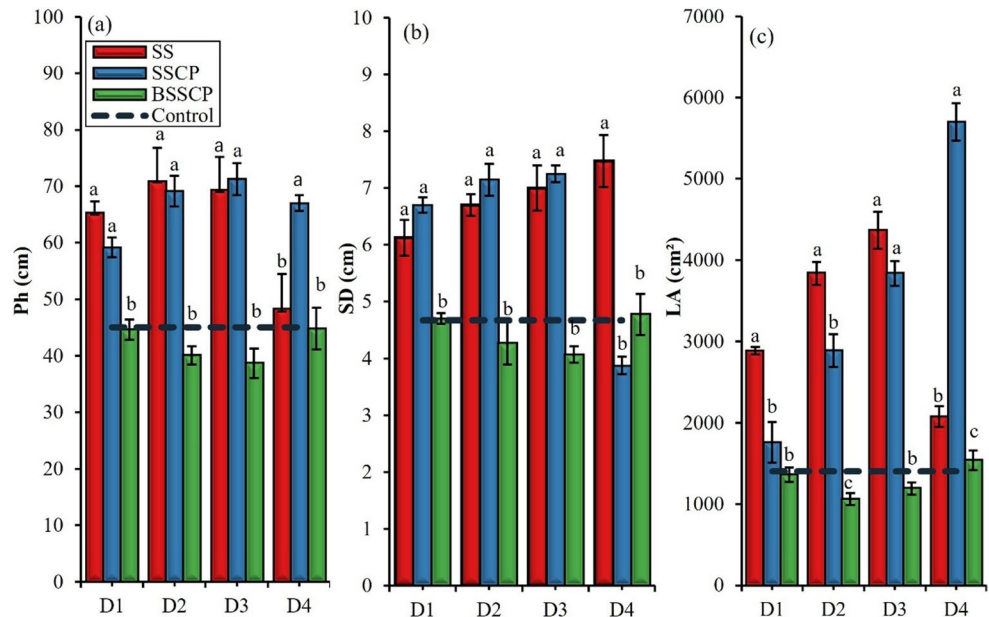
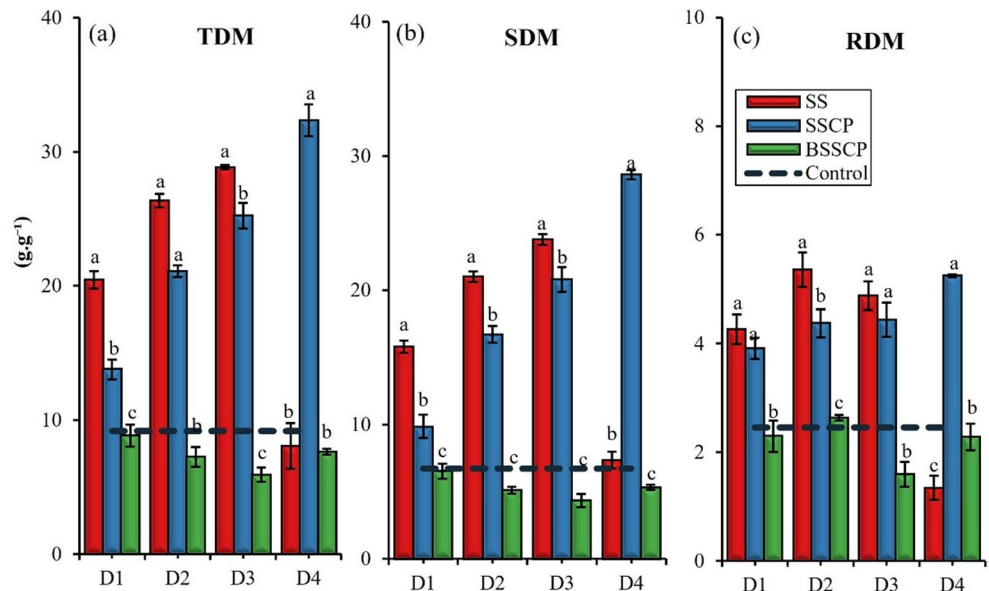


**Fig. 4** Total dry mass (a), dry mass of aerial part (b), dry mass of roots (c). D1 to D4 correspond to the applied doses of organic residues: sewage sludge – SS: 10.4, 20.8, 41.5, 83.1 Mg ha<sup>-1</sup>; sewage sludge with cashew pruning – SSCP: 17.5, 35.1, 70.2, 140.3 Mg ha<sup>-1</sup>; and biochar from sewage sludge with added cashew pruning – BSSCP: 5; 10; 20; 40 Mg ha<sup>-1</sup>. Lowercase letters indicate significant differences ( $p < 0.05$ )



Plant height (Ph) and stem diameter (SD) showed significant fits to second-order polynomial regression models with dominant coefficients ( $a < 0$ ) for SSCP and SS (Table 2). The maximum values for height were 71 and 72 cm for SSCP and SS, respectively, while SD reached 7.4 cm for SSCP and 7.5 cm for SS.

Leaf area (LA) responded to SS and SSCP doses following a quadratic polynomial model (Table 2). For SSCP, the positive correlation ( $a > 0$ ) resulted in a minimum leaf area of 1,304 cm<sup>2</sup> at dose 0.64 (11.2 Mg ha<sup>-1</sup>). For SS, the negative correlation ( $a < 0$ ) indicated a significant increase, reaching a maximum of 4,087 cm<sup>2</sup> at dose 2.25 (26 Mg ha<sup>-1</sup>). No significant correlation or regression model was observed for BSSCP (Table 2).

Total shoot biomass (TSB) increased linearly with increasing SSCP doses (Table 2). In contrast, BSSCP showed a decreasing linear response, with reductions of 16% in TSB and 21% in shoot dry mass (SDM) from the highest to the lowest dose (Table 2). For SS, TSB peaked at 22.6 g at dose 2.1 (22.1 Mg ha<sup>-1</sup>), with no further increases at higher doses. Root dry mass (RDM) followed a similar pattern, reaching a maximum of 5.4 g at dose 2 (20.8 Mg ha<sup>-1</sup>), as estimated by the model (Table 2). SSCP and SS doses increased SMR linearly, with 16% and 13% gains at D4. RMR decreased, showing lower root allocation at higher doses.

Soil chemical attributes and nutrient content at the end of the experiment varied according to the interaction between organic residues and dose treatments (Figs. 6 and 7, and

**Fig. 5** Shoot allocation ratio (SAR) and Root allocation ratio (RAR). D1 to D4 correspond to the applied doses of organic residues: sewage sludge – SS: 10.4, 20.8, 41.5, 83.1 Mg ha<sup>-1</sup>; sewage sludge with cashew pruning – SSCP: 17.5, 35.1, 70.2, 140.3 Mg ha<sup>-1</sup>; and biochar from sewage sludge with added cashew pruning – BSSCP: 5; 10; 20; 40 Mg ha<sup>-1</sup>. Lowercase letters indicate significant differences ( $p < 0.05$ )

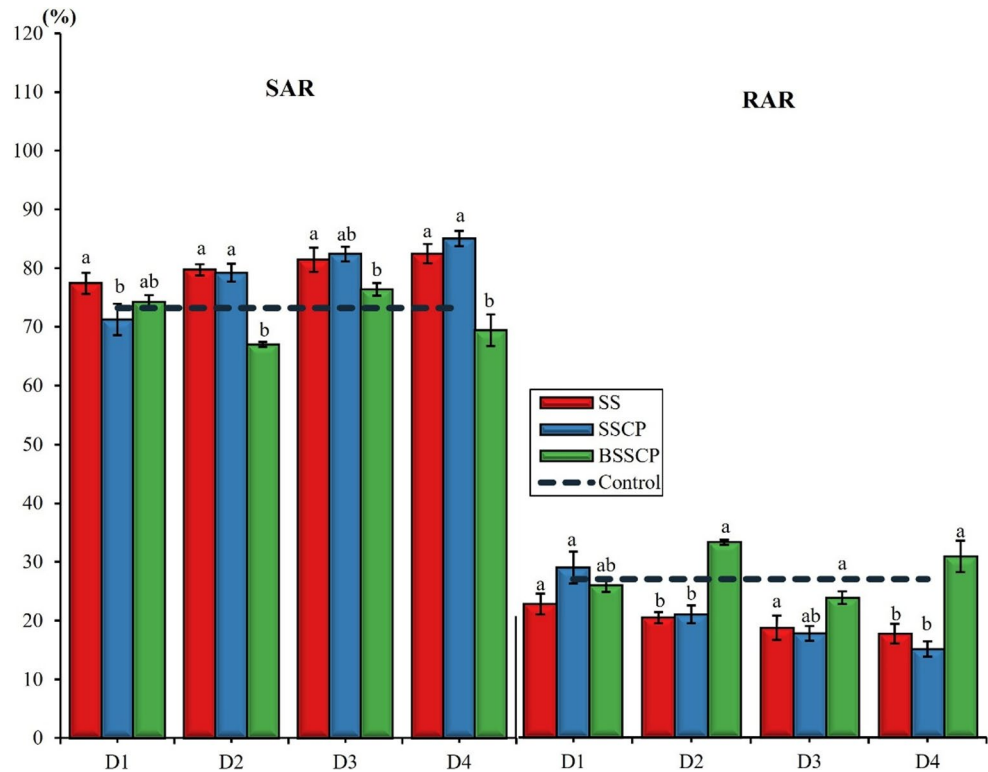


Table S2). Soil pH was highest in the BSSCP treatment, surpassing SSCP, SS, and the control across all doses, with BSSCP reaching 5.5 at the highest dose, 20.5% higher than the control (Fig. 6a). Electrical conductivity (EC) varied among residues, with BSSCP showing the lowest doses (Fig. 5b). At doses D1 and D2, SSCP had higher EC than SS, while at D3 and D4, SS surpassed SSCP, particularly in D4 with 7.34 dS m<sup>-1</sup> – 2, 10, and 23 times higher than SSCP, BSSCP, and the control, respectively (Fig. 6b).

Soil organic carbon (SOC) did not vary in D1 and D2, but in D3 and D4, SSCP application increased it by 1.7 times compared to other treatments (Fig. 7a). Total nitrogen (N) was lower with BSSCP at all doses, while SSCP and SS did not differ but had mean values twice as high as the control at doses 3 and 4 (Fig. 6b).

Regarding phosphorus (P), SS treatment at dose D1 (10.4 Mg ha<sup>-1</sup>) did not exceed the means of SSCP, BSSCP, and the control (Fig. 7c). However, at doses D2 and D3, SS outperformed SSCP, and at D4, SS stood out with values 1.2 times higher than SSCP and BSSCP, and 8 times higher than the control (Fig. 7c).

Soil potassium (K) levels were similar between BSSCP and SS in D1 and D2 treatments, both higher than the control (Fig. 7d). In D3 and D4, although SS remained higher than the control, it was lower than BSSCP. For SSCP, dose D4 (140.3 Mg ha<sup>-1</sup>) resulted in an average increase of 71% in K to the control (Fig. 7d).

Calcium (Ca) was higher in soil amended with BSSCP in D2, D3, and D4, peaking at D4 (40 Mg ha<sup>-1</sup>) with a mean of 2.85 cmol<sub>c</sub> kg<sup>-1</sup> (Fig. 7e). In contrast, LE at D4 decreased soil Ca content at the end of cultivation (Fig. 7e). For magnesium (Mg), at doses D1 and D2, the mean order was control > SSCP > SS > BSSCP. At D3, the order was SSCP > control > LE > BSSCP. In D4, SS had the highest Mg content in the soil (4.5 cmol<sub>c</sub> kg<sup>-1</sup>), approximately twice the other treatments and the control (Fig. 7f).

Soil property responses to organic residue doses followed quadratic patterns for all variables, except for pH and Ca when SS was applied (Table 3).

Soil pH in response to BSSCP showed a negative dominant coefficient ( $a < 0$ ), with a maximum value of 5.2 at dose 4 (20 Mg ha<sup>-1</sup>), representing a 20.5% increase over the control (dose 0). In contrast, for SS, pH followed a decreasing quadratic pattern, with a minimum estimated value of 4.1 at dose 2.3 (26.7 Mg ha<sup>-1</sup>). For SSCP, the negative linear coefficient ( $a < 0$ ) indicated pH decreased as the dose increased.

Electrical conductivity (EC) showed a positive dominant coefficient ( $a > 0$ ) for all tested residues, with significant increases from dose 3 onwards, after a slight decline at lower doses (Table 3).

For Total organic carbon (TOC), SSCP followed a quadratic model with a positive coefficient ( $a > 0$ ), reaching a minimum estimated value of 5.5 g kg<sup>-1</sup> at dose 0.1 (1.3 Mg ha<sup>-1</sup>). For LE and BSSCP, the TOC relationship was linear

**Table 2** Regression models adjusted for the relationship between plant growth variables and application rates of organic residues (OR): sewage sludge (SS), a mixture of sewage sludge and cashew pruning residues (SSCP), and the co-pyrolysis-derived biochar from this mixture (BSSCP). The evaluated variables included plant height (Ph), stem diameter (SD), leaf area (LA), shoot dry mass (SDM), root dry mass (RDM), total dry mass (TDM), and allometric indices (shoot-to-total dry mass ratio and root allocation ratio – RAR)

| Variable | OR    | Models    | Equation <sup>(1)</sup>                         | R <sup>2</sup> (%) | P-value |
|----------|-------|-----------|-------------------------------------------------|--------------------|---------|
| Ph       | SS    | Quadratic | $\hat{Y} = -6.41^{**}x^2 + 26.68x + 44.87$      | 99                 | <0.0001 |
|          | SSCP  | Quadratic | $\hat{Y} = -3.18^{**}x^2 + 18.30x + 44.77$      | 99                 | <0.0001 |
|          | BSSCP | ns        | -                                               | -                  | -       |
| SD       | SS    | Quadratic | $\hat{Y} = -0.80^{**}x^2 + 3.08x + 4.55$        | 93                 | <0.0001 |
|          | SSCP  | Quadratic | $\hat{Y} = -0.16^{**}x^2 + 1.28x + 4.78$        | 98                 | 0.0287  |
|          | BSSCP | ns        | -                                               | -                  | -       |
| LA       | SS    | Quadratic | $\hat{Y} = -569.3^{**}x^2 + 2559.50x + 1210.30$ | 90                 | <0.0001 |
|          | SSCP  | Quadratic | $\hat{Y} = 201.9^{**}x^2 + 259x + 1387.50$      | 99                 | <0.0001 |
|          | BSSCP | ns        | -                                               | -                  | -       |
| SDM      | SS    | Quadratic | $\hat{Y} = -3.81^{**}x^2 + 16.18x + 5.45$       | 88                 | <0.0001 |
|          | SSCP  | Quadratic | $\hat{Y} = 0.46^{**}x^2 + 3.62x + 6.53$         | 99                 | <0.0001 |
|          | BSSCP | Linear    | $\hat{Y} = -0.50^{**}x + 6.60$                  | 61                 | <0.0001 |
| RDM      | SS    | Quadratic | $\hat{Y} = -0.87^{**}x^2 + 3.34x + 2.23$        | 95                 | <0.0001 |
|          | SSCP  | Quadratic | $\hat{Y} = -0.12^{**}x^2 + 1.10x + 2.62$        | 93                 | 0.0459  |
|          | BSSCP | ns        | -                                               | -                  | -       |
| TDM      | SS    | Quadratic | $\hat{Y} = -4.824^{**}x^2 + 19.91^{**}x + 7.69$ | 89                 | <0.0001 |
|          | SSCP  | Linear    | $\hat{Y} = 5.78^{**}x + 8.76$                   | 99                 | <0.0001 |
|          | BSSCP | Linear    | $\hat{Y} = 0.60^{**}x + 8.95$                   | 53                 | 0.0190  |
| SAR      | SS    | Linear    | $\hat{Y} = 2.25^{**}x + 74.34$                  | 93                 | <0.0001 |
|          | SSCP  | Linear    | $\hat{Y} = 3.48^{**}x + 71.25$                  | 87                 | <0.0001 |
|          | BSSCP | ns        | -                                               | -                  | -       |
| RAR      | SS    | Linear    | $\hat{Y} = -2.25^{**}x + 25.66$                 | 93                 | <0.0001 |
|          | SSCP  | Linear    | $\hat{Y} = -3.48^{**}x + 28.74$                 | 87                 | <0.0001 |
|          | BSSCP | ns        | -                                               | -                  | -       |

<sup>(1)</sup> $\hat{Y}$ : Responses (%) estimated by the models for each organic residue. (\*) (\*\*) Angular coefficient (linear regression) or dominant coefficient (quadratic regression) significant at 1 and 5% probability, (ns) not significant

**Fig. 6** pH (a), electrical conductivity – EC (b). D1 to D4 correspond to the applied doses of organic residues: sewage sludge – SS: 10.4, 20.8, 41.5, 83.1 Mg ha<sup>-1</sup>; sewage sludge with cashew pruning – SSCP: 17.5, 35.1, 70.2, 140.3 Mg ha<sup>-1</sup>; and biochar from sewage sludge with added cashew pruning – BSSCP: 5; 10; 20; 40 Mg ha<sup>-1</sup>. Lowercase letters indicate significant differences ( $p < 0.05$ )

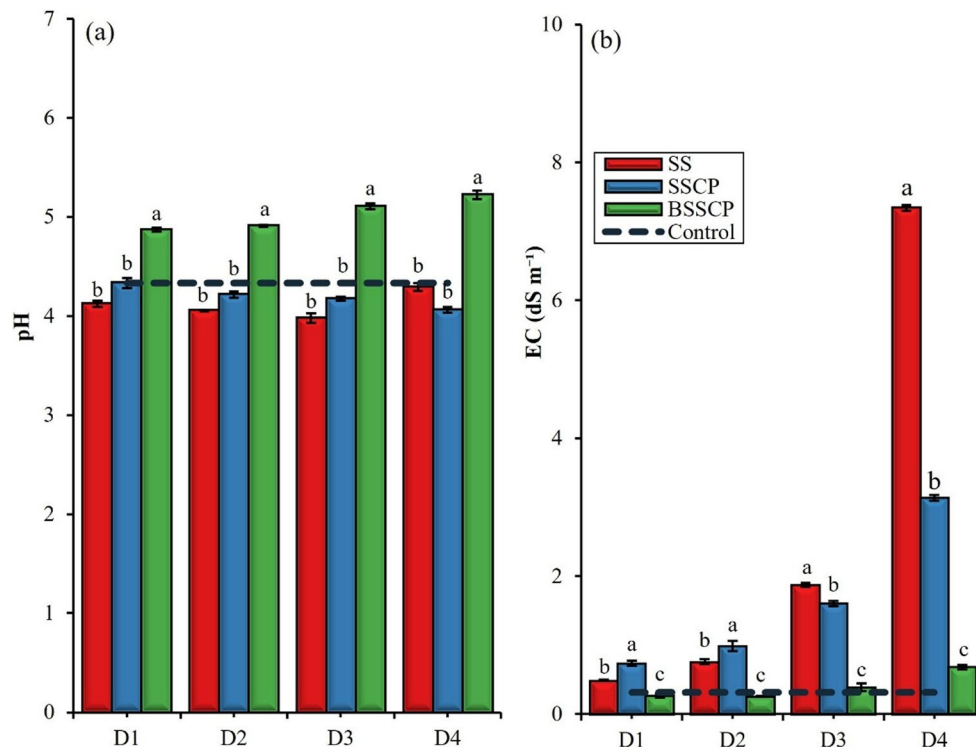
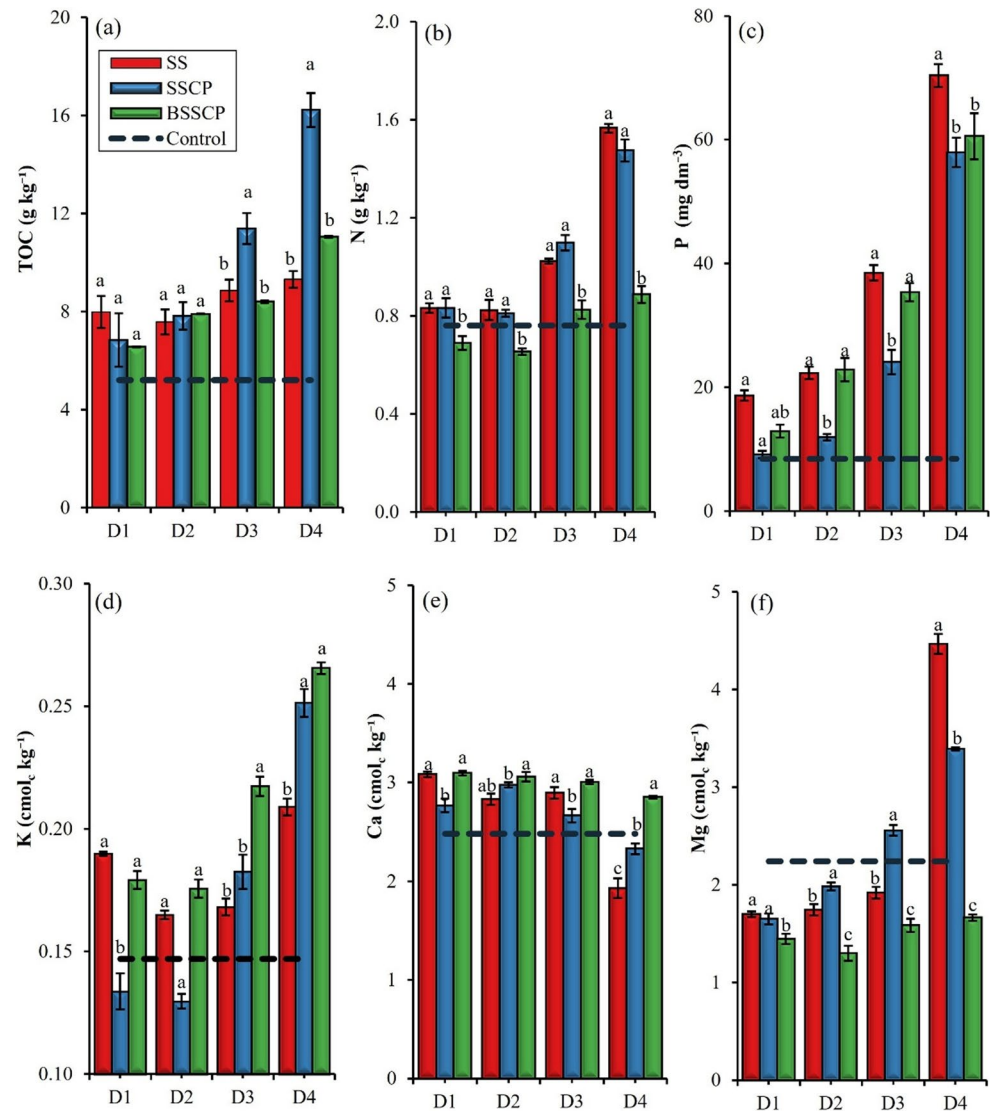


**Fig. 7** Total organic carbon (a), total nitrogen (b), available phosphorus (c), potassium (d), calcium (e) and magnesium (f). D1 to D4 correspond to the applied doses of organic residues: sewage sludge – SS: 10.4, 20.8, 41.5, 83.1 Mg ha<sup>-1</sup>; sewage sludge with cashew pruning – SSCP: 17.5, 35.1, 70.2, 140.3 Mg ha<sup>-1</sup>; and biochar from sewage sludge with added cashew pruning – BSSCP: 5; 10; 20; 40 Mg ha<sup>-1</sup>. Lowercase letters indicate significant differences ( $p < 0.05$ )



and positive, indicating an increase with higher doses — 79% for SS and 112% for BSSCP.

At the end of the experiment, soil nutrient responses (P, N, and Mg) followed a quadratic model with positive dominant coefficients ( $a > 0$ ), indicating a decline in nutrient addition rates until doses 2 and 3, followed by an increase at dose 4. The same pattern was observed for K in SSCP and BSSCP, while in SS the response was linear and positive, with a significant linear coefficient ( $a > 0$ ), indicating increased soil K with increasing doses. K at dose 4 was 42% higher than in the control.

Soil Ca responses were unimodal, with a positive dominant coefficient, showing peaks at doses 2–3 for all tested residues; higher doses did not further increase Ca content. Notably, the dose–response patterns for Ca and Mg were distinct, with increased Ca at higher doses being associated with reduced Mg.

## 4 Discussion

The application of sewage sludge–derived co-pyrolysis biochar (BSSCP) promoted marked physiological responses in *Mimosa caesalpinifolia* Bent, particularly at low to intermediate doses, highlighting its potential as a soil conditioner for degraded environments. At doses D1 and D2 (5 and 10 Mg ha<sup>-1</sup>), the increase in net photosynthetic rate ( $A_n$ ) and water use efficiency (WUE) indicates a significant improvement in soil–plant interactions. Greater soil water availability enhances root water uptake and, consequently, contributes to maintaining the hydraulic force required for the CO<sub>2</sub> diffusion gradient between the stomata and the atmosphere (Mao et al. 2024).

These responses are consistent with the porous structure and high surface area of biochar, characteristics that increase soil water retention and root water uptake

**Table 3** Regression models adjusted for the relationship between soil properties and organic residue (OR) dosages: sewage sludge (SS); mixture of SE and cashew pruning (SSCP), and biochar from the co-pyrolysis of the mixture (BSSCP)

| Variable | OR | Models          | Equation (1)                              | R <sup>2</sup><br>(%) | P-value |
|----------|----|-----------------|-------------------------------------------|-----------------------|---------|
| pH       | SS | Quadratic       | $\hat{Y} = 0.07^{**}x^2 - 0.32x + 4.35$   | 89                    | <0.0001 |
|          |    | SSCP Linear     | $\hat{Y} = -0.08^{**}x + 4.32$            | 98                    | <0.0001 |
|          |    | BSSCP Quadratic | $\hat{Y} = -0.05^{**}x^2 + 0.40x + 4.39$  | 94                    | <0.0001 |
| EC       | SS | Quadratic       | $\hat{Y} = 0.82^{**}x^2 - 1.72x + 0.70$   | 95                    | <0.0001 |
|          |    | SSCP Quadratic  | $\hat{Y} = 0.18^{**}x^2 - 0.09x + 0.42$   | 98                    | <0.0001 |
|          |    | BSSCP Quadratic | $\hat{Y} = 0.06^{**}x^2 - 0.15x + 0.33$   | 99                    | <0.0001 |
| TOC      | SS | Linear          | $\hat{Y} = 0.91^{**}x + 6.0$              | 81                    | <0.0001 |
|          |    | SSCP Quadratic  | $\hat{Y} = 0.64^{**}x^2 + 0.01x + 5.50$   | 99                    | <0.0001 |
|          |    | BSSCP Linear    | $\hat{Y} = 1.40^{**}x + 5.10$             | 95                    | <0.0001 |
| N        | SS | Quadratic       | $\hat{Y} = 0.08^{**}x^2 - 0.15x + 0.80$   | 96                    | <0.0001 |
|          |    | SSCP Quadratic  | $\hat{Y} = 0.07^{**}x^2 - 0.09x + 0.79$   | 98                    | <0.0001 |
|          |    | BSSCP Quadratic | $\hat{Y} = 0.03^{**}x^2 - 0.10x + 0.75$   | 85                    | <0.0001 |
| P        | SS | Quadratic       | $\hat{Y} = 3.98^{**}x^2 - 1.54x + 10.85$  | 98                    | <0.0001 |
|          |    | SSCP Quadratic  | $\hat{Y} = 5.40^{**}x^2 - 10.21x + 10.28$ | 98                    | <0.0001 |
|          |    | BSSCP Quadratic | $\hat{Y} = 3.14^{**}x^2 + 0.11x + 8.93$   | 99                    | <0.0001 |
| K        | SS | Linear          | $\hat{Y} = 0.01^{**}x + 0.16$             | 45                    | <0.0001 |
|          |    | SSCP Quadratic  | $\hat{Y} = 0.02^{**}x^2 - 0.04x + 0.15$   | 99                    | <0.0001 |
|          |    | BSSCP Quadratic | $\hat{Y} = 0.01^{**}x^2 + 0.01x + 0.15$   | 95                    | <0.0001 |
| Ca       | SS | Quadratic       | $\hat{Y} = -0.20^{**}x^2 + 0.68x + 2.50$  | 89                    | <0.0001 |
|          |    | SSCP Quadratic  | $\hat{Y} = -0.12^{**}x^2 + 0.46x + 2.47$  | 95                    | <0.0001 |
|          |    | BSSCP Quadratic | $\hat{Y} = -0.11^{**}x^2 + 0.51x + 2.55$  | 85                    | <0.0001 |
| Mg       | SS | Quadratic       | $\hat{Y} = 0.45^{**}x^2 - 1.33x + 2.38$   | 92                    | <0.0001 |
|          |    | SSCP Quadratic  | $\hat{Y} = 0.22^{**}x^2 - 0.56x + 2.16$   | 97                    | <0.0001 |
|          |    | BSSCP Quadratic | $y = 0.16^{**}x^2 - 0.72x + 2.16$         | 85                    | <0.0001 |

<sup>(1)</sup> $\hat{Y}$ : Responses (%) estimated by the models for each organic residue. (\*) (\*\*) Angular coefficient (linear regression) or dominant coefficient (quadratic regression) significant at 1 and 5% probability, (ns) not significant

(Khan Khanzada et al. 2023), thereby sustaining the hydraulic gradient necessary for CO<sub>2</sub> diffusion into the leaves (Antas et al. 2024; Mao et al. 2024). In line with these findings, although it is not a carbonaceous material such as biochar, Antas et al. (2024), when evaluating the effects of a hydrotentative polymer, a widely used soil conditioner, on gas exchange in *Mimosa caesalpiniiifolia* Bent., reported that moderate doses of the conditioner significantly improved plant physiological performance, mainly as a result of increased soil water availability.

In the present study, the enhanced physiological responses observed with BSSCP application are not limited to improvements in soil–plant water relations but may

also be associated with the enrichment of the soil with essential nutrients, particularly potassium (Figs. 2 and 7 and Table S2). This element plays a key role in regulating plant water status, as it is directly involved in stomatal opening and transpiration control, thereby favoring greater CO<sub>2</sub> assimilation and subsequent carbohydrate synthesis. This response is particularly relevant for tropical semi-arid environments, as at these application rates biochar can enhance the competitive capacity of native species such as *Mimosa caesalpiniiifolia* under prolonged drought conditions, in which exotic species often exhibit greater efficiency in resource acquisition and, consequently, superior physiological performance (Barros et al. 2020).

Beyond its immediate physiological effects, biochar should be regarded as a dynamic component of the soil system rather than an inert material. Soil management practices and water availability strongly regulate biochar aging through their effects on soil structure, aeration, and redox microenvironments (Ali et al. 2025; Danso et al. 2025). These conditions can stimulate microbial activity and oxidative reactions, accelerate biochar surface oxidation, and alter its interactions with minerals and organic compounds (Liao et al. 2025). Thus, biochar performance depends not only on its intrinsic properties but also on the soil biogeochemical context.

Water regime plays a central role in regulating these transformations. Under non-limiting moisture conditions, enhanced infiltration promotes interactions among biochar surfaces, dissolved organic matter, and soil minerals, favoring the formation of organo-mineral associations that stabilize carbon and modulate nutrient release (Liao et al. 2025). In contrast, water-limited conditions, common in semi-arid regions, constrain microbial metabolism and oxidative processes, increasing biochar persistence but slowing nutrient mobilization (Avila et al. 2023). These findings emphasize that biochar benefits are strongly modulated by hydric conditions.

At higher application rates (D3 and D4: 20 and 40 Mg ha<sup>-1</sup>), increases in internal CO<sub>2</sub> concentration (C<sub>i</sub>) were not accompanied by proportional gains in photosynthesis or chlorophyll content, suggesting biochemical rather than diffusional limitations to carbon fixation. Although higher biochar doses can further improve soil water retention (Haider et al. 2022). Excessive ash inputs may disturb nutrient balance, particularly involving potassium and magnesium, thereby impairing stomatal function and leaf gas exchange (Antonangelo et al. 2024). This indicates that increasing biochar rates does not necessarily translate into greater physiological benefits.

This imbalance may have reduced the uptake of these elements by the plants, compromised mineral nutrition, and consequently negatively affected leaf gas exchange.

These results align with previous studies using SS-derived biochar applied to sandy soils, which demonstrate benefits at doses between 10 and 50 Mg ha<sup>-1</sup>, including improved porosity, water retention, and crop productivity (Fischer et al. 2019; Namdari et al. 2024; Santos et al. 2022). However, excessive applications can reduce water availability to roots and negatively impact plant growth (Brtnicky et al. 2021). Antonangelo et al. (2024), reported that increasing the application rate of two biochars with contrasting ash contents (4.4% and 45.9%) led to reduced ryegrass yield, attributed to nutrient ratio imbalances in the soil. This reinforces the importance of careful management of the applied doses.

Intrinsic water use efficiency (iWUE) increased particularly under SSCP and at BSSCP dose D3, reflecting enhanced carbon fixation without proportional increases in stomatal conductance. This suggests improved coordination between CO<sub>2</sub> assimilation and transpiration, an advantageous trait under water-limited conditions. Even at higher doses, increased *C<sub>i</sub>* and instantaneous carboxylation efficiency (E<sub>i</sub>C) did not compromise photosynthetic capacity, indicating adaptive physiological adjustments rather than metabolic stress (Taiz et al. 2017). Similar responses have been reported in studies showing that sewage sludge amendments can enhance photosynthesis and activate antioxidant mechanisms under stress conditions (Calzone et al. 2024; Singh et al. 2024).

The quadratic relationships observed between biochar dose and photosynthetic parameters further support the hypothesis that plant responses are dose-dependent, with optimal performance at intermediate application rates. Such nonlinear patterns have been widely reported and reflect the complexity of soil–plant–biochar interactions (Gale and Thomas 2019). These results highlight the need for mechanistic studies addressing biochemical and molecular drivers of plant responses to biochar.

Despite enhanced photosynthetic performance at lower BSSCP doses, morphometric growth variables (height, stem diameter, leaf area, biomass) were not significantly improved compared to non-carbonized residues. Short experimental duration, nutrient availability, hormonal signaling, and species-specific traits may have constrained biomass accumulation (Xiong et al. 2023). This reinforces the importance of combining physiological and growth indicators when evaluating soil amendments (Suarez et al. 2025). Physiological gains do not always translate into immediate biomass responses.

In contrast, non-carbonized residues (SS and SSCP) promoted greater short-term growth, likely due to their higher content of readily mineralizable nutrients. To supply equivalent phosphorus amounts, these materials introduced substantially higher nitrogen inputs (Table S2), which

favor shoot growth and stem elongation. Such rapid nutrient availability is typical of untreated residues and explains their short-term effectiveness (Gonçalves et al. 2026). Conversely, biochar releases nutrients more slowly due to its recalcitrant structure, potentially supporting long-term soil fertility (Gonçalves et al. 2026; Ndoung et al. 2021; Zhang et al. 2021). Material choice should therefore align with the desired response time.

Beyond total biomass accumulation, treatments distinctly altered biomass allocation patterns, as reflected by allometric ratios, which indicate preferential investment among plant organs in response to soil conditions (Zhao et al. 2019). In plants under SS and SSCP treatments, biomass allocation followed a linear increasing pattern toward the shoot, while root allocation was reduced. This response can be attributed to the greater availability of readily assimilable nutrients, which decreases the need for root expansion to explore the soil and favors leaf expansion and stem elongation.

In contrast, plants grown under BSSCP exhibited a more balanced biomass distribution between shoots and roots, likely associated with the more recalcitrant nature of biochar and its slower nutrient release (Ruan and Wang 2024). The lower immediate nutrient availability may have stimulated more proportional growth between above- and below-ground organs. Such balanced allocation patterns are often linked to increased resilience under environmental fluctuations, particularly in water-limited or heterogeneous soil conditions (Giacomo Puglielli et al. 2021). However, long-term studies are still required to better elucidate the effects of BSSCP on the root system.

Beyond its effects on nutrient dynamics, biochar significantly influenced belowground processes, particularly plant–microbe interactions. Root nodules were observed exclusively in BSSCP-treated plants, indicating that biochar created favorable conditions for symbiotic N<sub>2</sub> fixation. This response likely reflects improved availability of phosphorus and essential micronutrients required for nitrogenase activity, combined with the development of protected microbial habitats within biochar pores (Quan et al. 2020). Similar increases in the abundance of diazotrophic microorganisms and enhanced nitrogen retention have been documented in biochar-amended soils (Azeem et al. 2019), underscoring biochar's role in strengthening carbon–nitrogen coupling in soil systems.

Within this biogeochemical context, nitrogen-fixing bacteria play a central role in regulating soil nitrogen dynamics following the application of biochar derived from organic residues. Biochar amendments improve key soil physical and chemical properties, including porosity, moisture retention, and cation exchange capacity, which collectively create stable microhabitats that favor the survival, colonization, and metabolic activity of diazotrophic microorganisms

(Quan et al. 2020). These conditions enhance nitrogenase activity by stabilizing soil moisture, improving aeration, and increasing the availability of essential micronutrients and organic substrates required for microbial growth.

Beyond stimulating biological nitrogen fixation, interactions between biochar and nitrogen-fixing microorganisms promote nitrogen immobilization within microbial biomass, thereby reducing nitrogen losses through leaching and gaseous emissions (Fungo et al. 2019). This microbial retention improves nitrogen use efficiency and reinforces the coupling between carbon and nitrogen cycles in soil systems (Pessoa et al. 2025). In the rhizosphere, biochar further intensifies plant–microbe interactions by stimulating root exudation and enhancing microbial colonization, supporting both symbiotic and free-living nitrogen fixation processes (Zhang et al. 2021).

Moreover, the highly porous structure of biochar facilitates the formation of heterogeneous microenvironments that sustain diverse soil biota involved in nutrient cycling and soil health maintenance (Sharma et al. 2025). Collectively, these processes promote the integration of biochar-derived carbon with biologically fixed nitrogen into soil biogeochemical cycles, enhancing nutrient availability, soil fertility, and the long-term sustainability of agroecosystems.

From a soil chemistry perspective, the application of sewage sludge-derived co-pyrolysis biochar (BSSCP) induced consistent changes in soil chemical attributes, highlighting its relevance as a soil amendment. The increase in soil pH observed with BSSCP is attributed to alkaline compounds formed during high-temperature pyrolysis, such as carbonates, oxides, and silicates, which promote acidity neutralization (Haider et al. 2022). This liming effect, widely reported in the literature, enhances the availability of nutrients such as calcium, magnesium, and phosphorus while reducing aluminum toxicity in acidic soils (Bian et al. 2022), thereby improving overall soil chemical fertility.

Electrical conductivity responses revealed contrasting nutrient-release dynamics among the treatments. Non-carbonized residues, particularly SSCP, caused a rapid release of soluble ions, explaining the higher EC observed at lower doses (Gwenzi et al. 2016). At these levels, ion release may facilitate nutrient mobility without impairing soil structure; however, higher SS doses increased EC due to greater inputs of base cations such as sodium, potassium, and calcium. In contrast, BSSCP released nutrients more gradually because of its chemical stability, preventing abrupt EC increases and minimizing the risk of osmotic stress, which is consistent with the improved photosynthetic performance associated with better hydraulic functioning.

All treatments increased soil organic carbon, although through different mechanisms. SSCP contributed more

markedly at higher doses due to its higher content of labile organic matter, while SS supplied soluble compounds that were rapidly stabilized in the soil. In comparison, BSSCP acted as a long-term carbon reservoir, contributing to sustained soil organic carbon storage and potentially improving soil structure (Protogene et al. 2024). These findings align with previous studies highlight the role of biochar in long-term carbon stabilization.

Lower soil nitrogen concentrations under BSSCP are explained by nitrogen losses during pyrolysis, which reduce total N content in the resulting biochar (Paiva et al. 2024). In addition, nitrogen in BSSCP occurs predominantly in more stable forms, limiting its mineralization and short-term availability to plants. The porous structure of biochar can further adsorb  $\text{NH}_4^+$  and  $\text{NO}_3^-$ , restricting their availability in the soil solution (Fidel et al. 2018), which likely contributed to the absence of significant growth differences between BSSCP-treated soils and the control.

Phosphorus availability was similar between SS and BSSCP, indicating effective P retention during co-pyrolysis. Potassium availability, however, increased under BSSCP at higher doses, demonstrating that nutrients derived from sewage sludge were preserved in the biochar matrix. Nonetheless, the recalcitrant nature of BSSCP limits rapid nutrient release, suggesting that its agronomic efficiency may be enhanced through strategies such as dose adjustment or combined application with organic or mineral amendments.

Calcium concentrations were higher in soils amended with BSSCP compared to non-carbonized residues, although a saturation threshold was observed beyond which additional inputs did not result in further benefits. In contrast, magnesium availability declined, reflecting competitive interactions among cations on biochar surfaces. Preferential calcium adsorption may displace other cations, such as magnesium, into less available forms (Antonangelo et al. 2024). Moreover, the chemical stability of biochar constrains the immediate release of magnesium, indicating the need for complementary nutrient sources in biochar-amended soils.

Overall, this study demonstrates that sewage sludge-derived co-pyrolysis biochar represents a promising strategy for the rehabilitation of degraded soils, particularly when applied at moderate rates. Its benefits arise from improved soil physical properties, enhanced physiological efficiency, and stimulation of beneficial plant–microbe interactions, while minimizing environmental risks associated with direct sludge application, such as contamination by microplastics and pesticide residues (Hassan et al. 2023). Careful dose calibration and integrated management strategies are essential to fully realize biochar's agronomic and environmental potential.

## 5 Conclusions

This study demonstrates that biochar produced via the co-pyrolysis of sewage sludge and cashew pruning residues modifies the regulatory mechanisms governing soil–plant system functioning in degraded soils. Compared with the direct application of organic residues, the carbonized material applied at moderate rates (5 and 10 Mg ha<sup>-1</sup>) promoted more efficient ecophysiological responses, particularly through improved photosynthetic performance and water-use efficiency, along with sustained functional changes in soil properties. These changes included increased soil pH, greater stabilization of organic carbon, and enhanced potassium availability, thereby confirming the hypothesis that thermally transformed residues provide functional benefits beyond those achieved with uncarbonized materials.

In parallel, the direct application of non-carbonized residues favored faster initial plant growth and greater short-term biomass accumulation due to the rapid release of nutrients. Taken together, these responses indicate a complementary dynamic in which biochar enhances long-term physiological efficiency and soil functional quality, whereas uncarbonized residues primarily support early growth and immediate productive responses.

The non-linear and dose-dependent nature of these effects highlights that the effectiveness of organic amendments depends on both the degree of material transformation and the application rate. Overall, these findings reveal that the co-pyrolysis of sewage sludge produces a functionally efficient amendment that reconciles waste valorization with improved plant performance in limiting soils. This approach represents a sustainable, nature-based strategy with direct implications for soil restoration programs.

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**Data Availability** The data supporting this study's findings are available from the corresponding author upon reasonable request.

## Declarations

**Conflict of interest** The authors declare that they have no financial or personal relationships that could have impacted on the work presented in this paper.

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