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Biochar as a Strategy to Mitigate Greenhouse Gases in Degraded Drylands of the Brazilian Semiarid Region: Carbon Stocks and CO_2 Fluxes

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ABSTRACT

Background: Biochar can enhance total organic carbon (TOC) stocks and reduce CO_2 emissions in degraded soils.

Aims: This study assessed the effects of pyrolytic biochars on TOC recovery and CO_2 emissions in a greenhouse experiment.

Methods: PVC columns (20 cm diameter, 50 cm height) were filled with soil and arranged in a factorial scheme ($2 \times 4 + 1$) with four replicates. Treatments included two biochars: co-pyrolyzed sewage sludge and cashew pruning (SPB) and cashew bagasse biochar (CBB), applied at 5, 10, 20, and 40 Mg ha^{-1}, plus a control. CO_2 flux was measured in two additional gas collection events. TOC content and bulk density were analyzed, and carbon stocks (CSs) were calculated.

Results: The application of 5 and 40 Mg ha^{-1} of SPB and CBB increased TOC and CSs compared to the control. CO_2 flux fluctuated between samplings, as expected with corn introduction. The highest CO_2 flux initially occurred in SPB40, followed by CBB20, whereas in the second sampling, CBB5 showed the highest flux and CBB20 the lowest.

Conclusion: These results suggest that SPB and CBB applications improve soil CSs and mitigate CO_2 fluxes, contributing to climate change mitigation and soil restoration.

1 | Introduction

The growing concern about climate change has intensified the search for innovative solutions to reduce carbon dioxide (CO_2) emissions and restore degraded soils (IPCC 2021). Brazilian dryland soils face severe degradation, primarily due to overgrazing by livestock that depend on native vegetation for forage. This, combined with adverse climatic and soil conditions, accelerates the degradation process (Araújo et al. 2024; de Araujo Pereira et al. 2021; Lima et al. 2024). Biochar produced through biomass pyrolysis has gained attention for its potential to improve soil quality and sequester carbon (Huang et al. 2023; Li et al. 2024; Liu, Wang, Song et al. 2022).

Degraded soils pose a significant environmental challenge on a global scale, affecting vast areas of agricultural land and natural ecosystems (Ma 2023). Soil degradation, often driven by erosion, compaction, organic matter loss, and unsustainable agricultural practices, not only reduces agricultural productivity but also contributes to CO_2 emissions (Liu et al. 2018; Ortiz et al. 2023; Xin et al. 2020). Soils are estimated to account for about one-third of annual CO_2 emissions, primarily due to organic carbon losses associated with degradation (Swails et al. 2024).

Biochar, a carbonaceous product derived from biomass pyrolysis, such as agricultural and forestry residues, has emerged as a promising soil amendment (Xião et al. 2022). The pyrolysis process converts biomass into a stable material resistant to biological decomposition, effectively sequestering carbon that would otherwise be released into the atmosphere (Xia et al. 2024; Xião et al. 2022).

When incorporated into the soil, biochar improves physical, chemical, and biological properties by enhancing water retention, increasing nutrient exchange capacity, and fostering beneficial microbial activity (Jiang et al. 2019; Pokharel et al. 2020; Siedt et al. 2021). The impact of biochar on soil properties is strongly modulated by its intrinsic characteristics—such as feedstock type, pyrolysis conditions, and particle size—as well as by the native soil attributes (Antonangelo et al. 2019; Lefebvre et al. 2023; Leng et al. 2021; Verheijen et al. 2019). For example, long-term reductions in BD may result from interactions between biochar's surface area and functional groups with soil particles, promoting enhanced aggregation and porosity (Blanco-Canqui 2017).

Biochar application has demonstrated potential for mitigating greenhouse gas emissions, particularly CO_2. Its effectiveness is influenced by factors such as application rate, soil properties, and the physicochemical characteristics of the biochar (Bovsun et al. 2021; Shen et al. 2017; Yerli et al. 2022). Biochar modifies soil moisture, temperature, and aeration, thereby affecting CO_2 emissions (Vasconcelos do Nascimento et al. 2023). Furthermore, it alters microbial communities and functional genes associated with greenhouse gas dynamics, contributing to the mitigation of N_2O, CH_4, and CO_2 emissions (Lyu et al. 2022).

The previous research has demonstrated that biochar can enhance soil carbon stocks (CSs) over time, acting as a long-term organic carbon reservoir (Canatoy et al. 2023; Xia et al. 2024). Additionally, biochar can influence soil CO_2 emission dynamics by affecting organic matter production and decomposition processes (Sanei et al. 2024; Xia et al. 2024). However, biochar's effects vary significantly depending on biomass type, production method, and environmental conditions (Lefebvre et al. 2023).

Despite this progress, limited research has explored biochar's impact on CSs and CO_2 emissions in degraded drylands. Furthermore, the role of biochars produced via co-pyrolysis of sewage sludge with cashew pruning or cashew bagasse in regulating soil carbon dynamics remains unexplored. Barbosa et al. (2024) found that biochar derived from co-pyrolysis of sewage sludge and cashew residues improved microbial biomass and enzymatic activity in degraded drylands. Similarly, Vasconcelos do Nascimento et al. (2024) reported that cashew bagasse biochar (CBB) improved the physical properties of cohesive soils.

On the basis of this context, the present study tested the following hypotheses: (1) Pyrolytic biochars produced from cashew bagasse and sewage sludge + cashew pruning (co-pyrolysis) increase soil organic CSs and mitigate CO_2 emissions from the soil to the atmosphere, and (2) there is an optimal biochar dose that maximizes CS enhancement while minimizing CO_2 emissions. The study aimed to examine biochar's impact on CSs and CO_2 emissions in degraded soils. By investigating these mechanisms, we sought to provide scientific insights into biochar's potential for promoting sustainability and resilience in terrestrial ecosystems in the context of global climate change.

2 | Materials and Methods

2.1 | Soil Collection, Location, Experimental Design, and Treatments

The soil used was classified as a Planosol (IUSS Working Group WRB 2022), with 760, 174, and 66 g kg^{-1} of sand, silt, and clay, respectively, indicating a sandy loam texture. Disturbed soil samples were collected from the 0 to 10 cm layer in Irauçuba municipality (State of Ceará, Brazil) (Figure 1), an area affected by desertification due to overgrazing (Araújo et al. 2024). After air-drying, the soil samples were subjected to chemical analysis following the methodology described by Teixeira et al. (2017) (Table 1).

The biochars were produced from CBB (*Anacardium occidentale* L.) and the co-pyrolysis of sewage sludge with cashew pruning residues (SPB) in a 1:1 ratio on a mass basis. The cashew bagasse was collected from a cashew-producing farm in the municipality of Aracati-CE, and the sewage sludge was obtained from a domestic wastewater treatment plant in Fortaleza-CE, Brazil, sourced from an UASB (Upflow Anaerobic Sludge Blanket) reactor. The biomass used in the production of both biochars was subjected to pyrolysis at 500°C, with a heating rate of 10°C min^{-1} under a moderate nitrogen flow. For the biochar derived from the co-pyrolysis of sewage sludge and cashew residues, the process lasted 1 h and 37 min. For the biochar obtained from cashew bagasse, pyrolysis took 3 h and 10 min.

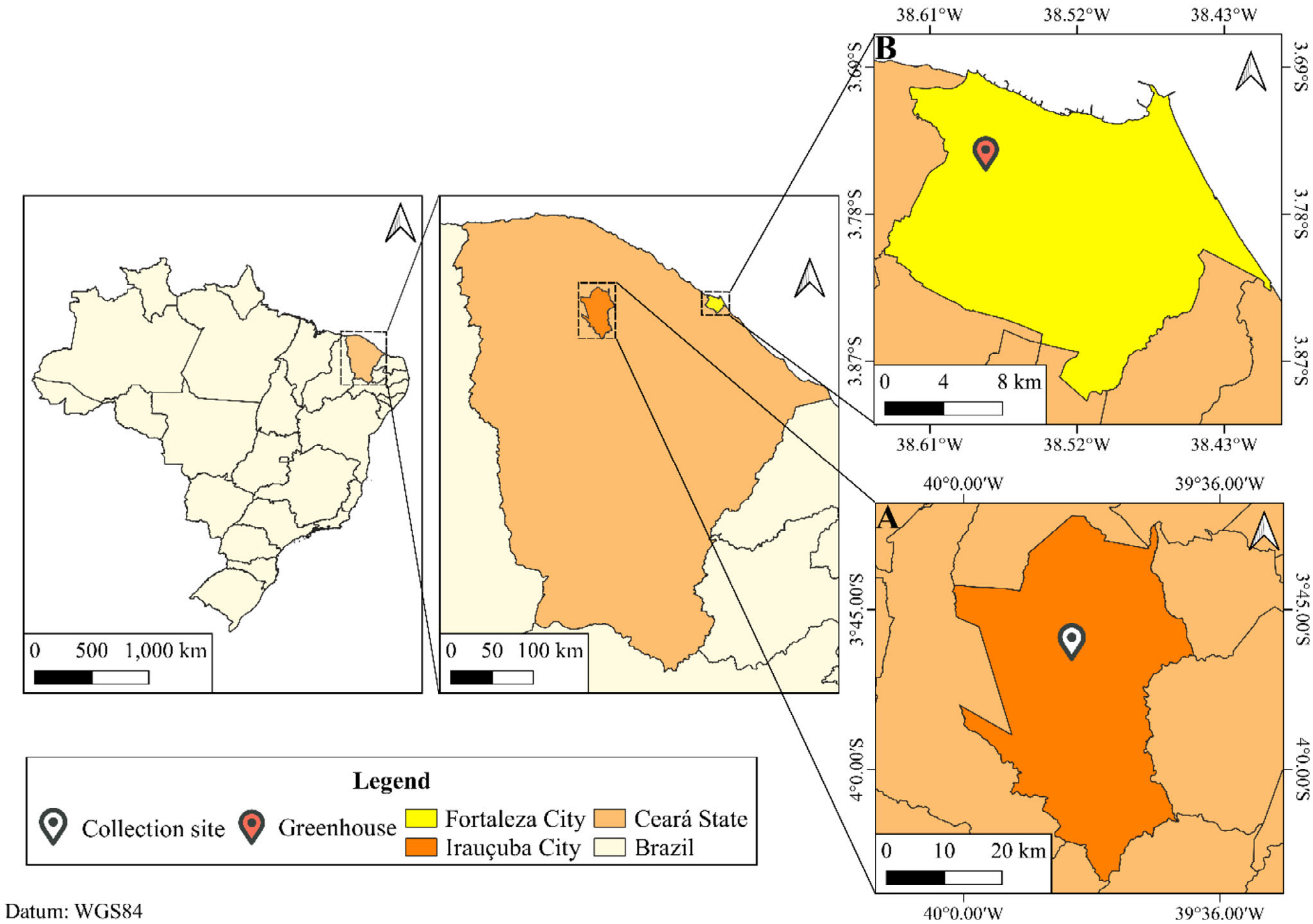

FIGURE 1 | Geographic location of the soil collection site and the greenhouse experiment setup in Ceará State, Brazil, where (A) indicates the municipality the soil was collected and (B) indicates the location where the experiment was conducted. *Source:* Barbosa et al. [6].

TABLE 1 | Chemical attributes of the soil.

pH (H_2O)	EC (dS m^{-1})	P (mg kg^{-1})	Ca ($cmol_c$ kg^{-1})	Mg (%)	K (g kg^{-1})	Na	Al	H + Al	SB	CEC	BS	C
5.1	0.03	8.44	6.97	0.46	0.09	0.08	0.54	2.52	7.52	10.04	74.90	6.07

Abbreviations: BS, base saturation; C, organic carbon; CEC, cation exchange capacity at pH 7.0; EC, electrical conductivity; SB, sum of the bases.
Source: Part of the data published in Barbosa et al. (2024).

In this study, we selected cashew bagasse and a blend of sewage sludge with urban pruning waste as feedstocks for biochar production. The choice of cashew bagasse is justified by its high local availability and the significant waste management challenges faced by the cashew industry in Brazil's Northeast region (Oliveira and Ipiranga 2011; Vasconcelos do Nascimento et al. 2024). For the second biochar, sewage sludge was co-pyrolyzed with pruning waste to address two issues simultaneously: he growing need for sustainable sludge disposal solutions (Sugurbekova et al. 2023) and the environmental burden of urban pruning residues, which, when landfilled, have a considerable carbon footprint (Carvalho et al. 2019). Co-pyrolyzing sludge with lignocellulosic pruning waste also helps dilute potential heavy metals in the final biochar, improving its suitability for soil application. Together, these factors make these biomass combinations regionally appropriate and more relevant than other potential feedstocks.

After pyrolysis, samples of each biochar underwent chemical characterization (Table 2), and the nutrient content in the biochar was determined using different analytical methods. Calcium, magnesium, aluminum, iron, manganese, and zinc were quantified by inductively coupled plasma optical emission spectrometry (ICP-OES), whereas potassium and sodium were analyzed by flame photometry (Enders and Lehmann 2012). Phosphorus was determined using the molybdovanadophosphoric acid colorimetric method, with absorbance measured at 400 nm (MAPA). Total nitrogen was quantified by the Kjeldahl method after acid digestion with sulfuric acid (Mendonça and Matos 2017). Carbon was determined using the Walkley–Black method.

The experiment was conducted in a greenhouse at the Department of Soil Science, Agricultural Sciences Center, Federal University of Ceará (Figure 1). A completely randomized experimental design was used, with a 2 × 4 + 1 factorial scheme. This

TABLE 2 | Chemical characterization of pyrolytic biochars.

Attributes	Unit	CBB	SPB
pH (H_20)	—	9.6	9.1
C	g kg^{-1}	480.10	348.00
N	g kg^{-1}	27.09	24.45
C/N	—	17.72	14.20
P	g kg^{-1}	11.62	17.70
Na	g kg^{-1}	0.35	4.09
K	g kg^{-1}	7.71	6.10
Ca	g kg^{-1}	1.95	19.30
Mg	g kg^{-1}	4.54	7.30
Cu	mg kg^{-1}	51.0	170.0
Fe	mg kg^{-1}	768	15,300
Mn	mg kg^{-1}	45.0	390.0
Zn	mg kg^{-1}	59.0	1390
Cd	mg kg^{-1}	0.0	1.0
Cr	mg kg^{-1}	2.0	40.0
Mo	mg kg^{-1}	1.0	10.0
Ni	mg kg^{-1}	4.0	23.0
Pb	mg kg^{-1}	1.0	16.0
Al	g kg^{-1}	1.35	26.8

Abbreviations: CBB, cashew bagasse biochar; SPB, sewage sludge + cashew pruning.
Source: Part of the data published in Barbosa et al. (2024).

design included two pyrolytic biochars (sewage sludge + cashew pruning—SPB; CBB), four biochar application rates (5, 10, 20, and 40 Mg ha^{-1}), a control treatment, and four replications, resulting in a total of 36 experimental units. Each experimental unit consisted of a PVC column (20 cm in diameter and 55 cm in height) with the lower end filled with a 5 cm layer of gravel (to facilitate drainage) and a layer of fabric (to prevent soil loss). Additionally, the upper 5 cm of the column was left unfilled to allow space for water addition during irrigation.

BD in overgrazed areas where the soil was collected reached a value of 1.85 g cm^{-3} (Lima 2022). However, considering the incorporation of biochar with plowing and subsequent grading, the density is reduced to a non-limiting condition for root growth, given the clay content of the studied soil—less than 1.6 g cm^{-3} (USDA-ARS 2001). Therefore, the experimental units were assembled with a BD of 1.55 g cm^{-3}.

On the basis of the criteria of the Fertilization and Soil Amendment Manual for the State of Ceará, in the section dedicated to maize (*Zea mays* L.) (Fernandes et al. 1993), and considering the results of the soil chemical analysis (Table 1), phosphate (single superphosphate), potassium (potassium chloride), and nitrogen (urea) fertilization were applied. Magnesium sulfate was used to adjust the Ca:Mg ratio due to the high calcium compared to magnesium. Each column was then filled with soil (with biochar already incorporated). After filling, all columns were irrigated to reach moisture at field capacity and were incubated for 30 days.

After the incubation period, three seeds of the BRS 2022 maize cultivar were sown at a depth of 3 cm from the soil surface. Five days after emergence, the first thinning was performed, and 3 days after the first thinning, the second thinning was conducted, leaving only one maize plant per experimental unit. The soil moisture throughout the experiment was maintained between field capacity and 70% of the available water capacity (AWC). The matric potential was monitored for irrigation management purposes using tensiometers with mercury manometers (one installed in each column at a depth of 20 cm). Distilled water was used to meet the water demand.

At the end of the experiment, samples with unpreserved structure were collected from each column, at the center of the 0–20 cm depth layer (7.5–12.5 cm), for the determination of total organic carbon (TOC). Samples with preserved structure (5 cm in height and 5 cm in diameter) were collected for the determination of BD.

2.2 | Evaluated Variables

BD was determined using the volumetric ring method and calculated as the ratio of the mass of soil dried at 105°C to the total volume of the ring (Blake and Hartge 1986). Soil organic carbon was determined using the potassium dichromate digestion method in an acidic medium, followed by titration with ammoniacal ferrous sulfate, using ferroin as an indicator (Yeomans and Bremner 1988).

The soil CS was calculated according to the methodology described by Sisti et al. (2004), using the following equation:

$$CS = (TOC \times BD \times T)/10, \qquad (1)$$

where CS is the organic carbon stock at a specific depth (Mg ha^{-1}), TOC is the TOC content (g kg^{-1}) in the soil sample, BD is the BD (kg dm^{-3}), and T is the thickness of the considered layer (in this case, 20 cm).

To evaluate CO_2 fluxes, PVC rings (7.5 cm in diameter, 20 cm in height) were used. The rings were inserted into the soil at a depth of 3 cm and maintained throughout the experiment. CO_2 was sampled twice: Time 1–2 days after the second nitrogen and potassium fertilization (25 days after seeding); Time 2—when maize plants were harvested for biomass evaluation (60 days after seeding).

At the time of sampling, PVC caps were attached to the rings, and a waiting period of 30 min was observed before collecting CO_2 using a standard syringe with a 20 mL capacity. The collected gas was then injected into penicillin vials, which had previously undergone a vacuum process and were sealed with acetic silicone (Allen et al. 2007; Keller et al. 2000). During CO_2 collection, the soil temperature inside the PVC rings was measured using a digital thermometer. The temperature and relative humidity of the air inside the greenhouse were also recorded at the time of gas collection.

The collected CO_2 was measured using gas chromatography with a Bruker 450GC, and the fluxes (mg of CO_2 m^{-2} h^{-1}) were calculated using the ideal gas law (PV = nRT). The calculations

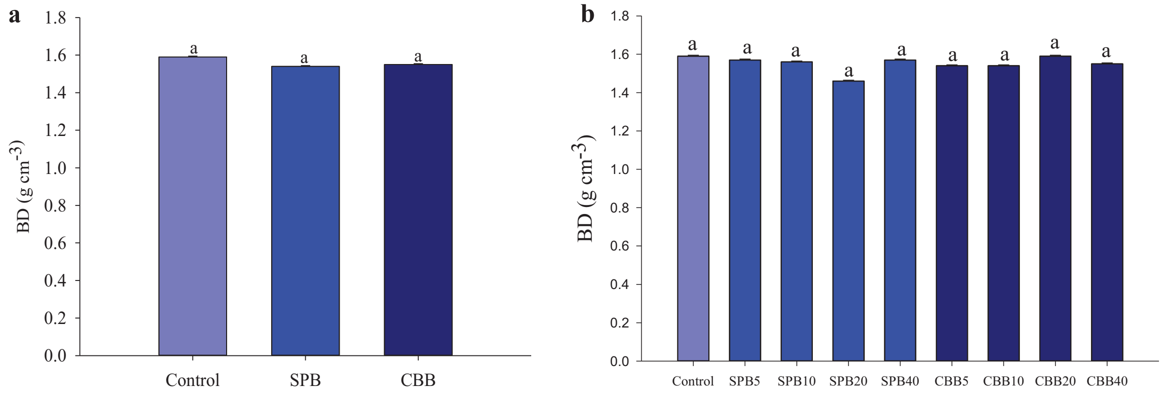

FIGURE 2 | Means of bulk density (BD) in response to biochar application (a) and rates (b) in soil cultivated with maize (*Zea mays* L.). Means followed by the same letter do not differ by the Tukey test at 5% probability. Biochar: $F = 0.29^{ns}$; rates: $F = 0.35^{ns}$; biochar × rates: $F = 2.83^{ns}$. ns, not significant.

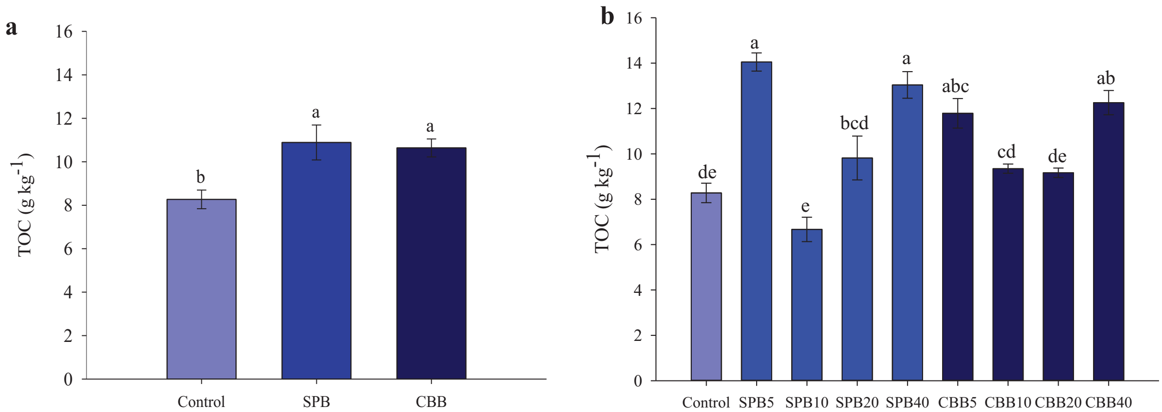

FIGURE 3 | Mean values of total organic carbon (TOC) in response to biochar application (a) and rates (b) in soil cultivated with maize (*Zea mays* L.). Means followed by the same letter do not differ by the Tukey test at 5% probability. Biochar: $F = 0.42^{ns}$; rates: $F = 38.53^{**}$; biochar × rates: $F = 0.40^{**}$. **: significant at 1% probability level, respectively. ns, not significant.

accounted for changes in gas concentration over time in the closed chamber, considering chamber volume and area, soil temperature, and atmospheric pressure (Howard et al. 2014).

2.3 | Statistical Analysis

The normality of residuals was assessed using the Shapiro–Wilk test, whereas the homogeneity of variances was evaluated using the Bartlett test. When necessary, data transformation was performed using the Box and Cox (1964) procedure to identify an optimal power (λ) that would make the transformed data as close to normal as possible. The statistical analysis of the data was performed using the online version of the statistical analysis system (SAS) software.

The collected data were analyzed using a completely randomized design with a 2 × 4 + 1 factorial scheme, consisting of two types of pyrolytic biochars (from cashew bagasse and sewage sludge + cashew pruning), four application rates (5, 10, 20, and 40 Mg ha^{-1}), and one control, with four replications. A 2 × 4 × 2 + 1 factorial scheme was employed to analyze CO_2 emissions, incorporating two pyrolytic biochars, four rates, and two collection times, along with one control and four replications.

Analysis of variance was performed using the *F*-test, and mean comparisons were conducted using the Tukey test, both at a 5% significance level. Regression analysis was performed to investigate the relationships between biochar rates and the measured variables. The significance of the regression coefficients was evaluated to determine how strongly biochar doses influence the outcomes, with significance levels set at 1% and 5%.

3 | Results

3.1 | Bulk Density

The application of biochar from sewage sludge + cashew pruning (SPB) and CBB did not result in significant changes in BD, despite the application rates (Figure 2a,b).

3.2 | Soil Organic Carbon

The incorporation of SPB and CBB increased soil organic carbon content (Figure 3a), with a significant difference compared to the control treatment (without biochar). Similar behavior was observed for both biochars (SPB and CBB), with the highest

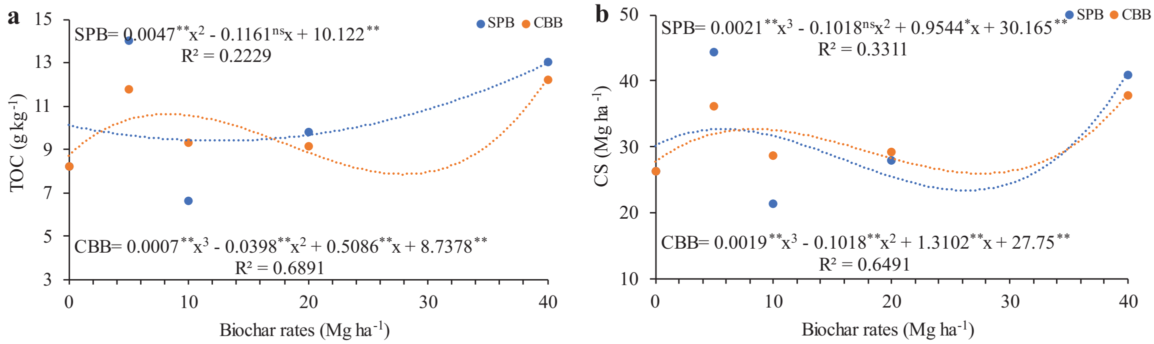

FIGURE 4 | Regression between means data of total organic carbon (TOC) (a) and carbon stock (CS) (b) and rates of biochar incorporated into soil cultivated with maize plants (*Zea mays L.*). ** and *: significant at 1% and 5% of probability, respectively.

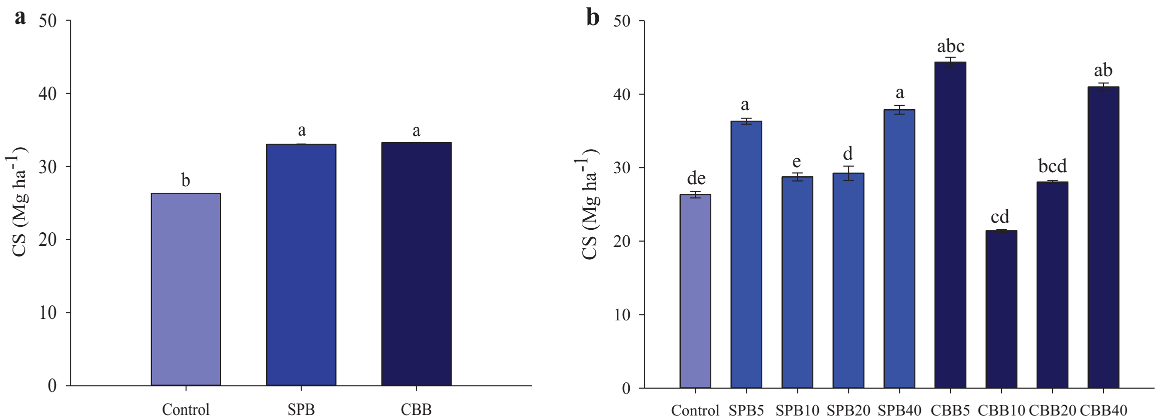

FIGURE 5 | Mean carbon stock (CS) values in response to biochar application (a) and rates (b) in soil cultivated with maize (*Zea mays* L.). Means followed by the same letter do not differ by the Tukey test at 5% probability. Biochar: $F = 0.10^{ns}$; rates: $F = 38.35$**; biochar × rates: $F = 7.71$**. **: significant at 1% probability level, respectively. ns, not significant.

organic carbon content found in the treatments where 5 and 40 Mg ha^{-1} rates were incorporated into the soil. Compared to the control treatment, the TOC increased by 59%, 63%, 70%, and 68% for the SPB5, SPB40, CBB5, and CBB40 treatments, respectively. The SPB10, SPB20, CBB10, and CBB20 treatments did not show a significant difference from the control treatment (Figure 3b).

From the second-degree polynomial regression analysis between TOC and SPB rates, we observed that the lowest TOC content occurred at a rate of 12.4 Mg ha^{-1}, corresponding to 9.4 g kg^{-1}, whereas the highest content was found at a rate of 40 Mg ha^{-1}, representing a 28% increase compared to the control. For CBB, the third-degree polynomial regression analysis revealed that the lowest organic carbon content occurred at a rate of 29.7 Mg ha^{-1}, with 7 g kg^{-1}, whereas the highest content was observed at a rate of 8.1 Mg ha^{-1}, with 10.6 g kg^{-1}, resulting in a 17% increase compared to the control (Figure 4a).

3.3 | Soil CS

The data obtained for soil CS followed a trend like that of soil organic carbon content. A significant difference in CS was observed when SPB and CBB were incorporated into the soil, compared to the control treatment (Figure 5a).

When rates of 5 and 40 Mg ha^{-1} of both SPB and CBB were applied to the soil, an increase in soil CS values was observed. This increase was 72% for SPB5, 69% for SPB40, 59% for CBB5, and 64% for CBB40, compared to the control without biochar (Figure 5b). The SPB10, SPB20, CBB10, and CBB20 treatments showed similar results to the control treatment, with no significant differences.

The data obtained for soil organic CS for both SPB and CBB were fitted using a third-degree polynomial model. For SPB, the highest CS was observed at a rate of 5.7 Mg ha^{-1}, resulting in 32.7 Mg ha^{-1} of CS, while the lowest CS was found at a rate of 26.6 Mg ha^{-1}, corresponding to 23 Mg ha^{-1} of CS. The 5.7 Mg ha^{-1} rate resulted in an 8% increase in CS compared to the control. Regarding CBB, the highest CS value was found at a rate of 8.4 Mg ha^{-1}, with 32.7 Mg ha^{-1} of CS, whereas the lowest value was observed at a rate of 27.3 Mg ha^{-1}, with 26.3 Mg ha^{-1} of CS. The 8.4 Mg ha^{-1} rate resulted in an 18% increase in CS compared to the 0 rate (Figure 4b).

3.4 | CO_2 Emissions

There was a significant difference in CO_2 emissions when applying CBB and SPB compared to the control treatment (Table 3). In both collection times, the control treatment emitted less CO_2 than

TABLE 3 | CO_2 emissions for the control treatment, sewage sludge + cashew pruning (SPB), and cashew bagasse biochar (CBB), based on sampling time.

	Collections	
	Time 1 (25 days after seeding)	Time 2 (60 days after seeding)
Sources of variation	***F* test**	
Biochars (B)	21.50*	15.27**
Rates (R)	35.92*	115.27*
B x R	43.82*	48.00*
Coefficient of variation (%)	18.31	14.61
Treatments	**Comparison of means (mg of CO_2 m^{-2} h^{-1})**	
Control	36.08 c	21.78 c
SPB	68.73 a	34.63 b
CBB	51.49 b	41.99 a

Note: Means followed by the same letter within each column do not differ from each other according to the Tukey test at a 5% significance level.
* and **: significant at the 1% and 5% probability levels, respectively. Transformed variable ($\lambda = 0.02$).

TABLE 4 | CO_2 emissions based on the control treatment, rates of sewage sludge + cashew pruning (SPB) and cashew bagasse biochar (CBB), and sampling times in soil cultivated with maize plants (*Zea mays* L.).

Sources of variation	***F* test**
Time	218.61**
Biochars	3.20^{ns}
Rates	125.19**
Time x biochars	14.21**
Time x rates	22.44**
Biochars x rates	47.29**
Time x biochars x rates	5.56**
Coefficient of variation (%)	3.05

	Comparison of means (mg of CO_2 m^{-2} h^{-1})	
Treatments	**Time 1 (25 days after seeding)**	**Time 2 (60 days after seeding)**
Control	36.08 cA	21.78 cdeB
SPB5	51.35 cA	38.69 bcB
SPB10	41.55 cA	31.70 cdA
SPB20	49.59 cA	15.06 deB
SPB40	132.43 aA	53.07 bB
CBB5	80.13 bA	83.54 aA
CBB10	44.04 cA	35.04 bcA
CBB20	35.60 cA	11.33 eB
CBB40	46.19 cA	38.06 bcA

Note: Means followed by the same lowercase letter within each column and the same uppercase letter in the row do not differ from each other according to the Tukey test at a 5% significance level.
Abbreviation: ns, not significant.
**: significant at the 1% probability level, respectively. Transformed variable: time 1 ($\lambda = 0.6$) and time 2 ($\lambda = -0.2$).

SPB and CBB. In the first collection (25 days after seeding), the highest emission was observed for SPB (68.73 mg of CO_2 m^{-2} h^{-1}), whereas in the second collection (60 days after seeding), the highest CO_2 flux was observed for CBB (41.99 mg of CO_2 m^{-2} h^{-1}).

There was a significant difference between the collection times, and the rates of CBB and SPB influenced the CO_2 flux compared to the control (without biochar) (Table 4). In the first collection (25 days after seeding), an increase in CO_2 flux was observed for the SPB40 treatment (132.43 mg of CO_2 m^{-2} h^{-1}) and the CBB5 treatment (80.13 mg of CO_2 m^{-2} h^{-1}), compared to the control (36.08 mg of CO_2 m^{-2} h^{-1}) and the other treatments, which did not differ significantly from each other. In the second collection (60 days after seeding), the highest CO_2 values were found for CBB5 and SPB40, followed by CBB10, CBB40, SPB5, and SPB10. The lowest CO_2 flux was observed for CBB20, followed by SPB20 and the control treatment (Table 4).

The collection times did not show significant differences for SPB10, CBB5, CBB10, and CBB40, indicating a consistent CO_2 flux during both collection times. For the control, SPB5, SPB20, SPB40, and CBB20, a higher CO_2 flux was observed in the first collection, but the flux decreased in the second collection compared to the previous one (Table 4).

Regression analysis revealed a significant effect on CO_2 emissions during both the first and second collection times for SPB. For CBB, however, a significant effect was observed only during the first collection (Figure 6).

On the basis of the second-degree polynomial regression data (Figure 6a), the highest CO_2 flux during the first collection was observed at a rate of 40 Mg ha^{-1}, with 132.43 mg of CO_2 m^{-2} h^{-1}. The lowest flux occurred at a rate of 6.5 Mg ha^{-1}, with 40.07 mg of CO_2 m^{-2} h^{-1}, representing an 8% reduction compared to the 0 rate. For the second collection, the lowest flux was observed at a rate of 14 Mg ha^{-1}, with an average flux of 23.94 mg of CO_2 m^{-2} h^{-1}, a 25% reduction compared to the 0 rate. This suggests that the optimal rates for reducing CO_2 emissions in degraded soil treated with SPB are between 6.5 and 14 Mg ha^{-1}.

In the third-degree polynomial regression analysis for CO_2 measured during the first collection time for CBB, the highest flux occurred at a rate of 7.4 Mg ha^{-1}, showing a 48% increase compared to the control. The lowest flux was observed at a rate of 29.8 Mg ha^{-1}, causing a 77% reduction compared to the 0 rate (Figure 6b). This indicates that the optimal CBB rate for reducing CO_2 emissions is 29.8 Mg ha^{-1}.

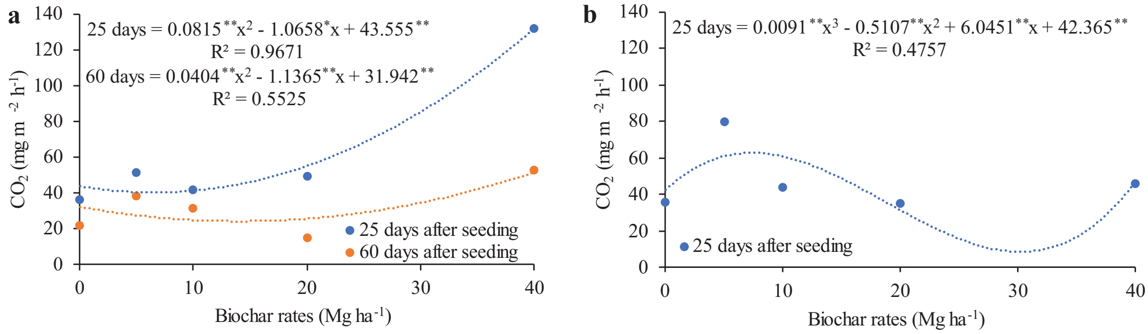

FIGURE 6 | Regression between the mean data of CO_2 emissions and rates of sewage sludge + cashew pruning (a) and cashew bagasse (b) incorporated into the soil under maize cultivation (*Zea mays* L.). ** and *: significant at 1% and 5% of probability, respectively.

4 | Discussion

4.1 | Bulk Density

There was no significant difference in BD in response to SPB and CBB application rates in this study. BD is a key indicator of soil physical quality because it reflects the packing arrangement of soil particles and pore spaces (Bhat et al. 2022; Verheijen et al. 2019). Biochar is generally expected to reduce soil BD due to its lower intrinsic density and high porosity (Blanco-Canqui 2017; Lehmann et al. 2011). However, the effect depends strongly on the biochar type, its density, and especially its particle size distribution.

In this experiment, although the sewage sludge pruning biochar (SPB) had a lower intrinsic density (0.28 g cm^{-3}) than the CBB (0.55 g cm^{-3}) (da Costa Dantas Moniz et al. 2025), both biochars contained a relatively high proportion of larger particles (approximately 31%–52%, >1 mm). Numerous studies have demonstrated that biochars with smaller particle sizes are effective in reducing BD (Botková et al. 2023; Duarte et al. 2019; Githinji 2014). This is because smaller biochar particles can settle between soil particles without blocking pores, instead forming additional pore networks that expand macroporosity while reducing BD (Steiner et al. 2011).

Furthermore, biochar-induced BD reduction tends to be more pronounced in clay-rich soils due to greater improvements in aggregation, microporosity, and pore connectivity (Bekchanova et al. 2024; Vasconcelos do Nascimento et al. 2024). For example, Vasconcelos do Nascimento et al. (2024) observed a significant BD decrease using CBB in a cohesive Typic Haplustult at higher application rates (up to 40 Mg ha^{-1}). However, in the present study, the same biochar applied to a sandy soil showed limited impact, likely due to its coarser texture and the predominance of larger biochar particles. Taken together, the relatively large particle size and the sandy nature of the soil explain why no significant change in BD was detected under the tested conditions.

4.2 | Soil Organic Carbon

Biochar application significantly increased TOC (Figure 3a,b), aligning with previous findings that highlight its potential to enhance soil quality through carbon enrichment, sequestration, and improved soil health (Canatoy et al. 2023; Huang et al. 2023; Liu, Wang, Penuelas et al. 2022; Shikha et al. 2023). This result confirms our hypothesis that SPB and CBB biochars would elevate TOC levels.

In degraded and desertified soils, increases in TOC improve soil structure (Wang et al. 2017), water retention (Karim et al. 2020), and microbial activity (Barbosa et al. 2024), all contributing to soil recovery. Biochar also stimulates TOC through enhanced biomass input (root exudates, plant residues), improved aggregation, and favorable microbial habitats (Jiang et al. 2019; Pokharel et al. 2020; Siedt et al. 2021; Xu et al. 2021).

Both SPB and CBB showed similar trends, with TOC peaking at 5 and 40 Mg ha^{-1} (Figure 3b). Although 40 Mg ha^{-1} yielded the highest TOC, the 5 Mg ha^{-1} rate offers a better cost–benefit ratio due to lower input, transport, and application costs. Importantly, neither biochar negatively affected plant growth nor soil biota, indicating their agronomic viability.

Intermediate rates (SPB10, SPB20, CBB10, and CBB20) did not differ significantly from the control, likely due to interactions with nitrogen fertilization, carbon turnover, and the balance between labile and recalcitrant carbon fractions (Hansen et al. 2017; Gross et al. 2021). The C:N ratio also influences these dynamics, with narrower ratios promoting mineralization and wider ones favoring immobilization (Brandani and Santos 2016).

The TOC increase at 5 Mg ha^{-1} is attributed to the rapid mineralization of labile carbon and microbial turnover, whereas higher TOC at 40 Mg ha^{-1} reflects contributions from recalcitrant carbon. Intermediate treatments suggest ongoing mineralization, but further research is needed to clarify these mechanisms (Brandani and Santos 2016; Gross et al. 2021; Hansen et al. 2017; Li et al. 2024; Yang et al. 2020).

Polynomial relationships were observed between biochar rates and TOC (Figure 4a), indicating dose-dependent effects. SPB at 40 Mg ha^{-1} and CBB at 8.1 Mg ha^{-1} were most effective in increasing TOC, offering insights for sustainable soil management and carbon sequestration.

In summary, applying SPB and CBB biochars—particularly at 40 and 8.1 Mg ha^{-1}, respectively—holds promise for enhancing TOC, with significant implications for soil restoration and climate change mitigation.

4.3 | Soil CS

There was a significant effect of biochar incorporation on soil CS, supporting the observed differences in soil organic carbon content. Both 5 and 40 Mg ha^{-1} rates of SPB and CBB resulted in substantial increases in soil CS. Biochar application can be an effective strategy for enhancing carbon storage in the soil, contributing to climate change mitigation, and improving soil quality, particularly in degraded soils. This is crucial, as degraded soils in dry environments often have low organic carbon content (the soil used in our study contained 6.07 g kg^{-1} of organic carbon), leading to a decline in their physical, chemical, and biological properties. Therefore, our findings on CS support one of the hypotheses of our study: that the application of SPB and CBB biochars increases soil CS.

In contrast, treatments with intermediate biochar rates (10 and 20 Mg ha^{-1} for SPB and CBB) did not show statistical differences compared to the control treatment. This suggests that the response to biochar is dose-dependent, with a significant effect observed only at extreme rates. This indicates that the effectiveness of biochar in increasing soil CS is more pronounced at higher rates, or that there is a threshold beyond which additional biochar does not enhance carbon storage.

Biochar addition can alter the soil priming effect, which refers to changes in the decomposition rate of TOC following the addition of an organic amendment. Biochar can either positively or negatively affect the mineralization of soil organic carbon, influencing soil CS (El-Naggar et al. 2015, 2018; Xu et al. 2018). The impact of biochar on the mineralization of native organic carbon also depends on the biochar's production temperature. Biochar produced at lower temperatures generally exhibits a positive priming effect, whereas biochar produced at higher temperatures stabilizes organic carbon, contributing to increased soil CS (El-Naggar et al. 2015).

The amount of biochar applied also affects soil CS. For instance, Sun et al. (2020) found a 14% decrease in CS at a 30 Mg ha^{-1} application rate, whereas 60 and 90 Mg ha^{-1} rates resulted in increases of 18.8% and 8.2%, respectively. The C/N ratio of biochar plays a significant role in determining its impact on carbon storage, as biochars with a C/N ratio below 20, such as SPB and CBB (Table 2), favor mineralization over immobilization. However, the application of nitrogen fertilizers, such as urea, may accelerate the mineralization of labile carbon in the short term, leading to carbon immobilization and a longer term increase in organic carbon content.

For example, Yang et al. (2020) reported that the application of 30 and 45 Mg ha^{-1} of biochar to drip-irrigated cornfields increased soil CS by 19% and 37%, respectively, in the first year. In the second year, the increases were 12% and 15% at 0–15 cm, and 23% and 34% at 15–30 cm. However, the application of 15 Mg ha^{-1} did not significantly affect CS. Similarly, Dejene and Tilahun (2019) found a significant increase in soil organic CS when 5 Mg ha^{-1} of biochar was applied.

Regression analysis revealed a significant polynomial relationship for both biochars, supporting the idea that biochar application can be optimized to maximize carbon retention in soil, with more pronounced positive effects at certain rates. Therefore, it is recommended that SPB and CBB be applied at rates of 5.7 and 8.4 Mg ha^{-1}, respectively, to effectively increase soil CSs. However, the absence of significant differences at higher rates emphasizes the need for careful biochar application to optimize its benefits.

4.4 | CO_2 Emissions

The results provide detailed insights into the impact of different biochar rates, both SPB and CBB, on CO_2 fluxes in the soil. The application of biochar, regardless of its source, led to significant differences compared to the control treatment, suggesting that these materials promote substantial changes in soil CO_2 fluxes, aligning with our hypothesis (Table 4).

Our findings are partly supported by Barbosa et al. (2024), who observed differences in soil basal respiration with varying rates of SPB and CBB. However, Barbosa et al. (2024) reported a linear increase in soil basal respiration as biochar rates increased, a pattern not observed in our study. It is important to note that the introduction of corn plants in our system may have contributed to the differences observed, as plant respiration is an additional factor influencing soil CO_2 emissions (Fidel et al. 2019).

On the other hand, the temporal data analysis revealed significant differences between collection times, indicating that fluctuations in CO_2 fluxes are associated with temporal variations, potentially influenced by environmental and biological factors (Alarefee et al. 2023; Mosa et al. 2023). For SPB10, CBB5, CBB10, and CBB40, the stability of CO_2 flux during both collection times suggests these treatments did not significantly alter soil respiration dynamics. However, for the control, SPB5, SPB20, SPB40, and CBB20, a distinct behavior was observed, with a reduced flux during the first collection, followed by an increase in the second collection. This pattern may indicate an initial adaptation of the soil microbial community to biochar addition, followed by stabilization (Kravchenko et al. 2023).

The fluctuations in CO_2 flux for the control, SPB5, SPB20, SPB40, and CBB20 treatments may be attributed to slight variations in soil moisture and temperature, as CO_2 flux is sensitive to both. Our findings corroborate Canatoy et al. (2023), who also observed variations in CO_2 flux based on collection times. Small temperature changes can significantly affect CO_2 flux (Abagandura et al. 2019; Hagemann et al. 2017; Kang et al. 2018; Yang et al. 2019).

Biochar's role in modulating soil structure (porosity, pore size distribution, and connectivity) is an important mechanism for CO_2 emissions (Fan et al. 2020). The recalcitrant nature of biochar, its water retention capacity, and its high potential to form soil aggregates with labile organic components enhance its impact on increasing soil carbon sequestration (Hawthorne et al. 2017). Li et al. (2022) suggest that biochar's effect on CO_2 flux is linked to the predominance of bacterial species involved in the tricarboxylic acid cycle. Moreover, biochar stimulates catalase, sucrose, urease, and β-glucosidase activities in the soil, acting as a protective factor against CO_2 emissions (Wang et al. 2022). These findings are supported by Barbosa et al. (2024), who reported variations in β-glucosidase and urease activity in degraded soil treated with biochar derived from sewage sludge + cashew pruning residue and cashew bagasse.

The second-degree polynomial regression analysis for SPB reveals that the 6.5 and 14 Mg ha^{-1} rates were associated with the lowest CO_2 flux in both collection times, indicating a significant reduction in carbon flux from soil treated with these doses. However, the same treatment showed higher CO_2 emissions when 40 Mg ha^{-1} was applied in both collection times, suggesting that 6.5 and 14 Mg ha^{-1} rates of SPB are more effective in reducing CO_2 flux, making them a promising strategy for mitigating CO_2 emissions in agriculture.

For CBB, the third-degree regression analysis for the first collection time shows variations in CO_2 flux, with the highest flux occurring at the 7.8 Mg ha^{-1} rate and the lowest at the 29.8 Mg ha^{-1} rate. This suggests that the 29.8 Mg ha^{-1} rate is optimal for mitigating CO_2 emissions.

Overall, the results indicate that SPB and CBB, particularly at the appropriate rates, can play a significant role in modulating CO_2 flux in the soil, contributing to the mitigation of greenhouse gas emissions. However, these effects depend on both the characteristics of the biochar and the temporal conditions and plant development.

5 | Conclusions

The established hypotheses were confirmed, illustrating that applying SPB and CBB to degraded soils is an environmentally beneficial strategy. These biochars effectively enhance soil organic CS and reduce CO_2 flux from the soil into the atmosphere. Specifically, the application of 5 and 40 Mg ha^{-1} of SPB and CBB, respectively, leads to significant increases in soil organic CS. Considering the cost–benefit ratio, the application of 5 Mg ha^{-1} of SPB and CBB is more advantages compared to 40 Mg ha^{-1} Additionally, incorporating 6.5 and 14 Mg ha^{-1} of SPB and 29.8 Mg ha^{-1} of CBB into the soil significantly reduces CO_2 emissions.

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Data Availability Statement

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

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