Hu *et al. Chem. Biol. Technol. Agric.* (2023) 10:46
https://doi.org/10.1186/s40538-023-00422-7

Chemical and Biological Technologies in Agriculture

RESEARCH

Open Access

Effects of bagasse biochar application on soil organic carbon fixation in manganese-contaminated sugarcane fields

Lening Hu[1], Yu Yang[1], Xue Hui Liu[1], SHuangli Li[1], Ke Li[2*] and Hua Deng[1]

Abstract

Background In recent years, there have been several studies on the remediation of heavy metal pollution in soil by the application of biochar. However, little attention has been paid to understanding the effects and underlying mechanisms of biochar on soil carbon sequestration in manganese-contaminated farmlands. Therefore, in this study, bagasse biochar was applied to the soil in different proportions (0%, 0.5%, 2%, and 5%) and the test was conducted indoors for 100 days at a constant temperature. Soil physical and chemical properties, organic carbon mineralization, organic carbon components, and enzyme activities were analyzed in this study.

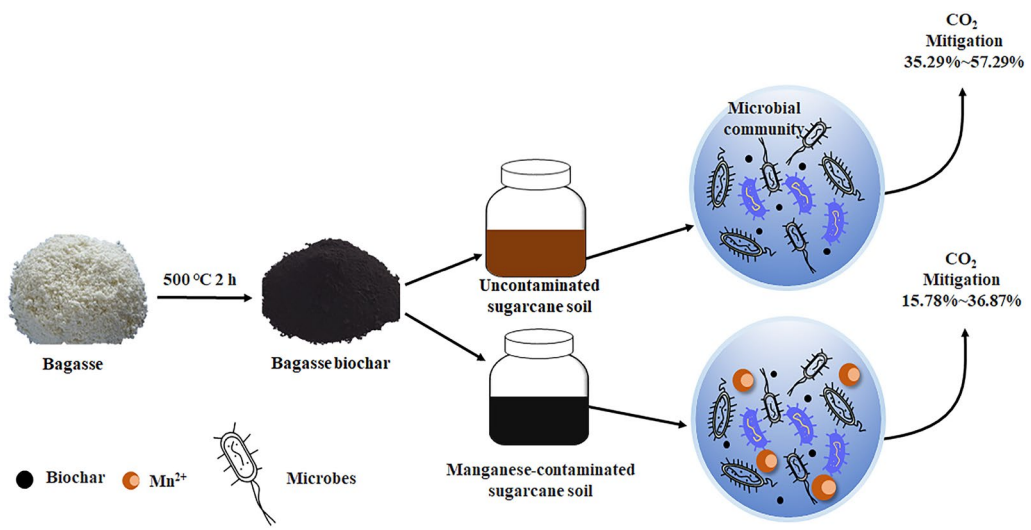
Results In this study, when compared with the control, the application of 0.5%, 2%, and 5% bagasse biochar to the manganese-contaminated sugarcane field soil effectively reduced the cumulative CO_2 emissions, i.e., decreased by 123.18 mg·kg^{-1}, 208.28 mg·kg^{-1}, and 287.79 mg·kg^{-1}, respectively. Among the different treatment groups, the highest decrease in cumulative CO_2 emissions was observed in the 5% bagasse biochar-treated soil when compared with the control. The application of bagasse biochar increased the soil microbial biomass carbon content by 12.72 mg·kg^{-1}, 13.71 mg·kg^{-1}, and 15.10 mg·kg^{-1}, respectively when compared with the control. The soil nutrients and enzyme activities significantly increased with the increase in biochar application amount.

Conclusions The application of bagasse biochar to manganese-contaminated sugarcane soil field effectively inhibited the mineralization of soil organic carbon, improved the carbon sequestration potential of manganese-contaminated sugarcane field soil, and provided a theoretical basis for the carbon sequestration mechanism in manganese-contaminated farmland soil.

Keywords Biochar, Mineralization, Soil enzymes, Soil nutrient, Organic carbon fraction

*Correspondence:
Ke Li
likeniko@126.com
Full list of author information is available at the end of the article

Graphical Abstract



Introduction

Farmland carbon storage accounts for about 8–10% of terrestrial carbon storage, which forms an active part of the global carbon pool. This pool is easily affected by human activities, which alters the farmland carbon pool, which in turn can influence climate change [1]. Traditionally, China is an agrarian country, and agriculture is an important source of greenhouse gases. The CO_2, CH_4, and N_2O emissions from agricultural sources are 310 million tons, 9.685 million tons, and 665,000 tons, respectively [2]. According to the statistics, soil heavy metal pollution is a critical issue in China, with about 10 million hectares of farmland soil affected by heavy metal pollution [3]. Heavy metal pollution may affect CO_2 emissions. Bian et al. [4] observed that heavy metal pollution significantly increased soil CO_2 emission rate in heavy metal-contaminated farmland. Zhou et al. [5] studied heavy metal-contaminated soil and revealed that heavy metal pollution can reduce CO_2 emissions. The processes by which heavy metal pollution affects soil CO_2 emissions are still debatable. Therefore, it is of great significance to explore the mechanism underlying carbon sequestration in heavy metal-contaminated farmland soils.

Sugarcane is an important raw material for sugar production. According to the statistics, the total output of sugarcane in southern China is more than 70 million tons, with the annual production of bagasse of about 20 million tons [6]. At present, most of the bagasse in China is used for power generation and paper manufacturing. The utilization rate of bagasse is low, which not only leads to the wastage of resources but also leads to environmental pollution. The mass fraction of bagasse cellulose is about 43.80%, with a carbon content of about 44.17%, and bagasse cellulose is an excellent raw material for biochar preparation [7]. Biochar is a carbon-rich solid with a developed pore structure, high aromatization, and large specific surface area, which is obtained by the pyrolysis of animal and plant residues at high temperatures and oxygen-limiting conditions (350–600 ℃) [8]. When applied to the soil, it can improve soil structure, increase soil nutrients and carbon sequestration, and reduce greenhouse gas emissions [9]. The application of biochar in heavy metal-contaminated paddy fields reduced soil CO_2 emissions by 16–24% [10]. Wu et al. [11] performed a 6-year field experiment and demonstrated that the application of biochar reduced CH_4 and N_2O emissions in soil by 11.2–17.5% and 19.5–26.3%, respectively. The conversion of bagasse into biochar can enhance its carbon sequestration capacity. In recent years, several studies were conducted on the remediation of heavy metal pollution in soil by biochar [12, 13], but only a few studies elucidate the mechanism underlying carbon sequestration in manganese-contaminated soil. Therefore, it is extremely important to study the greenhouse gas emissions from contaminated farmlands and improve the carbon sequestration capacity of contaminated soil to alleviate the global greenhouse effect.

Therefore, the soil from manganese-contaminated sugarcane fields in Guangxi, China was selected as the research object in this study. The different proportions of exogenous bagasse biochar were applied to carry

out a 100-day incubation experiment at room temperature. The effects of bagasse biochar on the physical and chemical properties, organic carbon mineralization, organic carbon components, and enzyme activities of manganese-contaminated farmland soil were analyzed to provide a conceptual framework for the carbon fixation mechanism of biochar in manganese-contaminated farmlands.

Materials and methods

Experimental materials

The soil samples were collected from uncontaminated sugarcane fields (23°20′57″ N, 108°51′41″ E) in Nanning, Guangxi, and manganese-contaminated sugarcane fields (23°56′47″ N, 109°16′27″ E) in Laibin, Guangxi. The selected soil is a typical acidic red soil in southern China. After the removal of the stones and plant roots, the soil samples were placed at room temperature and dried naturally. The samples were crushed with a mortar and passed through 2 mm nylon sieves. The sieved samples were then placed in sealed bags for use, and their chemical properties were analyzed. The basic chemical properties of the test soils are shown in Table 1.

Biochar was prepared by pyrolysis of bagasse in a muffle furnace at 500 ℃ for 2 h under oxygen-limiting conditions. The bagasse required for the preparation of biochar was collected from Laibin, Guangxi. The basic properties of biochar are shown in Table 2.

Experimental design

The research experiment was started in 2021 at the Key Laboratory of Ecology of Rare and Endangered Species and Environmental Protection (Guangxi Normal University), Ministry of Education, China. The experimental design included sugarcane field soil + 0% biochar, sugarcane field soil + 0.5% biochar, sugarcane field soil + 2% biochar, sugarcane field soil + 5% biochar, manganese-contaminated sugarcane field soil + 0% biochar, manganese-contaminated sugarcane field soil + 0.5% biochar, manganese-contaminated sugarcane field soil + 2% biochar, and manganese-contaminated sugarcane field soil + 5% biochar labeled as 0% ZSB, 0.5% ZSB, 2% ZSB, 5% ZSB, 0% MSB, 0.5% MSB, 2% MSB, and 5% MSB, respectively. A total of 24 treatments were carried out with each treatment repeated three times.

Table 2 Basic properties and elemental content of biochar

	pH	Productivity (%)	C%	H%	H/C
Bagasse biochar	8.56	28.13	78.19	2.87	0.51

The air-dried soil passed through a 2 mm sieve was taken into a 2 L polyethylene bottle, and biochar was applied according to the experimental design mentioned above. After mixing biochar with soil, deionized water was added, and the field water holding capacity was maintained at 40–60% by the weighing method. The soil was continuously cultured in a constant temperature incubator at 25 ℃. 150 g of soil samples were collected and analyzed on days 1, 3, 5, 10, 15, 20, 30, 40, 60, 80, and 100. Another batch of soil samples was set up and subjected to the same conditions for 1 week, with 50 g of soil and the corresponding proportion of biochar. A 10 mL beaker filled with a certain concentration of sodium hydroxide solution (0.1 mol·L^{-1}) was placed into a white polyethylene bottle, and the CO_2 emissions were analyzed on days 1, 3, 5, 10, 15, 20, 30, 40, 60, 80, and 100.

Measuring indices

Soil pH was measured by a pH meter (water–soil ratio of 2.5:1) [14]. The cation exchange capacity (CEC) was determined by the ammonium acetate method [15]. Available phosphorus (AP) was determined by the $NaHCO_3$ extraction–molybdenum antimony colorimetric method [16]. Available potassium (AK) content was determined by the ammonium acetate extraction method using a flame photometer [17]. Microbial biomass carbon (MBC) was determined by the chloroform fumigation extraction method [18]. Soil organic carbon (SOC) was determined by the potassium dichromate volumetric method with external heating [19]. Dissolved organic carbon (DOC) was extracted using deionized water and analyzed with a TOC analyzer [20]. Readily oxidized organic carbon (ROC) was determined using potassium permanganate oxidation [21]. Catalase activity was determined by potassium permanganate titration [22]. Urease activity was determined by the

Table 1 Chemical properties of soil

Properties	pH	AP (mg·kg^{-1})	AK (mg·kg^{-1})	SOC (g·kg^{-1})	CEC (cmol·kg^{-1})	Mn (mg·kg^{-1})
Uncontaminated sugarcane soil	6.59	18.52	5.39	1.01	18.9	/
Manganese-contaminated sugarcane soil	5.35	3.20	2.13	0.86	8.40	2075.13

AP available phosphorus, *AK* available potassium, *SOC* soil organic carbon, *CEC* Cation exchange capacity

indophenol blue colorimetric method [22]. Soil CO_2 emissions were measured using the alkali absorption method [23].

Calculations

The equation [24] for CO_2 emissions is given as follows:

$$CO_2\,(\mathrm{mL\,Kg^{-1}}) = \left\{\left[(V_0 - V) \times c \times 0.022 \times (22.4/44) \times 1000\right] \times 2 \times 1000\right\}/m \quad (1)$$

In Eq. (1), V_0 is the volume of standard hydrochloric acid consumed during blank titration, V is the volume of standard hydrochloric acid consumed during sample titration, c is the concentration of standard hydrochloric acid, 0.022 is the molar mass of carbon dioxide (1/2 CO_2), M (1/2 CO_2)=0.022 g·mmol^{-1}, 22.4/44 is milliliters per gram of CO_2 under standard conditions, and m is the weight of soil CO_2 during incubation.

CO_2 release rate (mg·kg^{-1}·d^{-1})=amount of organic carbon mineralized/Δt, where Δt is the culture interval (d).

Cumulative soil CO_2 emissions were calculated as the total CO_2 emissions from the 1 day of culture to the day of measurement.

The soil carbon mineralization under different culture conditions was fitted by a first-order kinetic equation [18].

$$C_t = C_0\left(1 - e^{-kt}\right) \quad (2)$$

In Eq. (2), C_t is the cumulative mineralization amount at culture time t (d), C_0 is the potential soil carbon mineralization (mg·kg^{-1}); k is the rate constant of soil carbon mineralization, d^{-1}, and t is the culture time, d.

Soil organic carbon stability coefficient [25] is given by Eq. (3).

$$\text{Soil organic carbon stability coefficient} = (\mathrm{SOC} - \mathrm{ROC})/\mathrm{SOC} \quad (3)$$

Statistical Analyses

Excel 2016 and SPSS 22.0 (IBM Corporation, United States) were used for data analysis and processing. The relevant index data were expressed as mean ± standard deviation, and the correlation diagram was drawn using Origin 2023 (OriginLab Corporation, United States).

Results

Effects of biochar on soil pH and CEC

The application of bagasse biochar increased the pH of both manganese-contaminated sugarcane field soil and uncontaminated sugarcane field soil (Fig. 1). pH also increased with the increase in biochar application amount, but the change was not obvious with time. The pH of the uncontaminated sugarcane field with 0.5% biochar decreased with the culture time, while there was no significant change in the pH of the 2% and 5%

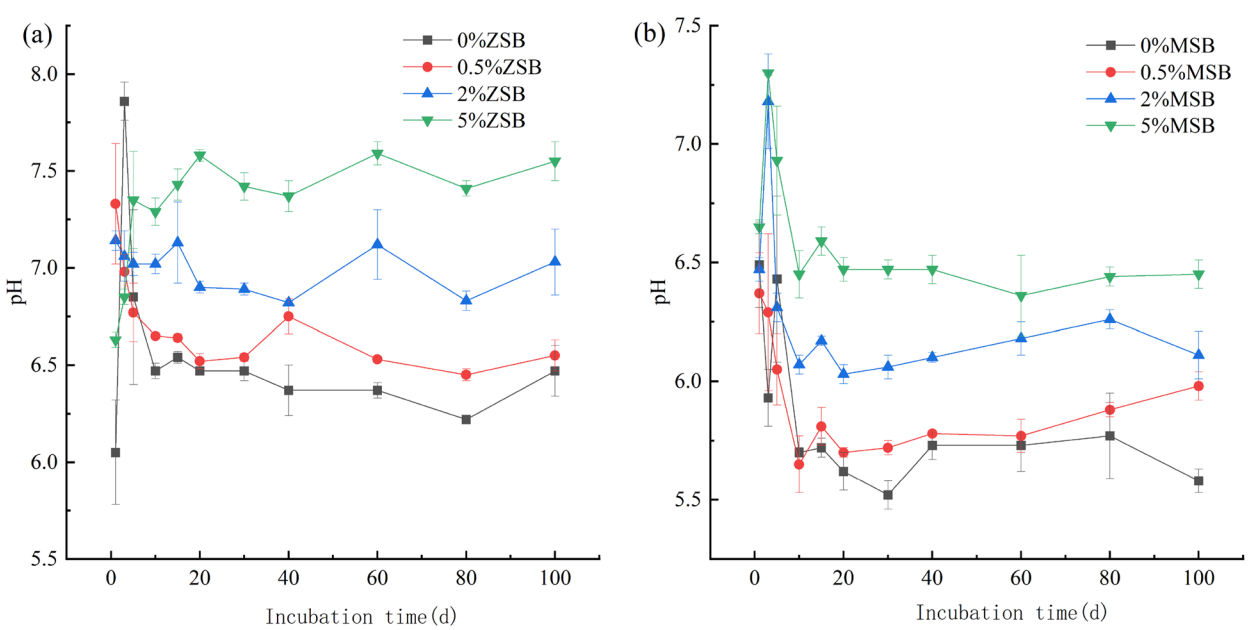


Fig. 1 Effects of biochar on soil pH. (**a**) Uncontaminated sugarcane field soil. (**b**) Manganese-contaminated sugarcane field soil

biochar-treated soil with time. The pH of manganese-contaminated sugarcane field soil with 0.5% biochar initially decreased and then increased with time, and the pH of the manganese-contaminated sugarcane field soil with 2% and 5% biochar decreased with time. The pH of the uncontaminated sugarcane field soil was higher than that of the manganese-contaminated sugarcane field soil. Biochar application had little effect on the pH of the manganese-contaminated sugarcane field soil.

As shown in Fig. 2, the CEC of uncontaminated sugarcane field soil during the entire incubation period was 3.56–61.01 cmol·kg^{-1}, and the CEC of manganese-contaminated sugarcane field soil was 3.62–49.13 cmol·kg^{-1}. Compared with that of the control, the CEC of uncontaminated sugarcane soil increased by 4.57–27.39%, 10.80–73.13%, and 17.57–74.80% when treated with 0.5%, 2%, and 5% biochar for 0–40 days, respectively. After 60 days of culture, the CEC increased gradually and then stabilized. The CEC of control (0% ZSB) increased to 61.01 cmol·kg^{-1}, which was higher than that of other treatments. The CEC of biochar treatment in manganese-contaminated sugarcane field soil increased with the proportion of biochar as well as with time. When compared with that of the control (0% MSB), the CEC of 0.5% MSB, 2% MSB, and 5% MSB increased by 0.87–50.83%, 7.30–65.11%, and 26.59–175.64%, respectively. It increased slowly after 40 days of culture and gradually stabilized.

Effects of biochar on soil nutrients

From Fig. 3, it can be observed that during the entire culture process, the AP content in manganese-contaminated sugarcane field soil and uncontaminated sugarcane field soil increased with the increase in bagasse biochar amount. When compared with the control, the application of biochar can significantly increase the soil AP content in the soil. The AP content of the uncontaminated sugarcane field followed the order: 5% ZSB > 2% ZSB > 0.5% ZSB > 0% ZSB. The AP content in 0.5% ZSB, 2% ZSB, and 5% ZSB increased by 143.85%, 417.06%, and 663.32%, respectively, when compared with that in the control (0% ZSB). The AP content in 2% ZSB and 5% ZSB was significantly higher than that in 0.5% ZSB. When biochar was applied to the manganese-contaminated sugarcane field soil, only a minimal change was observed in the AP content in each treatment during 0–40 days. After 40 days, the largest increase in the AP content was observed in 5% MSB followed by 2% MSB, and the smallest increase was observed in 0.5% MSB, which was significantly higher than that in the control (0% MSB). Thus, the increase in AP content followed the order: 5% MSB > 2% MSB > 0.5% MSB > 0% MSB.

As shown in Fig. 4, different bagasse biochar amounts applied to manganese-contaminated sugarcane field soil and uncontaminated sugarcane field soil during the entire culture process can increase the soil AK content to different degrees, which exhibited the following order: 5% ZSB > 2% ZSB > 0.5% ZSB > 0% ZSB and 5% MSB > 2%

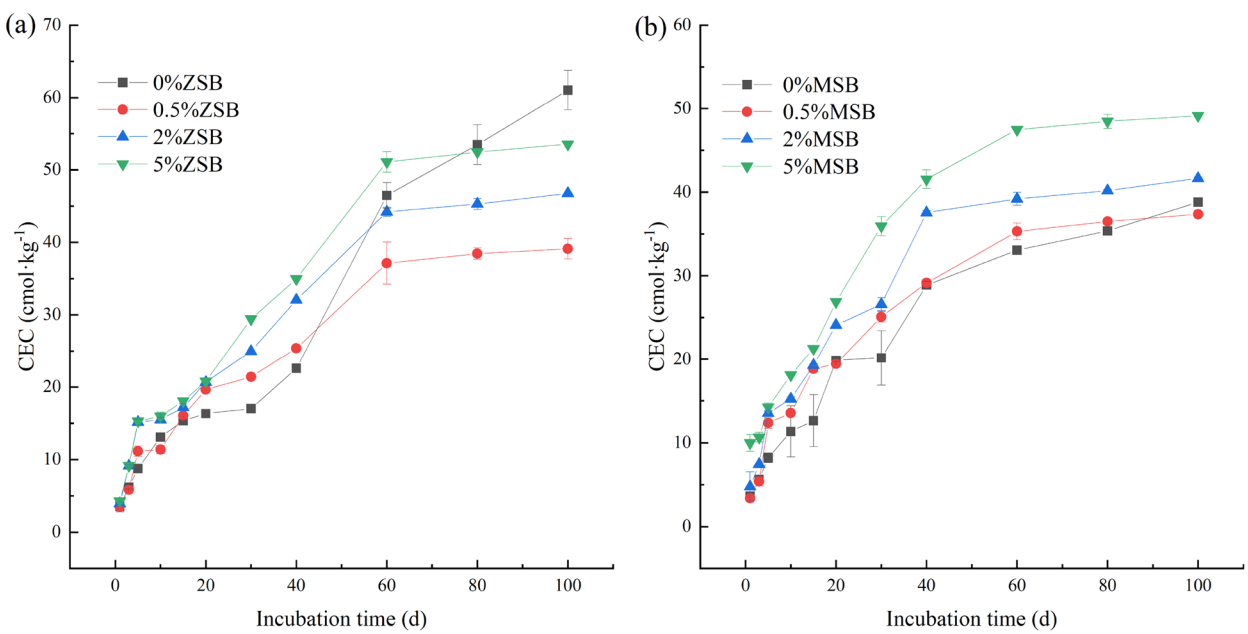


Fig. 2 Effects of biochar on soil cation exchange capacity (CEC). (**a**) Uncontaminated sugarcane field soil. (**b**) Manganese-contaminated sugarcane field soil

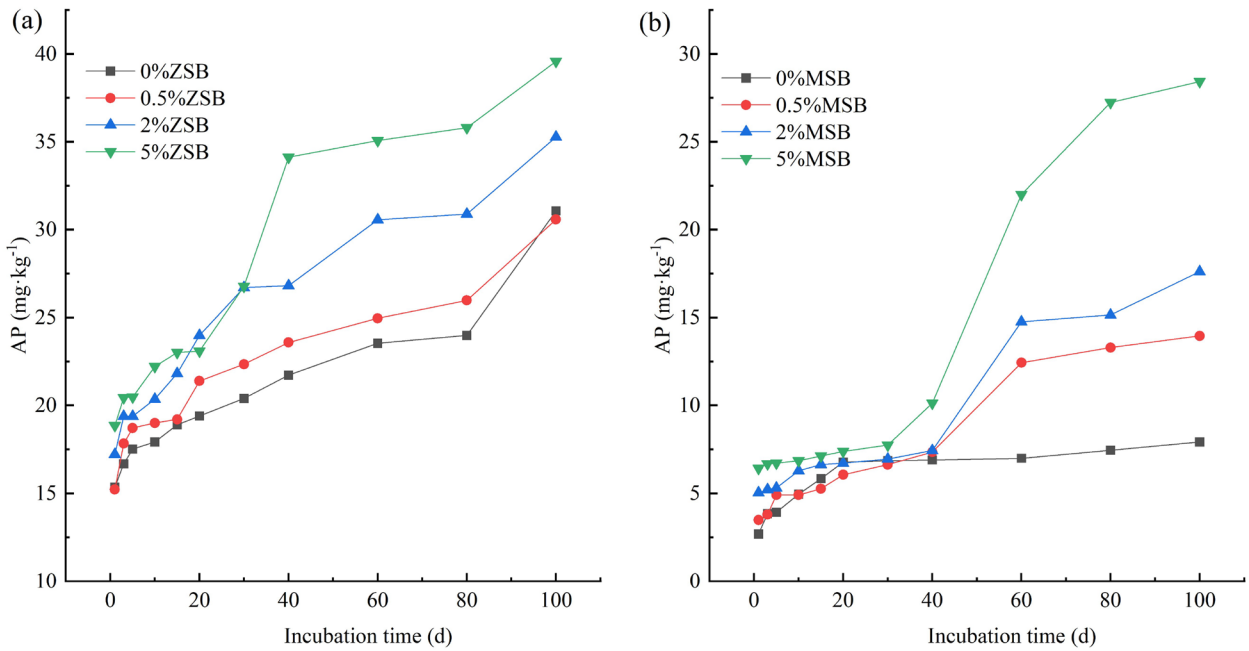


Fig. 3 Effects of biochar on soil available phosphorus (AP). (**a**) Uncontaminated sugarcane field soil. (**b**) Manganese-contaminated sugarcane field soil

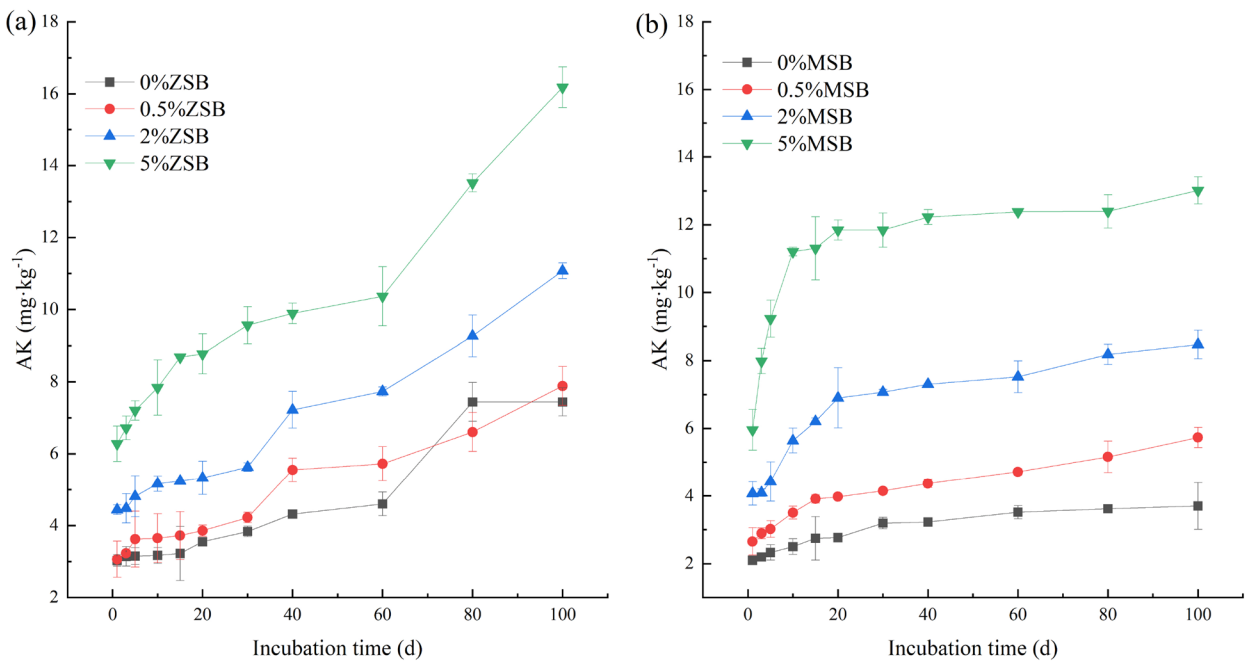


Fig. 4 Effects of biochar on soil available potassium (AK). (**a**) Uncontaminated sugarcane field soil. (**b**) Manganese-contaminated sugarcane field soil

MSB > 0.5% MSB > 0% MSB. During the incubation period, the AK content in 0.5% ZSB, 2% ZSB, and 5% ZSB increased by 5.95%, 48.85%, and 117.42% on average, respectively, when compared with that in the control (0% ZSB). When compared with that in the control (0% MSB), the AK content in 0.5% MSB, 2% MSB, and 5% MSB increased by 54.82%, 210.11%, and 251.66% on average, respectively, and the AK content in the soil treated

with biochar was significantly higher than that in the control.

Effects of biochar on SOC mineralization

As shown in Fig. 5, when compared with the control, the application of bagasse biochar significantly reduced the CO_2 emission rates in both the sugarcane fields, and the emission rate decreased with the increase in biochar amount. During the entire incubation period, the CO_2 emission rates in the two biochar-applied sugarcane fields were lower than those in the control. During the early stage of culture, the CO_2 emission rates from biochar-applied uncontaminated sugarcane field soil followed the order: 0% ZSB > 0.5% ZSB > 2% ZSB > 5% ZSB, and the CO_2 emission rates from biochar-applied manganese-contaminated sugarcane field soil followed the order: 0% MSB > 0.5% MSB > 2% MSB > 5% MSB. In the uncontaminated sugarcane field soil, the CO_2 emission rate decreased rapidly within 0–10 days. Compared with the control (0% ZSB), the application of 0.5%, 2%, and 5% biochar decreased the CO_2 emission rates by 17.83 times, 18.27 times, and 25.08 times, respectively. In the manganese-contaminated sugarcane soil, the application of 0.5%, 2%, and 5% biochar decreased the CO_2 emission rates by 14.74 times, 17.42 times, and 19.17 times, respectively, when compared with the control (0% MSB). During the entire incubation period, the CO_2 emission from each treated soil can be divided into three stages: a rapid declining stage of the soil CO_2 emission rate during 0–10 days, a gradual decrease in the soil CO_2 emission rate during 10–40 days, and a gradual stabilization of the CO_2 emission rate after 40 days.

As shown in Fig. 6, the cumulative CO_2 emissions from the two sugarcane fields decreased with the increase in the bagasse biochar application amount. After 0–40 days of incubation, the cumulative CO_2 emissions from each treatment increased rapidly and then gradually stabilized. During the entire incubation process, the cumulative CO_2 emissions from the uncontaminated sugarcane soil treated with different proportions of biochar were significantly lower than those in the control (0% ZSB). At the end of the incubation period, the cumulative CO_2 emissions from ZSB followed the order: 0% ZSB > 0.5% ZSB > 2% ZSB > 5% ZSB, and the cumulative CO_2 emissions from MSB followed the order 0% MSB > 0.5% MSB > 2% MSB > 5% MSB. When compared with those from the control (0% ZSB), the cumulative CO_2 emissions from the uncontaminated sugarcane field soil treated with different proportions of biochar decreased by 35.29–57.29%. Similarly, when compared with those from the control (0% MSB), the cumulative CO_2 emission from the manganese-contaminated sugarcane field soil treated with different proportions of biochar decreased by 15.78–36.87%.

As shown in Table 3, the first-order kinetic equation accurately simulated the mineralization dynamics of SOC during the 100-day incubation period. In general, the potential mineralization amounts of organic carbon

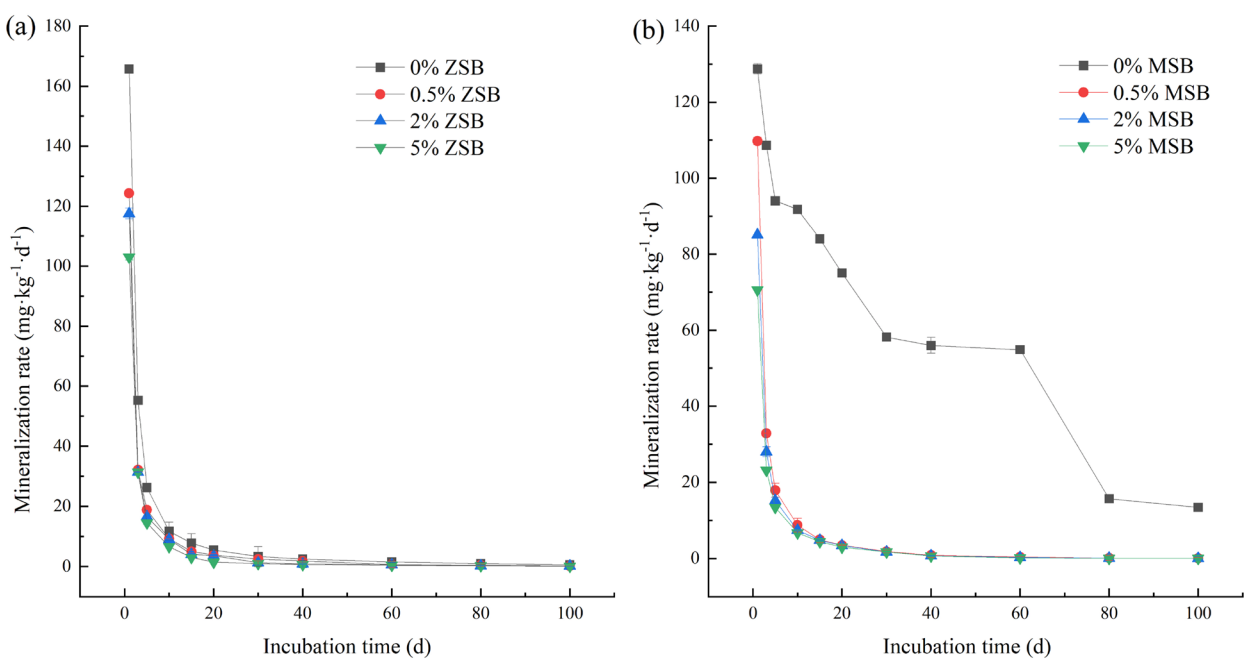


Fig. 5 Effects of biochar on mineralization rate. (**a**) Uncontaminated sugarcane field soil. (**b**) Manganese-contaminated sugarcane field soil

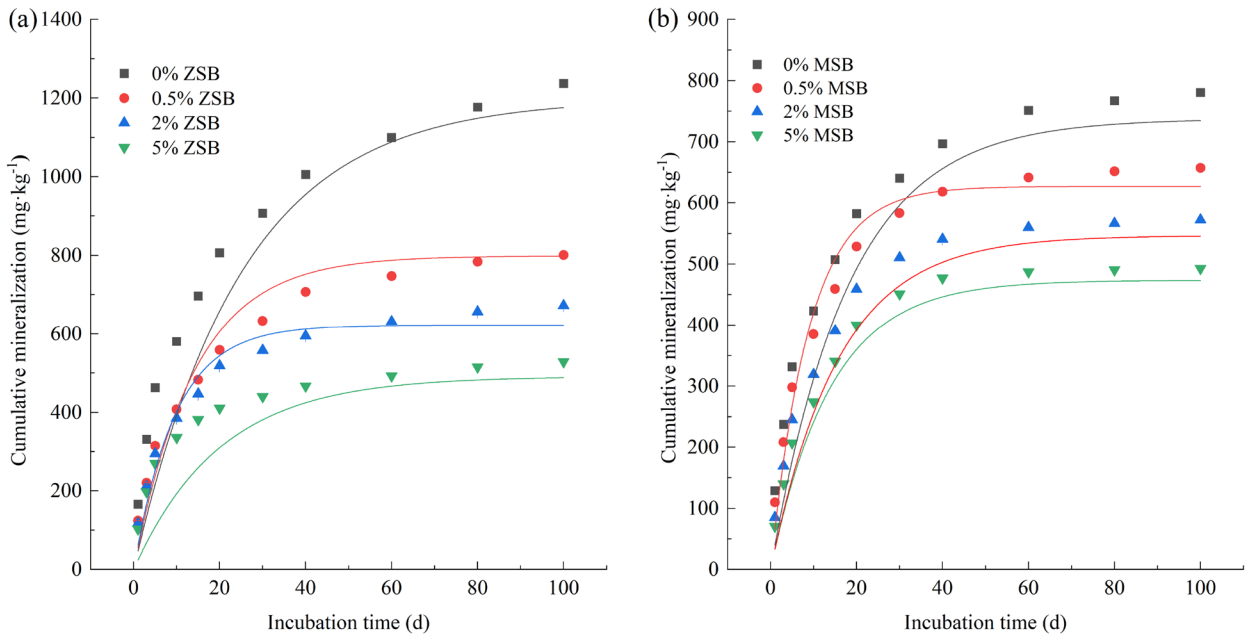


Fig. 6 Effects of biochar on cumulative mineralization. (**a**) Uncontaminated sugarcane field soil. (**b**) Manganese-contaminated sugarcane field soil

Table 3 Kinetic parameters of soil carbon mineralization in biochar-treated soils

Different Treatments	Fitting Parameters		
	C_0/μg·g^{-1}	k/d^{-1}	R^2
0%ZSB	1140.45 ± 48.48	0.069 ± 0.009	0.95
0.5%ZSB	758.529 ± 26.68	0.076 ± 0.010	0.95
2% ZSB	627.780 ± 20.03	0.099 ± 0.012	0.96
5% ZSB	481.268 ± 16.32	0.135 ± 0.019	0.94
0%MSB	740.359 ± 24.49	0.089 ± 0.010	0.95
0.5% MSB	634.238 ± 15.97	0.101 ± 0.010	0.97
2% MSB	557.396 ± 12.47	0.093 ± 0.007	0.97
5%MSB	486.594 ± 9.368	0.091 ± 0.006	0.98

ZSB indicates biochar applied to the uncontaminated sugarcane field soil, MSB indicates biochar applied to the manganese-contaminated sugarcane soil, C_0 represents the soil carbon mineralization potential, and k represents the soil carbon mineralization rate constant.

(C_0) in soils treated with different proportions of biochar were significantly different. C_0 in the uncontaminated soils treated with biochar ranged from 481.268 to 1140.45 μg·g^{-1}, and in the manganese-contaminated soils treated with biochar ranged from 486.594 to 740.359 μg·g-1. It can be observed that the mineralization potential of soil decreased with the increase in biochar amount. However, the soil carbon mineralization rate constant (k) demonstrated an opposite trend. The k value of the ZSB group varied between 0.069 and 0.135 d^{-1}, while that of the MSB group varied between 0.089 and 0.101 d^{-1}.

Effects of biochar on soil active organic carbon components

The addition of different proportions of bagasse biochar to the uncontaminated sugarcane field soil and manganese-contaminated sugarcane field soil could increase the SOC content, with the increase in biochar amount leading to increasing SOC content (Fig. 7). At the end of the incubation period, different amounts of biochar were added to the uncontaminated sugarcane field soil. When compared with the control, the addition of 5% and 2% biochar significantly increased the SOC content by 100% and 58.87%, respectively. The addition of 0.5% biochar did not significantly increase the organic carbon content. The SOC content in each treatment followed the order: 5% ZSB > 2% ZSB > 0.5% ZSB > 0% ZSB. The SOC content in the manganese-contaminated sugarcane field soil with 5%, 2%, and 0.5% biochar increased by 132.70%, 114.56%, and 33.41%, respectively, when compared with that in the control. The organic carbon content followed the order: 5% MSB > 2% MSB > 0.5% MSB > 0% MSB.

The effects of bagasse biochar application on the stability coefficient of SOC in two sugarcane fields were analyzed. As shown in Table 4, the stability coefficient of SOC in two sugarcane fields generally increased with the increase in biochar application amount.

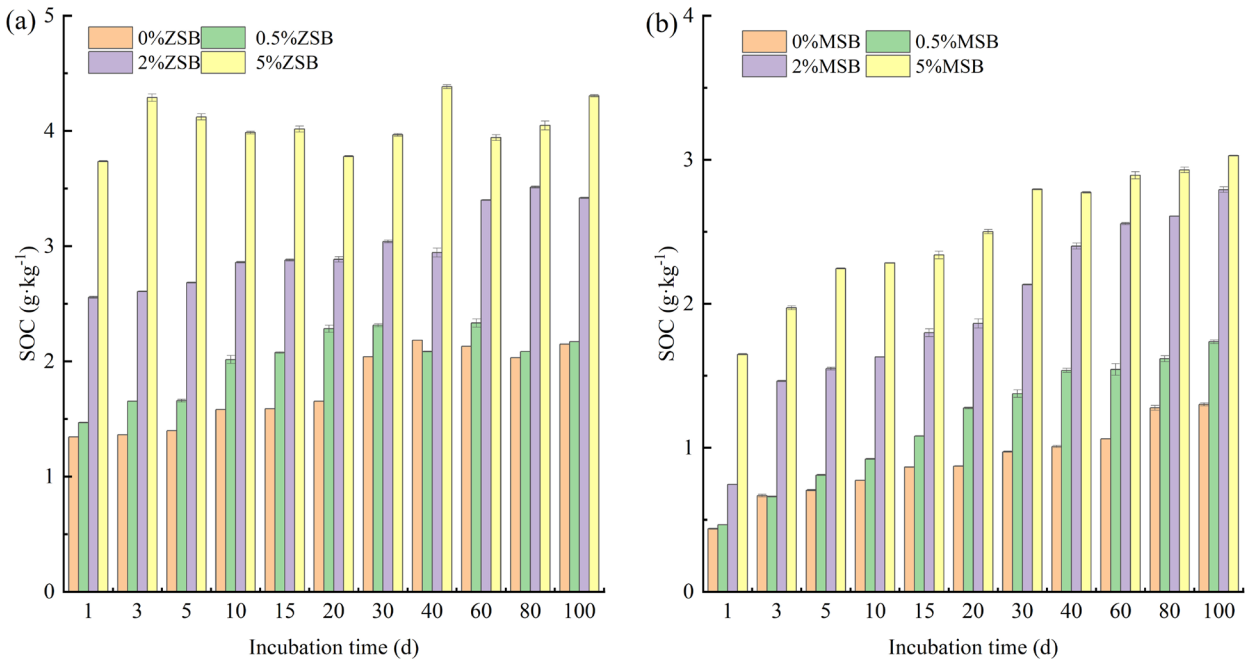


Fig. 7 Effect of biochar on soil organic carbon (SOC). (**a**) Uncontaminated sugarcane field soil. (**b**) Manganese-contaminated sugarcane field soil

Table 4 Stability coefficients of soil organic carbon (SOC) in each treatment

Stability Factors	0%	0.5%	2%	5%
ZSB	0.47	0.51	0.48	0.54
MSB	/	0.07	0.50	0.53

Figure 8 shows the changes in MBC of manganese-contaminated sugarcane field soil and uncontaminated sugarcane field soil with different bagasse biochar application rates. During the entire culture period, the MBC in the soil increased with the increase in the biochar application amount and culture time. At the end of the incubation period, the MBC of the uncontaminated sugarcane soil with 5%, 2%, and 0.5% biochar application was 39.42 mg·kg^{-1}, 37.92 mg·kg^{-1}, and 28.49 mg·kg^{-1}, respectively. When compared with the control (0% ZSB), the MBC content of 5% ZSB, 2% ZSB, and 0.5% ZSB increased by 117.55%, 109.29%, and 57.23%, respectively. The MBC content of the manganese-contaminated sugarcane field soil with 5%, 2%, and 0.5% biochar was 15.10 mg·kg^{-1}, 13.71 mg·kg^{-1}, and 12.72 mg·kg^{-1}, respectively. When compared with the control (0% MSB), the MBC content of 5% MSB, 2% MSB, and 0.5% MSB increased by 180.15%, 154.36%, and 135.99%, respectively.

As shown in Fig. 9, the soil DOC content initially increased and then decreased with time when different amounts of bagasse biochar were applied to the uncontaminated sugarcane field soil. During the entire culture period, the DOC varied from 32.24 to 14.99 mg·kg^{-1}, 37.03–15.64 mg·kg^{-1}, 43.50–16.11 mg·kg^{-1}, and 50.30–17.37 mg·kg^{-1}, respectively, when 0%, 0.5%, 2%, and 5% biochar were applied. The soil DOC content reached the maximum values of 32.24 mg·kg^{-1}, 37.03 mg·kg^{-1}, and 43.50 mg·kg^{-1} on the 10th day of culture with the application of 0%, 0.5%, and 2% biochar, respectively. The soil DOC content reached the maximum values of 50.30 mg·kg^{-1} on the 20th day with the application of 5% biochar. When different amounts of biochar were applied to the manganese-contaminated sugarcane field soil, the soil DOC content decreased with the increase in biochar amount. During the entire culture period, DOC varied from 43.82 to 13.96 mg·kg^{-1}, 34.44–13.59 mg·kg^{-1}, 30.95–13.00 mg·kg^{-1}, and 26.27–11.94 mg·kg^{-1}, respectively, with the application of 0%, 0.5%, 2%, and 5% biochar. The DOC content reached the maximum values of 34.44 mg·kg^{-1} and 30.95 mg·kg^{-1} on the 15th day when 0.5% and 2% biochar were applied, respectively. Similarly, the DOC content reached 43.82 mg·kg^{-1} and 26.27 mg·kg^{-1} on the 20th day of culture when 0% and 5% biochar were applied, respectively.

As shown in Fig. 10, the application of different amounts of bagasse biochar can increase the ROC content in uncontaminated sugarcane field soil and manganese-contaminated sugarcane field soil, with the increase in biochar application amount leading to

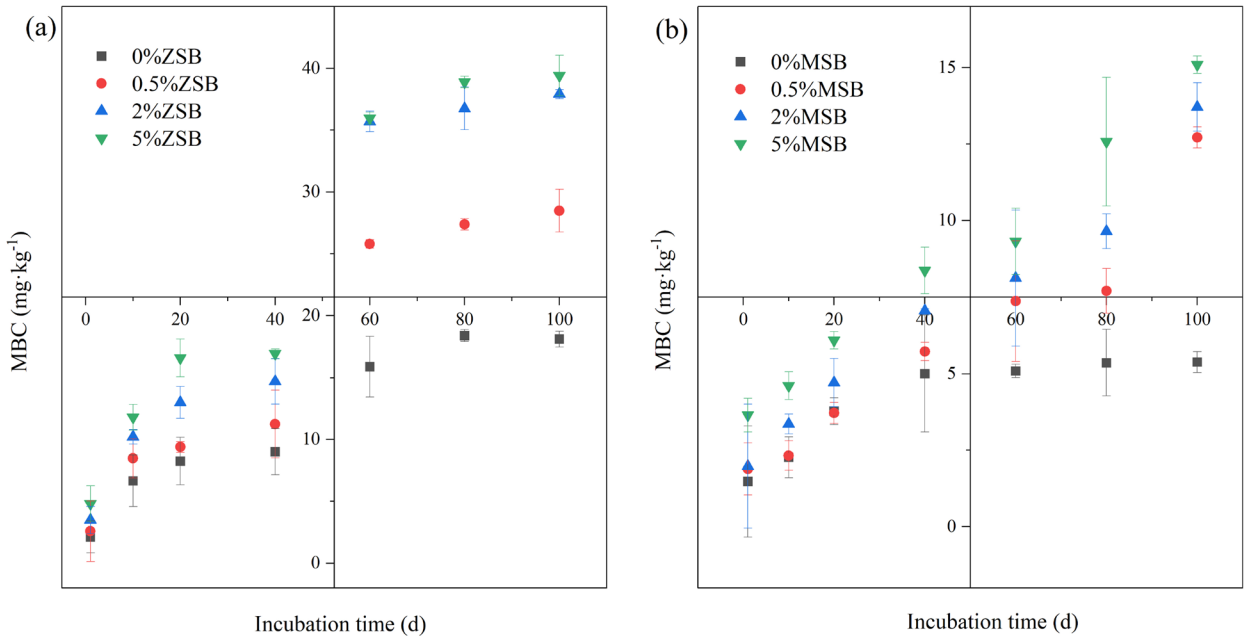


Fig. 8 Effects of biochar on soil microbial biomass carbon (MBC). (**a**) Uncontaminated sugarcane field soil. (**b**) Manganese-contaminated sugarcane field soil

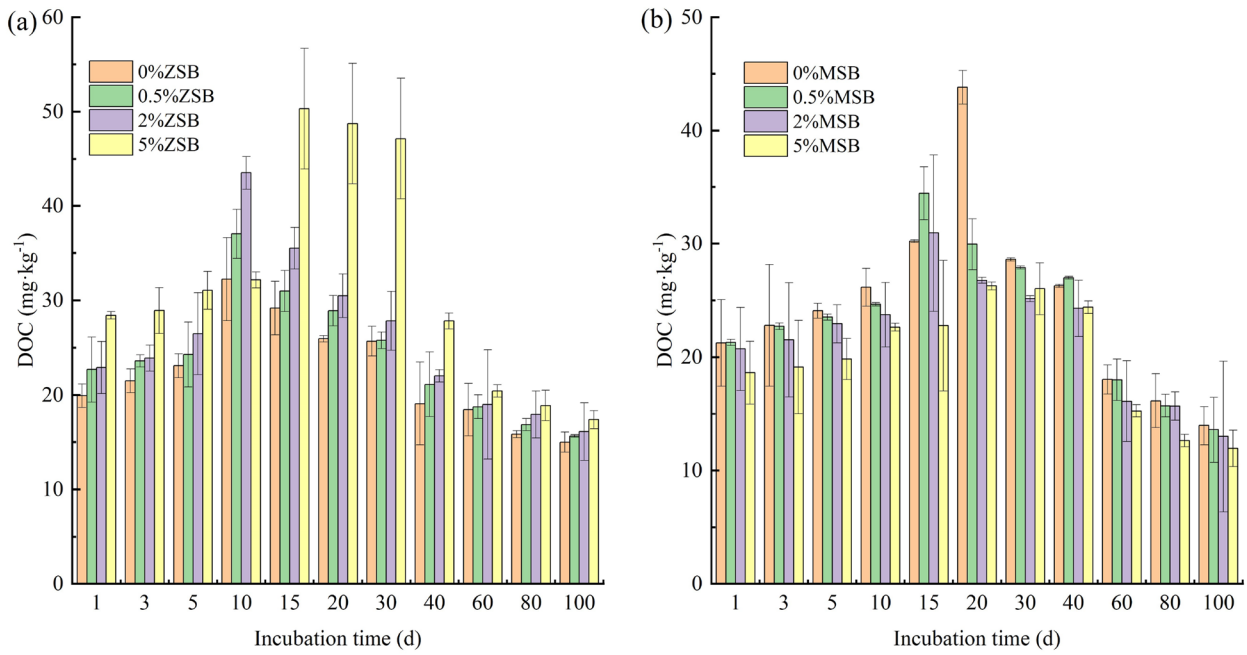


Fig. 9 Effects of biochar on soil dissolved organic carbon (DOC). (**a**) Uncontaminated sugarcane field soil. (**b**) Manganese-contaminated sugarcane field soil

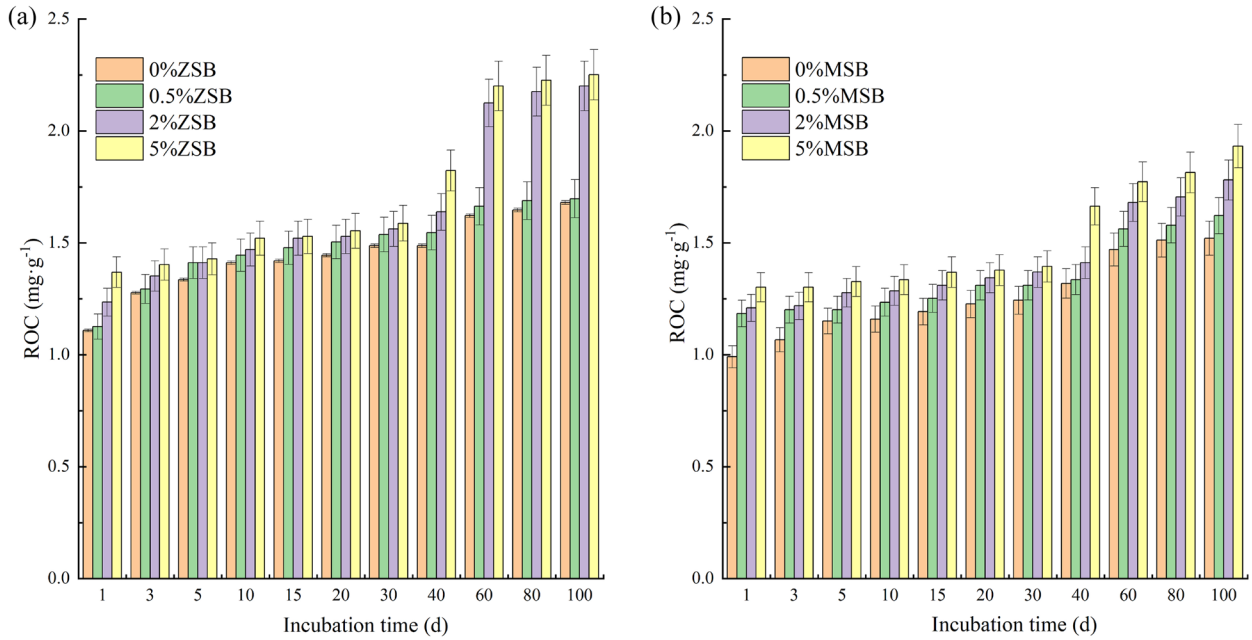


Fig. 10 Effects of biochar on soil readily oxidizable organic carbon (ROC). (**a**) Uncontaminated sugarcane field soil. (**b**) Manganese-contaminated sugarcane field soil

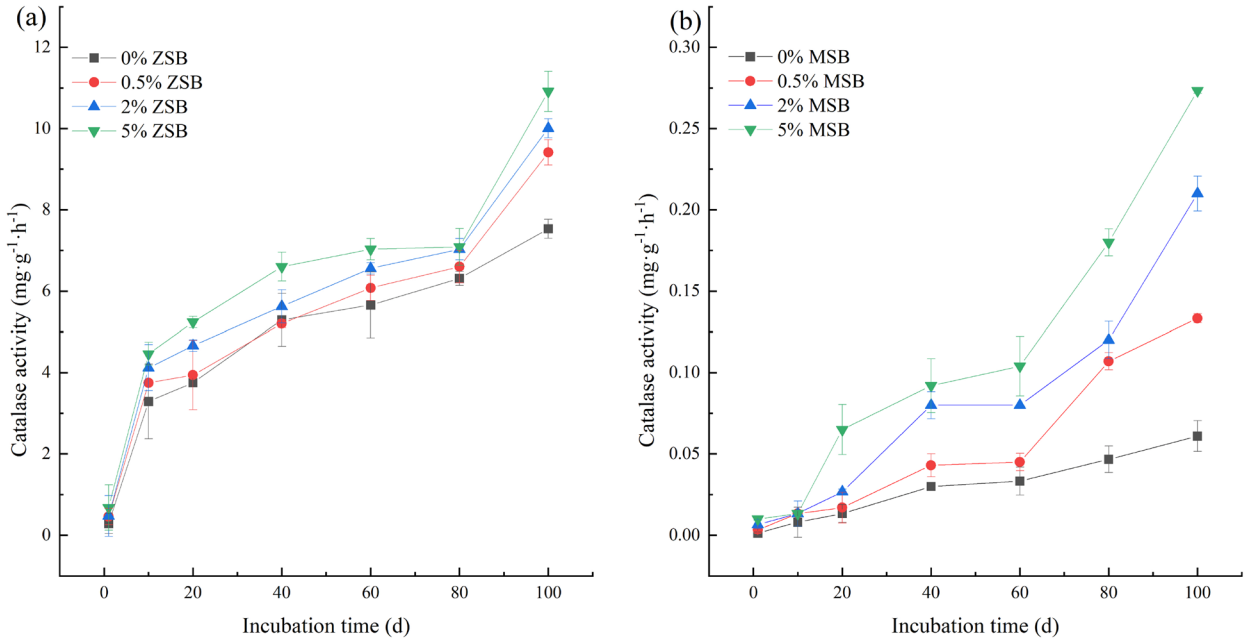


Fig. 11 Effects of biochar on soil catalase. (**a**) Uncontaminated sugarcane field soil. (**b**) Manganese-contaminated sugarcane field soil

increasing ROC content. When biochar was applied to the uncontaminated sugarcane field soil, the ROC content increased slowly from 0 to 40 days. After 40 days, the increase in 2% and 5% biochar-treated soil was more obvious, with ROC content increasing from 1.23 $mg \cdot g^{-1}$ to 2.20 $mg \cdot g^{-1}$ and 1.37 $mg \cdot g^{-1}$ to 2.25 $mg \cdot g^{-1}$, i.e., an increase by 78.86% and 64.23%, respectively. The ROC content ranged from 1.11 to 2.25 mg·g-1 during the entire culture period. The ROC content in the manganese-contaminated sugarcane field soil increased with the increase in biochar application amount and culture time. The ROC content increased by 6.63%, 17.13%, and 27.07%, respectively, with the application of 0.5%, 2%, and 5% biochar when compared with the control (0% MSB).

Effects of biochar on the soil enzyme activity

As shown in Fig. 11, the application of bagasse biochar in both the sugarcane fields could increase the catalase content. With the increase in biochar application amount, the catalase content in the uncontaminated sugarcane fields was much higher than that in the manganese-contaminated sugarcane fields. The catalase activity in the uncontaminated sugarcane fields increased with time. At the end of the culture period, the catalase activity of 0.5% ZSB, 2% ZSB, and 5% ZSB increased by 1.24 times, 1.33 times, and 1.47 times, respectively, when compared with that of the control (0% ZSB). The catalase content in the manganese-contaminated sugarcane field soil also increased with time. At the end of the culture period, the catalase activity of 0.5% MSB, 2% MSB, and 5% MSB increased by 2.19 times, 3.44 times, and 4.48 times, respectively, when compared with that of the control (0% MSB).

As shown in Fig. 12, the application of different amounts of bagasse biochar in the uncontaminated sugarcane field and manganese-contaminated sugarcane field soils could increase urease activity with time. The urease activity followed the order: 5% ZSB > 2% ZSB > 0.5% ZSB > 0% ZSB, 5% MSB > 2% MSB > 0.5% MSB > 0% MSB. In the uncontaminated sugarcane field soil, the urease activity reached the maximum value of 0.43 $mg \cdot g^{-1} \cdot h^{-1}$ on the 80th day with the application of 5% biochar. At the end of the culture period, the urease activities of 0.5% ZSB, 2% ZSB, and 5% ZSB were 0.28 $mg \cdot g^{-1} \cdot h^{-1}$, 0.34 $mg \cdot g^{-1} \cdot h^{-1}$, and 0.42 $mg \cdot g^{-1} \cdot h^{-1}$, respectively, which were 1.05 times, 1.29 times, and 1.59 times higher than those of the control (0% ZSB). Similarly, at the end of the culture period, the urease activities of 0.5% MSB, 2% MSB, and 5% MSB were 0.56 $mg \cdot g^{-1} \cdot h^{-1}$, 0.59 $mg \cdot g^{-1} \cdot h^{-1}$, and 0.60 $mg \cdot g^{-1} \cdot h^{-1}$, respectively, which were 1.03 times, 1.08 times, and 1.10 times higher than those of the control (0% MSB).

Correlation analysis

As shown in Fig. 13, when biochar was applied to the sugarcane field soil, CEC and ROC were significantly

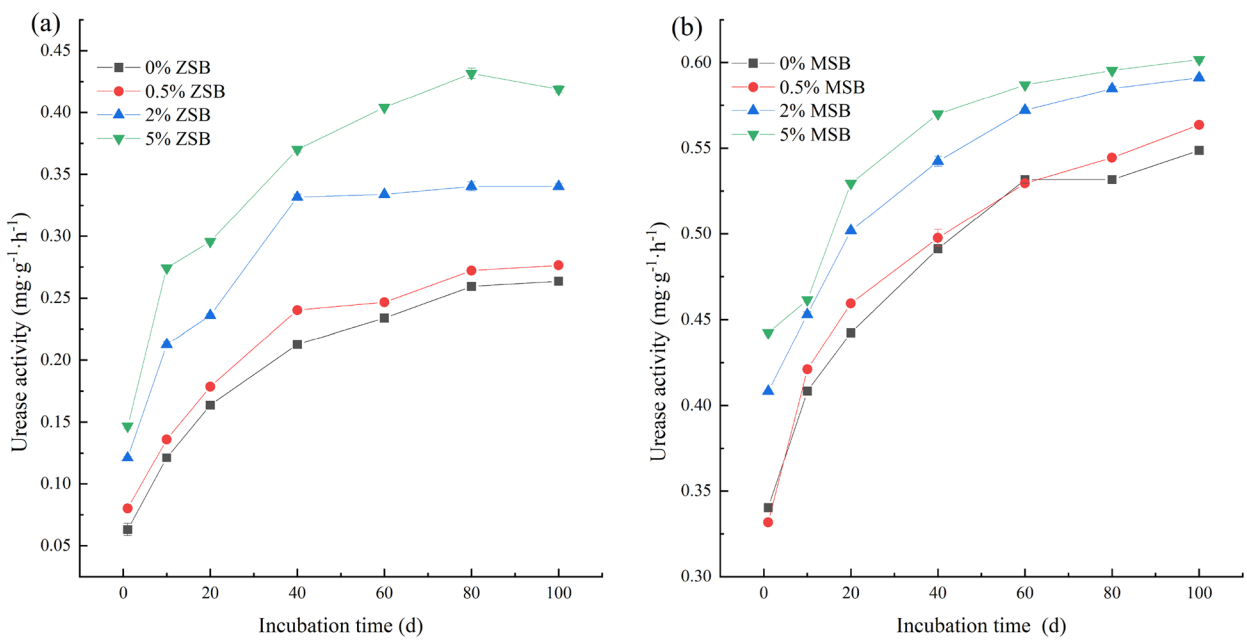


Fig. 12 Effects of biochar on the soil urease. (**a**) Uncontaminated sugarcane field soil. (**b**) Manganese-contaminated sugarcane field soil

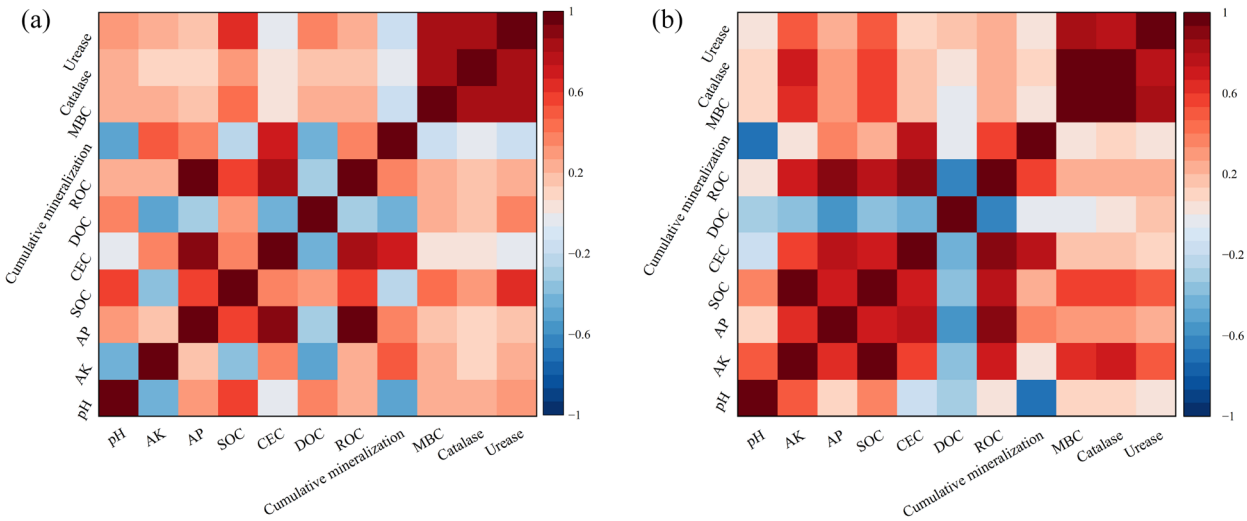


Fig. 13 Correlation analysis. (**a**) Uncontaminated sugarcane field soil. (**b**) Manganese-contaminated sugarcane field soil

positively correlated with AP; CEC was significantly positively correlated with ROC; and urease and catalase activities were significantly positively correlated with MBC. When biochar was applied to the manganese-contaminated sugarcane field soil, AK was significantly positively correlated with SOC; CEC and AP were significantly positively correlated with ROC; and urease and catalase activities were significantly positively correlated with MBC. Moreover, the cumulative CO_2 emission was negatively correlated with pH and positively correlated with CEC.

Discussion

Effects of biochar on soil pH and CEC

The application of biochar to the uncontaminated sugarcane field and manganese-contaminated sugarcane soil increased the field soils pH. Although the change in pH with time was not significant, the pH value was positively correlated with the biochar application amount. This indicated that the increase in pH value in this experiment may depend on the soil type and biochar application rate, and is not affected by the culture time, which is similar to research results from a previous study [26]. The application of biochar to the manganese-contaminated sugarcane field soil resulted in a slight increase in the pH value, probably due to the strong acidity of the soil (Table 1). Therefore, the addition of biochar has a little effect on the soil pH. This is consistent with the results of a study by Huang et al. [27], where a slight increase in soil pH was observed by the application of biochar to the heavy metal-contaminated soil. The increase in pH of the uncontaminated sugarcane field soil may be due to the application of bagasse biochar to the soil, which drives the oxygen-containing functional groups on the soil surface to combine with Al^{3+}, reduces the exchangeable aluminum content, and increases the abundance of exchangeable alkali cations [28]. In this study, bagasse biochar also increased the pH of the manganese-contaminated soil. The application of 5% bagasse biochar increased the soil pH to 6.45, which improved the acidity of manganese-contaminated soil to a certain extent.

CEC is one of the important indicators for the measurement of soil quality, which can reduce soil nutrient leaching [29]. The application of bagasse biochar to manganese-contaminated soil increased soil CEC due to the negatively charged oxygen-containing functional groups on the biochar surface, thereby increasing CEC [30], as well as due to the presence of alkaline substances in biochar, higher ash content, and potassium, calcium, and magnesium ions [26]. When compared with the control, the CEC increased with the increase in biochar application amount during 0–40 days following the bagasse biochar application to the uncontaminated sugarcane field soil. This may be due to the influence of biochar surface oxidation and porous structure [31]. After 60 days, the application of biochar reduced CEC, which is similar to research results from a previous study [26]. In that study, it was hypothesized that the decrease in CEC was due to the blockage of biochar pores by humic acid and fulvic acid in the soil, which would further block its physical adsorption, thereby reducing CEC. The correlation results demonstrated a significant positive correlation between soil CEC and cumulative CO_2 emissions from the two soils, indicating that an increase in the cumulative CO_2 emissions from bagasse biochar-treated soils led to an increase in soil CEC.

Effects of biochar on soil nutrients

Bagasse biochar was applied to the manganese-contaminated sugarcane field soil. During 0–40 days, the AP content gradually increased. This may be due to the acidic nature of the manganese-contaminated sugarcane field soil and the high activity of iron and aluminum in the soil, which leads to the formation of large quantities of insoluble iron phosphate and aluminum phosphate, and even leads to a closed phosphorus cycle with lower effectiveness, with most of the soil phosphorus getting converted into fixed phosphorus [32]. After 40 days, the application of 5% biochar resulted in the largest increase in AP content when compared with the control. This may be because of the increase in soil pH by biochar application, and the increase in soil pH leads to a decrease in iron and aluminum activity, leading to an increase in soil AP content. The application of bagasse biochar significantly increased the AP content in manganese-contaminated sugarcane field soil, with the increase in biochar amount leading to enhanced AP content, which is in agreement with research results from a previous study [33]. In that study, corn straw biochar, rice husk biochar, and wheat straw biochar were applied to the chromium-contaminated soil, and the results demonstrated a significant increase in the AP content, and this increase was influenced by the amount of biochar applied. Bagasse biochar exhibits a beneficial effect on enhancing AP levels in uncontaminated sugarcane field soil. This may be because biochar can adsorb soil phosphate and reduce AP leaching [34]. Huang et al. [35] demonstrated that the potassium and phosphorus content in sugarcane field soil was low. The ability of soil to supply phosphorus can be reflected by the AP content [36]. In this study, the application of raw bagasse biochar increased the soil AK content, with the increase in biochar amount leading to increasing AK content. This may be due to the porous adsorption and retention of soil potassium by biochar with a large specific surface area, leading to a reduction in the leaching of nutrients [28]. Similarly, Wang et al. [37] demonstrated that the application of biochar to tobacco fields increased soil AK content by 10.57%, which is consistent with the results of this study. In this study, the application of bagasse biochar to the manganese-contaminated sugarcane field soil alleviated the nutrient deficiency in the soil to a certain extent.

Effects of biochar on SOC mineralization

Biochar addition to soil can affect the basic physical and chemical properties of soil and soil structure, thereby influencing CO_2 emissions [28]. The application of biochar significantly reduced the CO_2 emission rates in both the sugarcane fields, which is similar to previous research results [38]. When compared with the control, the CO_2 emission decreased slightly with the application of bagasse biochar to the manganese-contaminated sugarcane field soil. The reasons for this are as follows: first, the quality of manganese-contaminated soil is poor, the nutrient content is low, and limited energy is provided by biochar for organic carbon mineralization in soil; second, the organic carbon mineralization is affected by microbial biomass. Manganese ions in the soil may be toxic and inhibitory to microorganisms, thus reducing the microbial decomposition of organic carbon and the mineralization rate of SOC [39]. Verma et al. [40] applied biochar to heavy metal-contaminated soils, and the results demonstrated that soil CO_2 emissions decreased with the increase in heavy metal concentration. In that study, it was revealed that heavy metal pollution may reduce soil microbial activity, thereby reducing soil respiration rate, which is consistent with the results of this study. Similarly, biochar can effectively reduce CO_2 emissions from heavy metal-contaminated soils, which has also been reported in other studies [41]. Manganese is an important metal element, which affects the soil carbon cycle by interfering with the soil anaerobic microbial redox under manganese-rich conditions [42]. A study by Tian et al. [43] has demonstrated that heavy metal pollution affects soil microbial communities, which in turn affects soil carbon emissions. The significant decrease in CO_2 emissions in the uncontaminated sugarcane field soil may be attributed to biochar, which contains Mg, Ca, and other elements. These elements combine with CO_2 in the soil to form $CaMg(CO_3)_2$ and other substances, thereby reducing CO_2 emissions [44]. Similarly, Mendez et al. [45] observed that the application of biochar to soil effectively reduced CO_2 emissions. In this study, soil pH was negatively correlated with cumulative mineralization, indicating that soil pH is also an important factor.

Effects of biochar on soil active organic carbon components

The application of biochar could increase the soil organic carbon (SOC) content in the two sugarcane fields, with the increase in biochar application amount leading to an increase in SOC, which is similar to previous research results [46]. SOC turnover is closely related to soil fertility and plays an important role in regulating ecosystem carbon cycle [47]. SOC can play a crucial role in providing carbon sources for soil microorganisms, plants, and animals [48]. When compared with the control, bagasse biochar had a limited impact on the increase in SOC content of manganese-contaminated sugarcane fields, because the soil DOC enters the biochar pores or is adsorbed on the biochar surface [49]. The increase in SOC content of the uncontaminated sugarcane field soil has a more positive effect, which may be due to the porosity of biochar

and the formation of aggregates, which enhances the protection of organic carbon and thus, inhibits the ability of microorganisms to decompose organic carbon [50]. Similarly, in a study by Liu et al. [51], the application of biochar to the soil increased SOC content by 7.88–30.05%, and the SOC content increased with the increase in biochar application, which was consistent with the results of this study. The SOC stability coefficient can be used to measure the stability of SOC, which can reflect the proportion of inert organic carbon in total soil carbon [52]. In this study, the stability coefficient of SOC increased with the amount of biochar application, indicating that biochar application could increase the stability of SOC to a certain extent. Moreover, the stability coefficients of SOC in manganese-contaminated sugarcane field soils were lower those that in uncontaminated sugarcane field soils, indicating that heavy metals may affect the stability of SOC to a certain extent. MBC is an important carbon source in the soil, and its variational trend indicates the carbon utilization efficiency of soil microorganisms [53]. Biochar had a minimal effect on the increase in MBC content of the manganese-contaminated sugarcane field soil, which may be partly due to the high manganese content of the sugarcane field soil, which destroys the microbial cell structure and function, thus inhibiting microbial activity. Another possible explanation for this is that microorganisms may slow down their growth and consume more energy to resist metal toxicity under the stress of manganese ions [54]. The MBC content in the uncontaminated sugarcane soil increased significantly, probably due to two major reasons. First, the porosity of biochar, makes the soil loose and improves soil aeration, thus increasing microbial activity [55]. Second, biochar has rich carbon content, which can provide additional carbon sources for microorganisms, thus providing good growth conditions for the microorganisms [55]. In a study by Jiang et al. [56], the application of pig manure biochar to tea garden soil increased MBC by 5.73–36.4%, which is consistent with the results of this study.

DOC and ROC are active components of SOC, which are directly involved in soil chemical cycling and provide nutrients for soil microbial growth [57]. This study demonstrated that the DOC content in two types of sugarcane field soils initially increased and then decreased with time, which is similar to previous research results [58]. It also demonstrated the same variational trend in the DOC content when the bagasse biochar was applied to the manganese-contaminated sugarcane field soil. In the early stage, biochar may adsorb manganese ions in the soil and reduce manganese toxicity in microorganisms [59]. Moreover, the application of exogenous organic carbon increased DOC content. In the later period, DOC may be used as a heavy metal ion carrier, which promotes the combination of manganese ions with DOC, thereby reducing the DOC content [60]. A similar phenomenon was also observed in a previous study [61]. In that study, the authors hypothesized that the surface functional groups of biochar and cations form complexes with DOC in the soil, thereby reducing the soil DOC content. The application of bagasse biochar to uncontaminated sugarcane field soil leads to a positive impact. This may be because the application of biochar can reduce the loss of soil nutrients, create a favorable environment for the growth of microorganisms, promote the microbial decomposition of soil organic matter, and increase DOC content [62]. The ROC content of the two sugarcane field soils increased with the application ratio of biochar. The application of 5% biochar exhibited the most significant impact, and 0.5% biochar yielded the least significant impact. The application of biochar to the soil can improve the soil structure and adsorb nutrients. Moreover, it can provide good growth conditions for microorganisms as well as promote soil respiration and organic carbon mineralization, thereby increasing the soil ROC content [63]. The correlation results demonstrated a significant positive correlation between ROC and AP, indicating that an increase in ROC content is also affected by AP.

Effects of biochar on soil enzyme activity

Soil enzyme activity is an important parameter to measure soil microbial activity. It is involved in the decomposition of soil organic matter and can affect soil fertility as well as the biological cycle [64]. The application of biochar to the manganese-contaminated sugarcane field soil and uncontaminated sugarcane field soil could increase the soil enzyme activity, with an increased amount of biochar application leading to increased enzyme activity, which is similar to previous research results [65]. When compared with the control, the soil catalase activity was lower during 0–40 days after the application of bagasse biochar to the manganese-contaminated sugarcane field soil, which may be due to the relatively stable catalase activity in the soil and low influence of the external environment. The application of biochar altered the soil moisture and inhibited the catalase activity [66]. After 40 days, the catalase activity increased significantly. Due to a large surface area and porous characteristics, biochar provides an environment conducive to the growth of microorganisms; enhances the flow of air, water, and nutrients in the soil; and improves microbial activity, thereby increasing enzymatic activity [67]. The inhibitory effect of catalase in the early stage following the application of biochar and then a promoting effect in the later stage was also reported in other studies [18]. The soil catalase activity was effectively improved in the uncontaminated sugarcane field soil, probably because

the application of biochar improved the soil structure by providing a habitat favorable for microbial growth and conducive to the oxidation activity of soil microorganisms, thereby increasing catalase activity [68]. The catalase activity increased with time, and this increasing trend was consistent with the variational trend of MBC, indicating a positive correlation of catalase activity MBC. Thus, the application of biochar enhances soil respiration, which in turn, improves the utilization of soil carbon.

Urease plays an important role in the transformation of soil nitrogen, which can catalyze the hydrolysis of urea in the soil to carbon dioxide and ammonium [69]. In this study, when compared with the control, the application of bagasse biochar had no significant effect on urease activity in the manganese-contaminated sugarcane field soil. The analysis revealed the following two reasons for this phenomenon: first, the combination of heavy metals and the active protein gene of the enzyme, can diminish the binding site of the enzyme, thereby inhibiting enzyme synthesis; second, heavy metals may deform proteins, thereby reducing enzyme activity and inhibiting enzyme synthesis [70]. The urease activity in the uncontaminated soil increase significantly when compared with that in the control. It is possible that the application of biochar increased urease activity by changing the composition of the soil microbial community and enhancing its biogeochemical cycle [71]. Urease activity was positively correlated with MBC, further indicating that microorganisms can affect urease activity.

Conclusions

This study applied different amounts of bagasse biochar to the manganese-contaminated sugarcane field soil to evaluate its effect on SOC sequestration. The results demonstrated significant differences in the mineralization characteristics of SOC between manganese-contaminated sugarcane field soil and uncontaminated sugarcane field soil. Among all the treatments, 5% bagasse biochar treatment significantly inhibited the mineralization of SOC. The application of bagasse biochar significantly increased the enzyme activity, organic carbon, MBC content, and ROC content in manganese-contaminated sugarcane field soil. Briefly, the application of 5% bagasse biochar demonstrated a good carbon sequestration effect on the manganese-contaminated sugarcane soil. The results of this study hold great significance in advancing our understanding of the mechanisms underlying carbon sequestration and emission reduction in manganese-contaminated farmland systems.

The applications of different amounts of bagasse biochar to both the manganese-contaminated sugarcane field soil and uncontaminated sugarcane field soil can improve the carbon sequestration capacity of the soil and this capacity increases with the increase in the biochar application amount. However, the carbon sequestration effects of bagasse biochar on the manganese-contaminated sugarcane field soil are slightly lower, probably due to the decrease in the soil carbon sequestration capacity of bagasse biochar mediated by manganese. However, the specific reason for this is not yet clear and needs further study.

Acknowledgements
We thank Zhi Yun for the linguistic editing and proofreading of the manuscript.

Author contributions
L.H: conceptualization and data curation. Y.Y: software, writing original draft preparation and data curation. X.H.L and S.L: data curation, supervision. H.D and K.L: supervised the experiment project and approved the final version. All authors have read and agreed to the published version of the manuscript.

Funding
This work was supported by Guangxi Surface project, grant number [2022GXNSFAA035555]. the Key Laboratory of Ecology of Rare and Endangered Species and Environmental Protection (Guangxi Normal University), Ministry of Education, China, grant number [ERESEP2022Z13].

Availability of data and materials
All data are presented in the manuscript.

Declarations

Ethics approval and consent to participate
The manuscript is an original work that has not been published in other journals.

Consent for publication
All authors agreed to the publication.

Competing interests
The authors declare that they have no competing interests.

Author details
[1]Key Laboratory of Ecology of Rare and Endangered Species and Environmental Protection, Ministry of Education, Guangxi Normal University & College of Environment and Resources, Guangxi Normal University, Guilin 541004, China. [2]College of Civil Engineering and Architecture, Guilin University of Technology, Guilin 541004, China.

Received: 11 April 2023 Accepted: 31 May 2023
Published online: 12 June 2023

References

1. Shen J, Zhao C, Liu R, Ye F, Li Y, Li L, Chen W. Effect of tillage practices on soil quality and soil carbon emission in dryland agriculture area. Soil Fert Sci China. 2022. https://doi.org/10.11838/sfsc.1673-6257.20547
2. Liu Y, Tang H, Muhammad A, Huang G. Emission mechanism and reduction countermeasures of agricultural greenhouse gases—a review. Greenh Gas-Sci Technol. 2019;9:160–74. https://doi.org/10.1002/ghg.1848.
3. Teng YG, Ni SJ, Wang JS, Zuo R, Yang J. A geochemical survey of trace elements in agricultural and non-agricultural topsoil in Dexing area China. J Geochem Explor. 2010;104:118–27. https://doi.org/10.1016/j.gexplo.2010.01.006.
4. Bian RJ, Cheng K, Zheng JF, Liu XY, Liu YZ, Li ZP, Li LQ, Smith P, Pan GX, Crowley D, Zheng JW, Zhang XH, Zhang LY, Hussain Q. Does metal

pollution matter with C retention by rice soil? Sci Rep. 2015. https://doi.org/10.1038/srep13233.
5. Zhou T, Pan GX, Li LQ, Zhang XH, Zheng JW, Zheng JF, Chang A. Changes in greenhouse gas evolution in heavy metal polluted paddy soils with rice straw return: a laboratory incubation study. Eur J Soil Biol. 2014;63:1–6. https://doi.org/10.1016/j.ejsobi.2014.03.008.
6. Liu Y, Hong Y, Yao Y, Xu L, Xing S, Hu X, Gao Y. Status analysis of bagasse comprehensive utilization in China. Chin J Trop Agric. 2017;37:91–5. https://doi.org/10.12008/j.issn.1009-2196.2017.02.021.
7. Hao J, Guo C, Gao X, Li M, Long H. Advances on synthesis and application of bagasse-based activated carbon. Mod Chem Ind. 2021;41:31–5. https://doi.org/10.16606/j.cnki.issn0253-4320.2021.03.007.
8. He F, Rong X, Liang Y, Wu A, Liu Q. Effects of biochar on physical and chemical properties, N_2O and CO_2 emissions of red soil vegetable fields. J Agro-Environ Sci. 2013;32:1893–900.
9. Bolan N, Hoang SA, Beiyuan J, Gupta S, Hou D, Karakoti A, Joseph S, Jung S, Kim K-H, Kirkham MB, Kua HW, Kumar M, Kwon EE, Ok YS, Perera V, Rinklebe J, Shaheen SM, Sarkar B, Sarmah AK, Singh BP, Singh G, Tsang DCW, Vikrant K, Vithanage M, Vinu A, Wang H, Wijesekara H, Yan Y, Younis SA, Van Zwieten L. Multifunctional applications of biochar beyond carbon storage. Int Mater Rev. 2022;67:150–200. https://doi.org/10.1080/09506608.2021.1922047.
10. Zhang A, Bian R, Li L, Wang X, Zhao Y, Hussain Q, Pan G. Enhanced rice production but greatly reduced carbon emission following biochar amendment in a metal-polluted rice paddy. Environ Sci Pollut Res. 2015;22:18977–86. https://doi.org/10.1007/s11356-015-4967-8.
11. Wu Z, Zhang X, Dong Y, Li B, Xiong Z. Biochar amendment reduced greenhouse gas intensities in the rice-wheat rotation system: six-year field observation and meta-analysis. Agric For Meteorol. 2019. https://doi.org/10.1016/j.agrformet.2019.107625.
12. Wang Q, Wang B, Ma YN, Zhang XY, Lyu WQ, Chen M. Stabilization of heavy metals in biochar derived from plants in antimony mining area and its environmental implications. Environ Pollut. 2022. https://doi.org/10.1016/j.envpol.2022.118902.
13. Ibrahim EA, El-Sherbini MAA, Selim EM. Effects of biochar on soil properties, heavy metal availability and uptake, and growth of summer squash grown in metal-contaminated soil. Sci Hortic. 2022. https://doi.org/10.1016/j.scienta.2022.111097.
14. Zhang XL, Teng ZY, Zhang HH, Cai DJ, Zhang JY, Meng FJ, Sun GY. Nitrogen application and intercropping change microbial community diversity and physicochemical characteristics in mulberry and alfalfa rhizosphere soil. J For Res. 2021;32:2121–33. https://doi.org/10.1007/s11676-020-01271-y.
15. Zhang Y, Li D, Zhang Z, Liao K. A comparison study of two methods for mensuration of soil cation exchange capacity. Guizhou For Sci Technol. 2010;38:45–9.
16. Das SK, Ghosh GK, Avasthe R. Biochar and organic manures on produce quality, energy budgeting, and soil health in maize-black gram system. Arabian J Geosci. 2022;15:1–15. https://doi.org/10.1007/s12517-022-10790-3.
17. Rong GH, Zhang XJ, Wu HY, Ge NN, Yao YF, Wei XR. Changes in soil organic carbon and nitrogen mineralization and their temperature sensitivity in response to afforestation across China's Loess Plateau. CATENA. 2021. https://doi.org/10.1016/j.catena.2021.105226.
18. Hu LN, Huang R, Zhou LM, Qin R, He XY, Deng H, Li K. Effects of magnesium-modified biochar on soil organic carbon mineralization in citrus orchard. Front Microbiol. 2023. https://doi.org/10.3389/fmicb.2023.1109272.
19. Hu LN, Li SL, Li K, Huang HY, Wan WX, Huang QH, Li QY, Li YF, Deng H, He TG. Effects of two types of straw biochar on the mineralization of soil organic carbon in farmland. Sustainability. 2020. https://doi.org/10.3390/su122410586.
20. Huang R, Tian D, Liu J, Sheng L, He X, Ming G. Responses of soil carbon pool and soil aggregates associated organic carbon to straw and straw-derived biochar addition in a dryland cropping mesocosm system. Agric Ecosyst Environ. 2018;256:576–86.
21. Lu X, Ren W, Hou E, Zhang L, Wen D, Liu Z, Lin Y, Wang J, Kuang Y. Negative effects of canopy N addition on soil organic carbon in wet season are primarily detected in uppermost soils of a subtropical forest. Globa Ecol Conserv. 2019;1:e00543.
22. Abay EZ, Gong L, Chen X, Luo Y, Wu X. Spatiotemporal variation and correlation of soil enzyme activities and soil physicochemical properties in canopy gaps of the Tianshan Mountains Northwest China. J Arid Land. 2022;14:824–36. https://doi.org/10.1007/s40333-022-0098-5.
23. Zhang Y, Yan Y, Fu X, Yang J, Zhang S, Xu S, Tang Z, Li Z, Lu S. Responses of soil microbial respiration to plantations depend on soil properties in subtropical China. J Integr Agric. 2016;15:1376–84. https://doi.org/10.1016/S2095-3119(15)61222-9.
24. Song MH, Jiang J, Xu XL, Shi PL. Correlation between CO_2 efflux and net nitrogen mineralization and its response to external C or N supply in an alpine meadow soil. Pedosphere. 2011;21:666–75. https://doi.org/10.1016/s1002-0160(11)60169-0.
25. Zheng J, Pan Gen WuX. Study on soil CO_2-C emission flux and organic carbon stability in dry season of Shengjin Lake. Wetland science. 2011;9:132–9. https://doi.org/10.13248/j.cnki.wetlandsci.2011.02.006.
26. Hailegnaw NS, Mercl F, Pracke K, Szakova J, Tlustos P. Mutual relationships of biochar and soil pH, CEC, and exchangeable base cations in a model laboratory experiment. J Soils Sed. 2019;19:2405–16. https://doi.org/10.1007/s11368-019-02264-z.
27. Huang DL, Liu LS, Zeng GM, Xu P, Huang C, Deng LJ, Wang RZ, Wan J. The effects of rice straw biochar on indigenous microbial community and enzymes activity in heavy metal-contaminated sediment. Chemosphere. 2017;174:545–53. https://doi.org/10.1016/j.chemosphere.2017.01.130.
28. Li YF, Hu SD, Chen JH, Muller K, Li YC, Fu WJ, Lin ZW, Wang HL. Effects of biochar application in forest ecosystems on soil properties and greenhouse gas emissions: a review. J Soils Sed. 2018;18:546–63. https://doi.org/10.1007/s11368-017-1906-y.
29. Lago BC, Silva CA, Melo L, de Morais EG. Predicting biochar cation exchange capacity using Fourier transform infrared spectroscopy combined with partial least square regression. Sci Total Environ. 2021. https://doi.org/10.1016/j.scitotenv.2021.148762.
30. Li XB, Che WK, Piao JL, Li X, Jin F, Yao TX, Li PY, Wang W, Tan T, Shao XW. Peanut shell biochar's effect on soil physicochemical properties and salt concentration in highly saline-sodic paddy fields in Northeast China. BioResources. 2022;17:5936–57. https://doi.org/10.15376/biores.17.4.5936-5957.
31. Das SK, Choudhury BU, Hazarika S, Mishra VK, Laha R. Long-term effect of organic fertilizer and biochar on soil carbon fractions and sequestration in maize-black gram system. Biomass Convers Biorefinery. 2023. https://doi.org/10.1007/s13399-023-04165-1.
32. Zhang X. Effect of peanut shell biochar on acid soil improvement and growth of navel orange seedlings [Master Thesis]: Huazhong Agricultural University. 2014. https://doi.org/10.7666/d.Y2565898.
33. Guo R, Hong J. Effects of biochar and humic acid on chemical properties and chromium contents of chromium-contaminated soil in potted rape. Acta Agric Boreali-Occident Sin. 2019;34:192–200.
34. Wang QJ, Xu LP, Guo DJ, Wang GF, Song XC, Ma Y. The continuous application of biochar in field: effects on P fraction P sorption and release. Chemosphere. 2021. https://doi.org/10.1016/j.chemosphere.2020.128084.
35. Huang S, Huang J. Status of soil fertility and formula fertilization of sugarcane in sugarcane area. Guangxi Cane Sugar. 2006:10–2+7.
36. Jing YL, Zhang YH, Han I, Wang P, Mei QW, Huang YJ. Effects of different straw biochars on soil organic carbon, nitrogen, available phosphorus, and enzyme activity in paddy soil. Sci Rep. 2020. https://doi.org/10.1038/s41598-020-65796-2.
37. Wang Y, Dong JX, Zheng XB, Zhang JG, Zhou PL, Song XP, Song WJ, Wang SS. Wheat straw and biochar effect on soil carbon fractions, enzyme activities, and nutrients in a tobacco field. Can J Soil Sci. 2021;101:353–64. https://doi.org/10.1139/cjss-2019-0092.
38. Xie L, Xu J, Guo L, Sun X, Zhao H, Zheng Y. Impacts of biochar application on CO_2 and N_2O emissions from brown soil with maize. Chinese J Agrometeorol. 2018;39:493–501. https://doi.org/10.3969/j.issn.1000-6362.2018.08.001.
39. Dumat C, Quenea K, Bermond A, Toinen S, Benedetti MF. Study of the trace metal ion influence on the turnover of soil organic matter in cultivated contaminated soils. Environ pollut (Barking, Essex : 1987). 2006;142:521–9. https://doi.org/10.1016/j.envpol.2005.10.027.
40. Verma RK, Yadav DV, Singh CP, Suman A, Gaur A. Effect of heavy metals on soil respiration during decomposition of sugarcane (Saccharum

officinarum L.) trash in different soils. Plant Soil Environ. 2010;56:76–81. https://doi.org/10.17221/1773-pse.
41. Xu YL, Seshadri B, Sarkar B, Wang HL, Rumpel C, Sparks D, Farrell M, Hall T, Yang XD, Bolan N. Biochar modulates heavy metal toxicity and improves microbial carbon use efficiency in soil. Sci Total Environ. 2018;621:148–59. https://doi.org/10.1016/j.scitotenv.2017.11.214.
42. Wang X, Xie GJ, Tian N, Dang CC, Cai C, Ding J, Liu BF, Xing DF, Ren NQ, Wang QL. Anaerobic microbial manganese oxidation and reduction: a critical review. Sci Total Environ. 2022. https://doi.org/10.1016/j.scitotenv.2022.153513.
43. Tian HJ, Feng J, Zhang LM, He JZ, Liu YR. Ecological drivers of methanotrophic communities in paddy soils around mercury mining areas. Sci Total Environ. 2020. https://doi.org/10.1016/j.scitotenv.2020.137760.
44. Lyu H, Zhang H, Chu MW, Zhang CF, Tang JC, Chang SX, Masek O, Ok YS. Biochar affects greenhouse gas emissions in various environments: a critical review. Land Degrad Dev. 2022;33:3327–42. https://doi.org/10.1002/ldr.4405.
45. Mendez A, Tarquis AM, Saa-Requejo A, Guerrero F, Gasco G. Influence of pyrolysis temperature on composted sewage sludge biochar priming effect in a loamy soil. Chemosphere. 2013;93:668–76. https://doi.org/10.1016/j.chemosphere.2013.06.004.
46. Jiang MH, Li CB, Gao WC, Cai K, Tang Y, Cheng JZ. Comparison of long-term effects of biochar application on soil organic carbon and its fractions in two ecological sites in karst regions. Geod Reg. 2022. https://doi.org/10.1016/j.geodrs.2021.e00477.
47. Yang Y, Su Y, He Z, Yu M, Chen X, Shen A. Transformation and distribution of straw-derived carbon in soil and the effects on soil organic carbon pool: a review. Chin J Appl Ecol. 2019;30:668–76. https://doi.org/10.13287/j.1001-9332.201902.026.
48. Lin SY, Wang WQ, Penuelas J, Sardans J, Fernandez-Martinez M, Su CJ, Xu XP, Singh BP, Fang YY. Combined slag and biochar amendments to subtropical paddy soils lead to a short-term change of bacteria community structure and rise of soil organic carbon. Appl Soil Ecol. 2022. https://doi.org/10.1016/j.apsoil.2022.104593.
49. Lu WW, Ding WX, Zhang JH, Li Y, Luo JF, Bolan N, Xie ZB. Biochar suppressed the decomposition of organic carbon in a cultivated sandy loam soil: a negative priming effect. Soil Biol Biochem. 2014;76:12–21. https://doi.org/10.1016/j.soilbio.2014.04.029.
50. Han MJ, Zhao Q, Li W, Ciais P, Wang YP, Goll DS, Zhu L, Zhao Z, Wang JM, Wei Y, Wu FC. Global soil organic carbon changes and economic revenues with biochar application. Global Change Biol. 2022;14:364–77. https://doi.org/10.1111/gcbb.12915.
51. Liu GT, Xie MP, Zhang SY. Effect of organic fraction of municipal solid waste (OFMSW)-based biochar on organic carbon mineralization in a dry land soil. J Mater Cycles Waste Manag. 2017;19:473–82. https://doi.org/10.1007/s10163-015-0447-y.
52. Deng M, Zhang S, Zhu B, Li M, Pu Y. Effects of pig manure and corn residue on the organic carbon fractions and stability of purple soil. J Sichuan Agric Univ. 2021;39:205–11. https://doi.org/10.16036/j.issn.1000-2650.2021.02.010.
53. Shi D, Wang X, Liu A, Hou Z, Liang G. Responses of microbial biomass carbon and nitrogen and rice quality to biochar combined with nitrogen fertilizer in yellow paddy fields. Chin J Envir Sci. 2021;42:443–9. https://doi.org/10.13227/j.hjkx.202005186.
54. Tang B, Xu HP, Song FM, Ge HG, Chen L, Yue SY, Yang WS. Effect of biochar on immobilization remediation of Cd center dot contaminated soil and environmental quality. Environ Res. 2022. https://doi.org/10.1016/j.envres.2021.111840.
55. Manirakiza E, Ziadi N, Hamel C, Levesque V, Antoun H, Karam A. Soil microbial community dynamics after co-application of biochar and paper mill biosolids. Appl Soil Ecol. 2021. https://doi.org/10.1016/j.apsoil.2021.103960.
56. Jiang Y, Wang X, Zhao Y, Zhang C, Jin Z, Shan S, Ping L. Effects of biochar application on enzyme activities in tea garden soil. Front Bioeng Biotechnol. 2021. https://doi.org/10.3389/fbioe.2021.728530.
57. Liu Z, Li P, Huang S, Jin X, Zhang A. Effects of wheat straw biomass carbon application on soil carbon content under different tillage practices. Chin J Envir Sci. 2021;42:3000–9. https://doi.org/10.13227/j.hjkx.202010090.
58. Luo M, Tian D, Gao M, Huang R. Response of organic carbon active components to biochar application in purple soil. Chin J Envir Sci. 2018;39:4327–37. https://doi.org/10.13227/j.hjkx.201711067.
59. Azadi N, Raiesi F. Biochar alleviates metal toxicity and improves microbial community functions in a soil co-contaminated with cadmium and lead. Biochar. 2021;3:485–98. https://doi.org/10.1007/s42773-021-00123-0.
60. Li Y, Li X, Zhou C. Ecologically toxic effect of biochar on earthworms under copper pollution. Chin J Appl Environ Biol. 2021;27:1226–32. https://doi.org/10.19675/j.cnki.1006-687x.2020.06058.
61. Oladele SO, Adetunji AT. Agro-residue biochar and N fertilizer addition mitigates CO_2-C emission and stabilized soil organic carbon pools in a rain-fed agricultural cropland. Inte Soil Water Conserv Res. 2021;9:76–86. https://doi.org/10.1016/j.iswcr.2020.09.002.
62. Wang FL, Wang XX, Song NN. Biochar and vermicompost improve the soil properties and the yield and quality of cucumber (Cucumis sativus L.) grown in plastic shed soil continuously cropped for different years. Agric Ecosyst Environ. 2021. https://doi.org/10.1016/j.agee.2021.107425.
63. Wu P, Wang J, Li L, Wang X. Effects of organic materials applications on soil organic carbon fractions and nutrient contents in lime concretion black soil under chemical fertilizer reduction. Acta Agric Nucl Sin. 2022;36:2286–94.
64. Zhang Y, Guo RY, Li SH, Chen Y, Li ZD, He PY, Huang XY, Huang KF. Effects of continuous cropping on soil, senescence, and yield of tartary buckwheat. Agron J. 2021. https://doi.org/10.1002/agj2.20929.
65. Wang QY, Yuan J, Yang X, Han XR, Lan Y, Cao DY, Sun Q, Cui X, Meng J, Chen WF. Responses of soil respiration and C sequestration efficiency to biochar amendment in maize field of Northeast China. Soil Tillage Res. 2022. https://doi.org/10.1016/j.still.2022.105442.
66. Gao W, Guo Z, Xue C, Yin H, Chang MY, Zhou Q, Wang G, Li F, Liu Y. Effect of biochar and biochar compound fertilizer on soil enzyme activity of soybean. J Huaibei Norm Univ (Nat Sci). 2020;41:48–53.
67. Pokharel P, Ma ZL, Chang SX. Biochar increases soil microbial biomass with changes in extra- and intracellular enzyme activities: a global meta-analysis. Biochar. 2020. https://doi.org/10.1007/s42773-020-00039-1.
68. Khan Z, Zhang KK, Khan MN, Bi JG, Zhu KM, Luo LJ, Hu LY. How biochar affects nitrogen assimilation and dynamics by interacting soil and plant enzymatic activities: quantitative assessment of 2 years potted study in a rapeseed-soil system. Front Plant Sci. 2022. https://doi.org/10.3389/fpls.2022.853449.
69. Futa B, Oleszczuk P, Andruszczak S, Kwiecinska-Poppe E, Kraska P. Effect of natural aging of biochar on soil enzymatic activity and physicochemical properties in long-term field experiment. Agron-Basel. 2020. https://doi.org/10.3390/agronomy10030449.
70. Ogunkunle CO, Falade FO, Oyedeji BJ, Akande FO, Vishwakarma V, Alagarsamy K, Ramachandran D, Fatoba PO. Short-term aging of pod-derived biochar reduces soil cadmium mobility and ameliorates cadmium toxicity to soil enzymes and tomato. Environ Toxicol Chem. 2021. https://doi.org/10.1002/etc.4958.
71. Yang K, Wang XL, Cheng HF, Tao S. Effect of aging on stabilization of Cd and Ni by biochars and enzyme activities in a historically contaminated alkaline agricultural soil simulated with wet-dry and freeze-thaw cycling. Environ Pollut. 2021. https://doi.org/10.1016/j.envpol.2020.115846.

Publisher's Note