

The Effect of Straw Biochar Application on CO₂ Emission from Farmland Soil

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Abstract: In this study, biochar was produced from maize straw and applied to farmland soils to investigate, through indoor simulated incubation experiments, the effects of different application rates of straw-derived biochar on CO₂ emission characteristics at various soil depths in Baotou. The soils were incubated under controlled indoor conditions for 28 days, and CO₂ emissions were measured using gas chromatography. The results showed that in the 0–10 cm surface soil, cumulative CO₂ emissions increased significantly by 26.16% and 34.53% under 1% (BC1) and 2% (BC2) biochar treatments, respectively, compared to the control (CK). In contrast, in the 10–50 cm subsoil, cumulative CO₂ emissions under the BC1 treatment decreased by an average of 18.72% compared to the control, with a reduction of up to 24.35% observed in the 40–50 cm soil layer. Dose–response analysis indicated that the application of 1% biochar achieved the optimal emission reduction effect in the 20–30 cm soil layer. This study reveals the vertical differentiation effect of straw-derived biochar on soil CO₂ emissions, providing scientific support for the synergistic regulation of straw resource utilization and greenhouse gas emission reduction in Baotou's farmland.

Keywords: CO₂ emissions, farmland soil, biochar, subsoil

1. Introduction

Since the 20th century, global surface temperatures have continued to rise. IPCC model projections predict that from 2018 to 2100, the Earth's average surface temperature will increase by 0.3–4.8°C, with global warming posing serious threats to both the natural environment and human life [1]. Among various sources, greenhouse gases generated by agricultural production constitute a major portion of global greenhouse gas emissions, with soil-derived CO₂ emissions accounting for approximately 15% of total emissions [2–4].

As a major agricultural nation, China has extensive maize cultivation and an abundant supply of straw resources. Statistics show that China's straw output exceeded 800 million tons in 2016. However, maize straw is often either burned in situ or discarded into farmland after harvest, leading not only to environmental pollution but also to a significant waste of valuable resources [2]. Incorporating biochar into farmland soil is considered a promising emission reduction strategy, capable of reducing soil CO₂ emissions by altering soil physicochemical properties such as moisture content, bulk density, nitrate nitrogen (NO₃[–]-N) levels, and ammonium nitrogen (NH₄⁺-N) levels [5–6]. Wu Jie [7] found that direct straw incorporation into soil increased CO₂ emissions, whereas biochar application significantly reduced CO₂ emissions. Guo Ru [8] observed that, under

conventional nitrogen application rates, applying straw-derived biochar in dryland farmland resulted in a greater reduction in soil CO₂ emissions than direct straw return. Jia Xiaoyu [9] reported that the effect of biochar on soil CO₂ emissions varies with soil depth.

In Baotou, maize is a major crop, and the harvest produces a large quantity of straw each year, most of which remains underutilized. Therefore, this study selected farmland soil near the Xiaobai River in Baotou as the experimental material. Using indoor incubation methods, biochar derived from maize straw was applied to soils at different depths to explore the CO₂ emission patterns and changes in soil physicochemical properties under varying treatment conditions. The objective was to investigate how different soil depths and biochar application rates influence CO₂ emissions and soil properties, thus providing a theoretical basis for the rational utilization of maize straw resources and the reduction of CO₂ emissions.

2. Research methods

2.1. Experimental materials

Corn straw collected from farmland near the Xiaobai River in Baotou City was used as the raw material for biochar production. Soil samples were collected from different soil layers at 10 cm intervals using a spade and a triangular shovel, resulting in five soil layers. The soils were air-dried after being brought back to the laboratory and stored for further use.

The corn straw was washed with deionized water, oven-dried, and then pulverized for 10 minutes using a grinder. After cooling, the straw powder was placed into a porcelain boat, covered with a lid, and inserted into a tube furnace. Biochar was prepared via fast pyrolysis, heating the material at a rate of 5 °C·min⁻¹ to 400 °C and holding it at this temperature for 1 hour. After cooling, the porcelain boat was removed, and the biochar was ground uniformly using a mortar and pestle for 10 minutes. The resulting straw biochar was stored in bags and labeled as BC. The surface morphology of the straw biochar was observed using a scanning electron microscope (ZEISS Sigma 360), and its surface functional groups were analyzed using a Fourier-transform infrared spectrometer (PerkinElmer Spectrum Two).

2.2. Experimental design

Referring to the studies by Wu Huang et al. [2–4,10], the addition rates of straw biochar were determined. Three treatments were set for each soil layer: a control without biochar (CK), 1% biochar by soil mass (BC1), and 2% biochar by soil mass (BC2). Each treatment had three replicates. The soils were placed into incubation bottles and adjusted to a 10% water content using deionized water. After a 3-day pre-incubation period indoors, biochar was added according to the treatment groups and mixed thoroughly, marking the start of formal incubation. The formal incubation period lasted 28 days. During incubation, soil moisture was maintained by the gravimetric method every two days. After incubation, soil samples were collected to measure total organic carbon (TOC) content, pH, NO₃⁻-N content and NH₄⁺-N content.

2.3. Sample collection and measurements

Gas sampling was conducted on days 0, 4, 8, 12, 16, 20, 24, and 28 of the formal incubation to measure the CO₂ emission rates. Gas sampling was performed at 9:00 a.m. on each sampling day. Before collecting the gas samples, fresh air was injected into the incubation bottles using a syringe and the gas inside was replaced three times to ensure that the internal and ambient air compositions were consistent. Then, the bottles were tightly sealed, and the sealing time was recorded. After 6 hours, a 50 mL syringe was used to extract gas from the bottle. The three-way valve was rotated to

open the sampling bag valve, and the extracted gas was injected into the gas sampling bag. Gas concentrations were analyzed using a gas chromatograph (Agilent GC-8890).

After incubation, soil samples from each treatment were collected to determine soil physicochemical properties: soil bulk density was measured using the cutting ring method; soil pH was measured using a pH meter (Leici pH-3c); soil $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ contents were determined by the KCl extraction method; and TOC content was determined by the potassium dichromate external heating method.

The formulas for calculating the CO_2 emission rate and cumulative emissions are shown in Equations (1) and (2) [11–14]:

$$F = \frac{(c - c_0) \cdot M \cdot V}{22.4 \cdot m \cdot t} \cdot \frac{T_0}{T} \quad (1)$$

$$T = \sum_{i=1}^n \frac{F_i + F_{i+1}}{2} \cdot (t_{i+1} - t_i) \quad (2)$$

Where F is the gas emission rate per unit soil mass, $\mu\text{g} \cdot \text{kg}^{-1} \cdot \text{h}^{-1}$; C is the gas concentration in the syringe, ppm; C_0 is the atmospheric gas concentration, ppm; V is the effective volume of the incubation bottle, L; M is the molar mass of the gas, $\text{g} \cdot \text{mol}^{-1}$; m is the mass of soil in the incubation bottle kg; t is the closure time of the incubation bottle, h; T is the thermodynamic temperature of indoor air, K; T_0 is the thermodynamic temperature at standard conditions, 273.15K. F_i and F_{i+1} are the CO_2 emission rates at the i -th and $(i+1)$ -th samplings, respectively; $t_{i+1} - t_i$ is the time interval between two successive samplings (h), n is the total number of samplings.

2.4. Data analysis

Data analysis and graph plotting were conducted using Origin (version 9.0) and Excel (version 2022) software.

3. Results and analysis

3.1. Characterization of straw biochar

3.1.1. Basic physicochemical properties of straw biochar

The basic physicochemical properties of straw biochar are shown in Table 1. Under the preparation condition of 400 °C, the yield of straw biochar was 35.10%. It has been reported that the yield of biochar decreases continuously with increasing pyrolysis temperature [15]. Additionally, the pH value significantly increases with temperature, but when the pyrolysis temperature is between 400–600 °C, the increase in pH slows down gradually [16]. As the preparation temperature rises, the C/N ratio of biochar increases significantly, while the O/C and H/C ratios vary depending on the raw material used [17–19].

Table 1: Physicochemical properties of straw biochar

matter	BC
yield(%)	35.1
pH	7.21
C(%)	61.9
N(%)	3.5

Table 1: (continued)

O(%)	0.75
H/C	16.45
O/C	0.05
C/N	0.265
surface area($\text{m}^2 \cdot \text{g}^{-1}$)	82.53
pore size(nm)	1.919
pore volume($\text{cm}^3 \cdot \text{g}^{-1}$)	3.00

3.1.2. SEM analysis

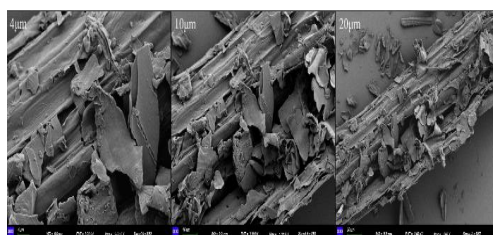


Figure 1: SEM image of straw biochar

Figure 1 shows the SEM image of straw biochar. As can be observed, the surface of the straw biochar appears relatively rough, which is attributed to the destruction of fibrous chains in the straw during pyrolysis. Numerous fine particles are attached to the surface, exhibiting a typical porous structure [20–21]. The structural characteristics of biochar can vary depending on the type of feedstock used [18].

3.1.3. FTIR analysis

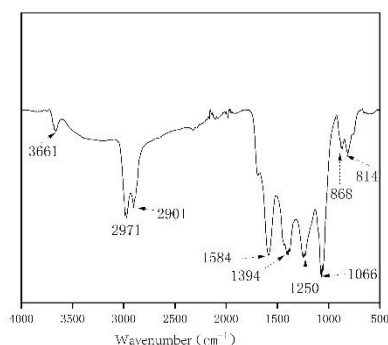


Figure 2: FTIR spectrum of straw biochar

Figure 2 presents the FTIR spectrum of straw biochar. Analysis of the spectrum shows: The peak at 3661 cm^{-1} corresponds to the absorption of phenolic hydroxyl groups; Peaks at 2971 cm^{-1} and 2901 cm^{-1} are associated with the stretching vibrations of aliphatic C-H bonds; Peaks at 1584 cm^{-1} and 1390 cm^{-1} represent COO^- groups; A prominent peak at 1066 cm^{-1} indicates the presence of directional structures in the straw biochar; Peaks at 868 cm^{-1} and 814 cm^{-1} correspond to the bending vibrations of aromatic C-H bonds.

3.2. Effects of biochar application on soil CO₂ efflux rate

3.2.1. Variations in CO₂ efflux rates at different application rates within the same soil layer

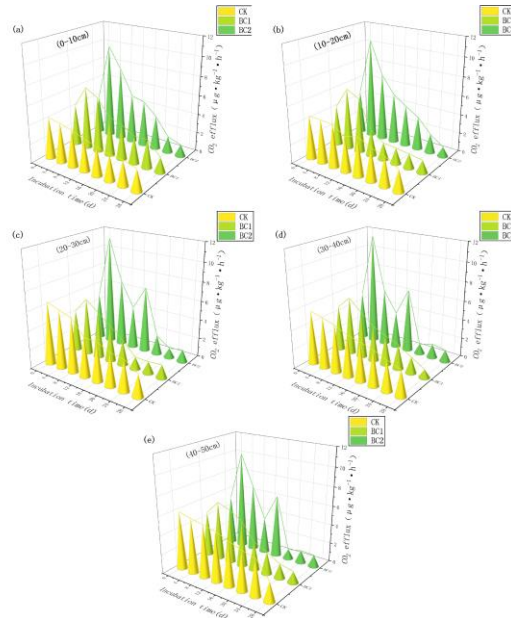


Figure 3: CO₂ efflux rate changes in straw biochar-amended soils at 0-10, 10-20, 20-30, 30-40, and 40-50 cm depths (panels a-e)

Figure 3(a) illustrates the changes in CO₂ efflux rates in the 0–10 cm soil layer following straw biochar application. In the CK (control) treatment, the CO₂ efflux rate gradually declined throughout the incubation period. In the BC1 treatment (1% biochar addition), a significant increase in CO₂ efflux was observed on the 4th day of incubation. In the BC2 treatment (2% biochar addition), the CO₂ efflux rate increased even more sharply on the 4th day compared to BC1. For soil layers other than 0–10 cm and 10–20 cm, a notable rise in CO₂ efflux occurred on the 20th day, followed by a decline and stabilization at lower levels.

As shown in Figure 3(b), in the CK treatment, the CO₂ efflux rate in the 10–20 cm layer remained relatively stable during the early incubation period (0–8 days), slightly decreased by the 12th day, temporarily increased on the 16th day, and then declined gradually in the later stages. In the BC1 treatment, the CO₂ efflux rate showed a distinct rise on the 4th day, remained stable until the 8th day, and then was significantly lower than that of CK between the 12th and 28th days. When the biochar application rate increased to 2% (BC2), the CO₂ efflux rate rose more markedly, peaking at 10.55 $\mu\text{g}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$, followed by a continuous decline to 1.99 $\mu\text{g}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$ on the 28th day, which was lower than both CK and BC1.

With increasing soil depth, the effect of biochar on CO₂ efflux varied. In the CK treatment, CO₂ efflux rates declined slowly over time, decreasing from 6.55 $\mu\text{g}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$ on day 0 to 3.21 $\mu\text{g}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$ by day 28. In BC1, the efflux rate peaked at 5.89 $\mu\text{g}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$ on the 4th day. In BC2, CO₂ efflux increased from 5.00 $\mu\text{g}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$ on day 0 to 11.35 $\mu\text{g}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$ on day 4, decreased thereafter, reaching 6.89 $\mu\text{g}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$ on day 20, and dropped to 2.30 $\mu\text{g}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$ by the end of incubation.

The changes in CO₂ efflux rates in the 30–40 cm and 40–50 cm soil layers during the incubation period are shown in Figures 3(d) and 3(e), respectively. In these two layers, there was no significant difference in CO₂ efflux rates between the CK and BC1 treatments at the early stage. However, as incubation progressed, the efflux rate in BC1 decreased more rapidly than in CK, and after the 20th day, BC1 exhibited significantly lower CO₂ efflux rates compared to CK. On the 4th day, the CO₂

efflux rate for BC2 was $11.55 \mu\text{g}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$ in the 30–40 cm layer, higher than the $10.22 \mu\text{g}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$ recorded for the 40–50 cm layer.

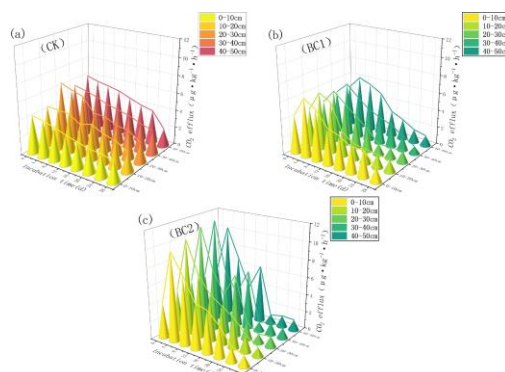


Figure 4: CO₂ efflux rate changes across five soil layers for CK, BC1, and BC2 panels (a-c)

As shown in Figure 4(a), on day 0, the CO₂ efflux rate followed the order: 20–30 cm > 40–50 cm > 30–40 cm > 10–20 cm > 0–10 cm. The efflux rates in all five soil layers decreased continuously throughout the incubation period. In Figure 4(b), a significant increase in CO₂ efflux rates was observed across all soil layers on the 4th day. The 0–10 cm and 10–20 cm layers were more sensitive to biochar application, showing increases of 50.92% and 52.00%, respectively, compared to day 0. By the end of incubation, the CO₂ efflux rate in the 0–10 cm layer was significantly higher than in the other layers, with the 30–40 cm layer having the lowest rate at $0.86 \mu\text{g}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$ on day 28. As the biochar application rate increased, the impact on CO₂ efflux rates across the soil layers also varied. On the 4th day, all five layers exhibited a marked rise in CO₂ efflux rates, which then declined gradually. Notably, except for the 0–10 cm and 10–20 cm layers, the other three layers showed a secondary peak in CO₂ efflux rates on the 16th day before decreasing significantly thereafter.

3.3. Effects of biochar application on soil cumulative CO₂ emissions

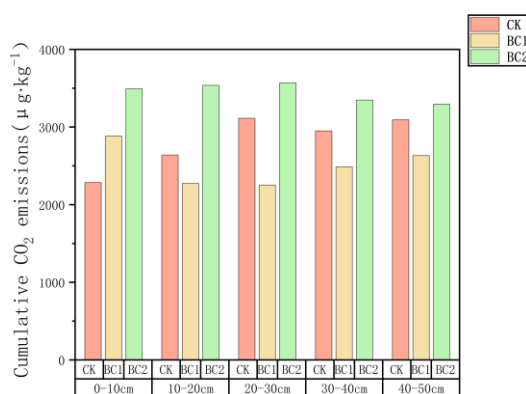


Figure 5: Cumulative CO₂ emissions from five soil layers under varying biochar application rates

The cumulative CO₂ emissions of the five soil layers under CK treatment are shown in Figure 5. Overall, cumulative emissions increased with soil depth. The cumulative CO₂ emission at the 0–10 cm layer was $2,285.52 \mu\text{g}\cdot\text{kg}^{-1}$, while at the 40–50 cm layer it reached $3,392.32 \mu\text{g}\cdot\text{kg}^{-1}$. Although the cumulative emission from the 30–40 cm layer was lower than that from the 20–30 cm layer, it was still higher than that of the 10–20 cm layer. The 0–10 cm layer exhibited the highest cumulative CO₂ emission among all layers, reaching $2,883.36 \mu\text{g}\cdot\text{kg}^{-1}$, while the 10–20 cm and 20–30 cm layers showed no significant difference. For the other two layers, cumulative emissions increased with depth.

When the straw biochar application rate increased to 2%, cumulative CO₂ emissions generally increased with soil depth in the 0–10 cm, 10–20 cm, and 20–30 cm layers, though the differences were not significant. In the 0–10 cm layer, cumulative CO₂ emissions increased with higher biochar addition, whereas in other layers, cumulative emissions under BC1 treatment were lower than those under CK and BC2 treatments.

3.4. Effects of biochar application on soil physicochemical properties

3.4.1. Effects of biochar application on soil TOC content

Figure 6 compares the TOC content across different soil layers after straw biochar application. In the 20–30 cm layer, there was no significant difference in TOC content between BC1 and BC2. Except for the 0–10 cm layer under BC1 treatment, the TOC content in BC1 treatments was significantly higher than that of CK treatments across the other four layers.

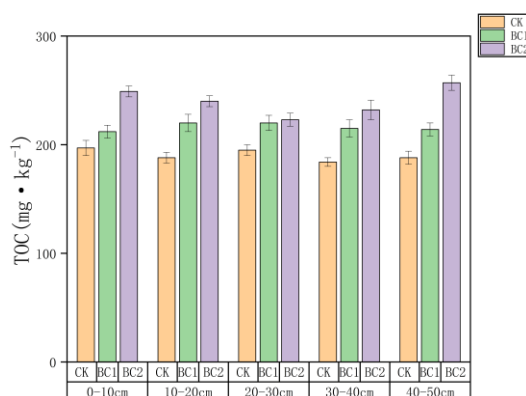


Figure 6: TOC content comparison in straw biochar-amended treatments

3.4.2. Effects of biochar application on soil pH

Figure 7 presents the pH comparison across treatments. In the 0–10 cm and 40–50 cm soil layers, no significant differences in pH were observed among the three treatments. In the 10–20 cm and 20–30 cm layers, pH values in BC1 and BC2 treatments were higher than those in CK, with no significant difference between BC1 and BC2. In the 30–40 cm layer, pH increased with higher biochar application rates.

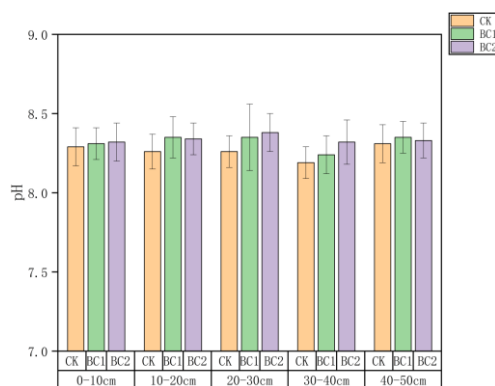


Figure 7: Comparative analysis of pH in straw biochar-amended treatments

3.4.3. Effects of biochar application on soil NO_3^- -N content

Figure 8 shows the NO_3^- -N content across treatments. In the 0–10 cm and 10–20 cm layers, NO_3^- -N contents in BC1 and BC2 were significantly higher than in CK, indicating that biochar application increased NO_3^- -N content in these layers. In the 20–30 cm and 30–40 cm layers, NO_3^- -N content under BC1 showed no clear trend compared to CK, while BC2 significantly increased NO_3^- -N content compared to CK. In the 40–50 cm layer, NO_3^- -N content under BC1 was significantly lower than CK, and BC2 showed a content similar to CK, suggesting that higher biochar application rates had limited effects on NO_3^- -N content at this depth.

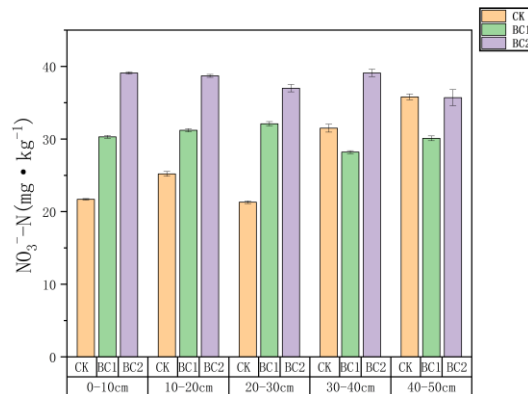


Figure 8: Comparative analysis of NO_3^- -N across straw biochar-amended treatments

3.4.4. Effects of biochar application on soil NH_4^+ -N content

Figure 9 illustrates the NH_4^+ -N content across different treatments. In the 0–10 cm layer, NH_4^+ -N contents in BC1 and BC2 were significantly higher than in CK. In the 10–20 cm and 20–30 cm layers, NH_4^+ -N content decreased with increasing biochar application rates. In the 30–40 cm layer, the highest NH_4^+ -N content was observed in BC1, while the lowest was in CK. In the 40–50 cm layer, BC1 showed the highest content, while CK showed the lowest.

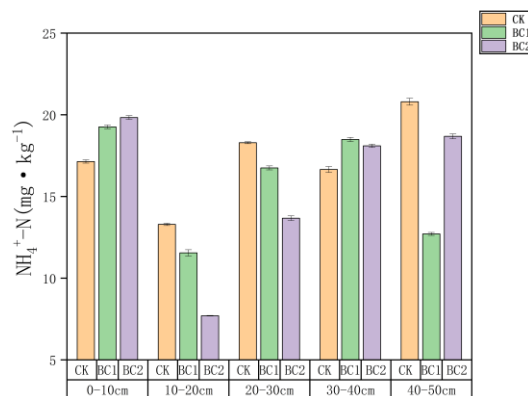


Figure 9: Comparative analysis of ammonium NH_4^+ -N across biochar-amended treatments

3.5. Correlation analysis between CO_2 emissions, biochar, and soil physicochemical properties

According to Table 3, the CO_2 efflux rate showed a significant negative correlation ($P < 0.05$) with cumulative CO_2 emissions and NO_3^- -N content, and a significant positive correlation ($P < 0.05$) with pH, NH_4^+ -N content, and TOC content.

Cumulative CO₂ emissions were negatively correlated ($P < 0.05$) with pH, NH₄⁺-N content, and TOC content, although the correlation with TOC content was not significant. In addition, cumulative emissions were positively correlated ($P < 0.05$) with NO₃⁻-N content and biochar application rate.

Table 2: Correlation analysis between soil CO₂ emission and soil physicochemical properties

	CO ₂ Emission Rate	Cumulative CO ₂ Emission	pH	NO ₃ ⁻ N	NH ₄ ⁺ -N	TOC	Biochar Application Rate
CO ₂ Emission Rate	1						
Cumulative CO ₂ Emission	-0.579*	1					
pH	0.802*	-0.64*	1				
NO ₃ ⁻ -N	-0.380*	0.906*	0.378*	1			
NH ₄ ⁺ -N	0.468*	-0.838*	0.524*	0.768*	1		
TOC	0.522*	-0.09	0.730*	0.161	0.066	1	
Biochar Application Rate	0.126	0.227*	0.392*	0.446*	0.09342	0.7078*	1

* $P \leq 0.05$

4. Discussion

Biochar is composed primarily of aromatic and alkyl structures, and its inherent stability prevents it from rapid degradation in the soil, thereby contributing to the enhancement of soil total organic carbon (TOC) content [22-23]. A higher TOC content, in turn, strengthens the nutrient cycling capacity of the soil [24-25]. Due to its well-developed pore structure and extensive specific surface area, biochar readily interacts with inorganic substances in the soil to form aggregates, thereby protecting organic matter within aggregates from microbial decomposition and reducing CO₂ emissions. Moreover, functional groups such as -NH₂ and -OH on biochar surfaces exhibit stronger CO₂ adsorption capacities compared to other functional groups [16]. The type and quantity of biochar functional groups are closely related to the feedstock material and pyrolysis temperature [26-28]; as pyrolysis temperature increases, the C/N and O/C ratios of biochar decrease, resulting in the decomposition and reduction of functional groups [15].

The overall trend in soil CO₂ emission rates was similar across treatments, with a peak in the early incubation period followed by a gradual decline, eventually stabilizing at later stages. Chen Hui et al. [29] reported that the application of biochar increased soil porosity, which enhanced microbial activity and consequently elevated soil respiration, leading to higher CO₂ emission rates. Liu Benjuan [30] also found that biochar application produced a positive priming effect, temporarily boosting CO₂ emissions. Yang et al. [31] indicated that biochar derived from wood, which contains more cellulose, hemicellulose, and carbohydrates than straw biochar, contributed more significantly to the increase in soil CO₂ emissions.

CO₂ cumulative emissions were significantly positively correlated with the biochar application rate ($P < 0.05$). Cheng Gong et al. [32] found that applying biochar at 15 t·hm⁻² achieved the optimal CO₂ mitigation effect, whereas increasing the application rate weakened the suppression of CO₂ emissions.

Biochar addition increases the availability of carbon substrates for soil microbes, stimulating microbial respiration [33]. Zheng Jian et al. [34] observed that applying biochar to different soil layers in the rhizosphere of tomatoes led to varying degrees of NO_3^- -N content increases across layers. Due to its strong adsorption properties, biochar can also reduce nitrogen losses. Wang Xuanming [25,35] demonstrated that field application of $12 \text{ t} \cdot \text{hm}^{-2}$ of biochar significantly enhanced NH_4^+ -N levels, although the effect was less pronounced with aged biochar compared to fresh biochar. Given that biochar typically exhibits weak alkalinity, its application initially induces a "liming effect," markedly raising soil pH levels during the early incubation period before gradually returning to baseline [10].

5. Conclusion

The experimental results showed that the BC1 treatment had the most significant impact on CO_2 emission rates in the 0–10 cm and 10–20 cm soil layers, increasing the rates by 50.92% and 52.00%, respectively, compared to the CK treatment. In the 20–30 cm layer, the emission rate was higher during the early incubation stage but declined over time. The 30–40 cm soil layer exhibited a weaker response to biochar application, with an overall emission rate lower than that of the 0–10 cm and 10–20 cm layers. In the 40–50 cm layer, CO_2 emission rates continued to decrease over time, with a more pronounced suppressive effect of biochar. Under the BC1 treatment, the cumulative CO_2 emissions in the 0–10 cm layer increased by 26.16% compared to CK, while cumulative emissions in the other four layers were lower than those under CK and BC2, particularly with the 20–30 cm layer showing the most significant reduction. Overall, applying 1% (w/w) straw biochar to deeper soil layers effectively reduced soil CO_2 emissions, with the 20–30 cm layer demonstrating the greatest mitigation effect relative to other layers.

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