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Biochar and bentonite application improves aeolian sandy soil health and enhances soil carbon sequestration and emission reduction potential

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Aeolian sandy soil is barren and readily leads to low fertilizer utilization rates and yields. Therefore, it is imperative to improve the water and fertilizer retention capacity of these soils. In this paper, three kinds of biochar (rice husk, corn stalk, and bamboo charcoal) and bentonite were used as amendments in the first year of the experiment. In the second year, only corn stalk biochar was applied. The effects of biochar and bentonite on the physicochemical and biological characteristics of aeolian sandy soil and corn agronomic traits were studied through a 2-year field experiment, and the carbon sequestration and emission reduction potential of biochar in aeolian sandy soil were explored. The results showed that the input of biochar and bentonite effectively improved water content and reduced soil bulk density. Compared with the same treatment in the first year, the content of water-stable aggregates with particle sizes greater than 0.25 mm, mean weight diameter and geometric mean diameter of the corn stalk biochar mixed with bentonite treatment significantly increased in the second year. Biochar and bentonite significantly increased the soil organic matter content, pH, cation exchange capacity (CEC) and available nitrogen, phosphorus and potassium contents, and CEC increased by 150.4%. Soil available phosphorus increased 2.6 times compared with that of the fertilizer treatment. Soil alkali-hydrolyzable nitrogen content increased by 211.5%, respectively. The plant height, leaf area index and ground dry matter mass also increased significantly, and the corn yield increased by 36.6% in response to the mixed application of 1.9 t/hm² corn stalk biochar and 12 t/hm² bentonite. The contents of urease, sucrase and catalase increased first and then decreased with crop growth through the jointing, silking and maturity stages. The microbial carbon content increased 2.4 times in the second year when corn stalk biochar was applied compared with that in the first year. The carbon sequestration potential of biochar application was equivalent to offsetting CO_2 emissions by approximately 100 million tons per year of the study.

Keywords Aeolian sandy soil, Biochar, Bentonite, Physicochemical properties, Biological properties, Carbon sequestration and emission reduction

Globally, land degradation is a major challenge to the sustainable development of human societies because it has adverse impacts on the amount of arable land available, food production, water security, economic development and environmental integrity[1]. China is one of the most affected countries in the world in terms of the extent, intensity and economic impact of land degradation[2]. Desert and desertification areas are distributed in the Taklimakan Desert in Northwest China through the Great Gobi to the Horqin and Hulunbuir Sandy Lands in Northeast China[3]. The northern part of western Liaoning is located on the southern edge of the Horqin Sandy Land, and the soil type is mainly aeolian sand. Aeolian sand is mainly gravel, with a low clay content, large pores, poor soil quality and a poor farmland surface layer, which cannot meet the growth needs of plants and is a major

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obstacle to agricultural development in this region. However, areas with aeolian sand are important agricultural land resources in China. Therefore, improving the properties of aeolian sand, preventing soil desertification and improving plant productivity are important components of sustainable agricultural production[4]. If a soil conditioner is added to improve the properties of aeolian sand and promote crop growth, the environmental quality of weathered sandy soils can be markedly improved, which is the best route for achieving ecological restoration and rapid economic development in desert areas.

Biochar is regarded as an important material to address climate change, agricultural production safety, the energy crisis, agricultural waste recycling, environmental pollution and other issues affecting sustainable human development and has become a research hotspot in the fields of soil science and environmental science[5]. Improving soil fertility and fixing and transforming pollutants in agricultural soil is one way to improve aeolian sand. Biochar modification of agricultural soils has been recognized as a means of reducing greenhouse gases, improving soil quality and adapting to agri-climate changes and extremes[6,7]. Biochar is a carbon-rich material produced from the thermochemical conversion of various biomass wastes in an environment with limited oxygen[8]. It has a porous structure, large specific surface area, strong stability, abundant oxygen-containing functional groups, abundant Ca^{2+}, Mg^{2+} and other polyvalent cations, and high nutrient content, which can effectively improve the physical and chemical properties of soil, affect the growth and development of soil microorganisms and aboveground vegetation, and directly or indirectly affect the carbon sequestration and emission reduction potential of treated soil[9,10]. Through long-term biochar culture experiments, Liang[11] et al. found that the addition of biochar significantly increased soil microbial biomass. Bohara et al.[12] also reported that pine biochar increased the soil water holding capacity, plant available water, saturated water permeability and drought tolerance in very fine sandy loam. Biochar has an aromatic hydrocarbon structure, so it can persistence for up to 200 years in soils, serving as a resource-based renewable raw material for storing carbon[13]. Soil is the largest organic carbon reservoir in terrestrial ecosystems[14], and approximately two-thirds of the available carbon is in the form of soil organic carbon (SOC)[15]. To ensure crop yield and food security, appropriate amounts of organic materials can be applied to effectively increase soil organic carbon content and reduce greenhouse gas emissions. Biochar extracted from agricultural waste is estimated to absorb approximately 500 million tons of CO_2 per year, equivalent to 1.5% of total annual global CO_2 emissions[16,17]. Zhang et al. reported that corn stalk biochar application can significantly increase soil organic carbon by 13.0% [18]. Thus, biochar can be used as a carbon-negative tool to promote soil carbon sequestration and reduce greenhouse gas emissions[19]. Because of the low content of silt and clay in aeolian sand, the most direct way to improve it is to sprinkle powder and clay on its surface to promote the formation of aggregates. Bentonite is a mineral clay, with its main component being montmorillonite, which is abundant in China and inexpensive[20]. Bentonite has unique properties, such as high water absorption capacity, adsorption capacity and expandability[21], and can improve different soil environments in different ways. Adding bentonite to aeolian sand can improve plant fertilizer utilization rates and soil organic matter content and promote crop growth[22]. It can also be used as a soil additive to increase soil water content[23], increase millet yield[24], and improve drought tolerance for sustainable agricultural production in semiarid regions[25].

In summary, biochar and bentonite can be used as excellent amendments to improve aeolian sandy soil and increase crop productivity. Biochar and bentonite as soil amendments have been widely studied by scholars in China and other countries, but the effect of the combined application of biochar and bentonite to aeolian sandy soil is still unclear. Therefore, in this paper, the aeolian sandy soil of northwestern Liaoning Province was considered the research object, field tests were carried out by adding different amounts of biochar and bentonite, and the effects of biochar and bentonite on aeolian sandy soil was analyzed over two years. In this study, the changes in the physical, chemical and biological properties of aeolian sandy soil under the application of different types and amounts of amendments, the effects of the amendments on the growth of corn crops, and the potential of biochar for carbon sequestration and emission reduction were investigated.

Materials and methods
Experimental site and experimental design
The experiment was carried out in the experimental field (42° 43′–42°51′ N, 121°53′–122°22′ E) of Zhanggutai Town, Zhangwu County, Fuxin City, Liaoning Province, China, from 2021 to 2022. The site was located on the southern edge of the Horqin Sandy Land, and the soil was composed of aeolian sand, soil sand accounted for 92.70% (particle size 0.02–2 mm), silt accounted for 6.32% (0.002–0.02 mm), clay particle accounted for 1.13% (< 0.002 mm). The average altitude was 226.5 m, the annual rainfall was 450–550 mm, the rainfall mostly occurred from June to August, the annual average temperature was 5.7 °C, and the annual average temperature was 155 d during the frost-free period, which is typical of a temperate continental monsoon climate. The monthly rainfall, relative humidity and average environment temperature from May to September 2021 and from May to September 2022 are shown in Table S1. The modified agent used in the experiment was biochar prepared from corn stalk, bamboo and rice husk under the condition of high temperature with limited oxygen cracking at 450 °C, which was purchased from Zhengzhou Lize Environmental Protection Technology Co., LTD., Henan Province. Bentonite was purchased from Qinghemen District Qingbei Bentonite Co., Ltd., Fuxin city. It consisted of calcium bentonite. Before the experiment, the basic physical and chemical properties of the soil (0–20 cm) were 6.537 pH, 1.492 g/cm³ bulk density, 8.225 g/kg organic matter, 10.03 mg/kg available phosphorus, 119.560 mg/kg available potassium, and 10.850 mg/kg alkaline hydrolytic nitrogen. The cation exchange capacity (CEC) was 1.610 cmol/kg, the mean weight diameter (MWD) was 0.29 mm, the geometric mean diameter (GMD) was 0.27 mm, and the water-stable aggregate content ($WR_{> 0.25 mm}$) was 18.21%. The basic physicochemical properties of biochar and bentonite are shown in Table S2. The scanning electron microscopy, Fourier transform infrared spectroscopy and X-ray powder diffraction analysis of biochar and bentonite are respectively given in Supplementary Fig. S1, Fig. S2, and Fig. S3.

The total area of the test area was 0.2 hm^2. On May 15, 2021, corn stalk biochar (CB), bamboo charcoal (BC), rice husk biochar (RB) and bentonite (BT) were applied as amendments alone or in combination, and two addition levels were used: biochar (0.94 t/hm^2, 1.9 t/hm^2), bentonite (6 t/hm^2, 12 t/hm^2). Two blank controls were set, one with fertilizer and one without fertilizer. There were 22 treatments in total, and 4 replicates were used for each treatment. On May 15, 2022, only corn stalk biochar was applied (1.9 t/hm^2), and a total of 6 treatments were applied, with 4 replicates per treatment. The schematic diagram of the test area is shown in Figure S4. The crop planted was corn (Yi Mei Yu 192), the sowing depth was 6 cm, the base fertilizer was compound fertilizer, the ratio of nitrogen, phosphorus pentoxide and potassium oxide is 15:15:15 and the dose was 568 kg/hm^2. No additional fertilizer was applied during this period. Other management methods were based on local production practices. The test treatment types are shown in Table 1. Please refer to the Supplementary for the specific period of sample collection.

Methods for the determination of soil properties and corn agronomic traits

Measurement of soil physical indices

The soil bulk density and soil water content were measured by the ring knife method. Dry and wet screening methods were used to determine the content of soil aggregates at all levels and the content of water-stable aggregates[26].

Determination of soil chemical indices

The pH of the soil was measured by a magnetic pH meter. OM content was determined by the potassium dichromate volumetric method and the dilution heating method. The amount of alkali-hydrolyzable nitrogen was determined by the alkali-diffusion method. The available phosphorus was determined by sodium bicarbonate leaching with molybdenum-antimony absorbance spectrophotometry. Available potassium was determined by ammonium acetate extraction and flame photometry. The cation exchange capacity was determined by sodium acetate flame spectrophotometry. All of them refer to the determination methods in Soil Agrochemical Analysis[27].

Soil biological index determination

Catalase activity was determined by the volumetric method. Urease content was determined by the colorimetric method involving sodium phenol-sodium hypochlorite. The activity of sucrase was determined by

Sampling year	Types of soil amendments	Volume of addition(t/hm^2)	Rate of fertilizer application(kg/hm^2)	Serial number
2021	Not fertilized	0	0	T1
	Fertilization	0	568	T2
	Rice husk biochar	0.94	568	T3
		1.9	568	T4
	Corn stalk biochar	0.94	568	T5
		1.9	568	T6
	Bamboo Charcoal	0.94	568	T7
		1.9	568	T8
	Bentonite	6	568	T9
		12	568	T10
	Rice husk biochar + bentonite	6 + 0.94	568	T11
		6 + 1.9	568	T12
		12 + 0.94	568	T13
		12 + 1.9	568	T14
	Corn stalk biochar + bentonite	6 + 0.94	568	T15
		6 + 1.9	568	T16
		12 + 0.94	568	T17
		12 + 1.9	568	T18
	Bamboo Charcoal + bentonite	6 + 0.94	568	T19
		6 + 1.9	568	T20
		12 + 0.94	568	T21
		12 + 1.9	568	T22
2022	Not fertilized	0	568	2T1
	Fertilization	0	568	2T2
	Corn stalk biochar	1.9	568	2T6
	Bentonite(the year 2021)	12	568	2T10
	Corn stalk biochar + bentonite(the year 2021)	0.94 + 6	568	2T15
		1.9 + 12	568	2T18

Table 1. Test treatment.

3,5-dinitrosalicylic acid colorimetry. Soil microbial biomass carbon was determined by chloroform fumigation extraction. All of them were measured according to the methods in Soil Enzymes and Their Research Method[28].

Determination of plant samples
Plant height was measured with a tape measure in the growing and maturity stages of maize; Corn leaf length L and maximum leaf width D were measured when the corn was harvested, and leaf area index = $\Sigma(L \times D \times 0.75)$; After the corn matured, it was cut along the stem base during harvest and placed in a clean plastic bag. Soil was shaken off the corn roots, the roots were rinsed, air-dried and placed in bags, and the aboveground parts of the corn were mixed with the underground parts. The corn was placed in a blast drying oven to deactivate the plant cells, the oven temperature was set to 105 °C for 30 min, and then the temperature was adjusted to 65 °C to dry the corn to a constant weight, after which it was weighed. At the maturity stage of maize growth, the yield was calculated via random selection in each plot, and the water content of the grain was measured by threshing, which was ultimately converted to 14% of the water content of the grain[29].

Data analysis and processing
In this study, the total carbon sequestration and emission reduction potential of biochar improved aeolian sand soil was estimated, mainly including two action processes of carbon sequestration and emission reduction. The ideas were as follows[30]:

Estimation of carbon sequestration and emission reduction potential of biochar

$$P = P_1 + P_2 \tag{1}$$

where P represents the carbon sequestration and emission reduction potential of biochar;
P_1 is the potential of the carbon storage component of biochar soil to offset CO_{2e} emissions.
P_2 is the net change in soil CO_{2e} induced by biochar.

$$CO_{2e} = CO_2 + 25CH_4 + 298N_2O \tag{2}$$

$$P_1 = M_i \times Y_i \times C_i \times 3.7 \tag{3}$$

where CO_{2e} is the equivalent of the annual CO_2 emissions from biochar to soil;
M_i is the annual availability of biomass (tons), In this study, the value is 100 million tons;
Y_i is the estimated biochar yield (%), in this study, the value is 35%;
C_i is the estimated value of the biochar carbon content (%), In this study, the value is 65%.

$$K = P_2/P_1 \tag{4}$$

$$K = -12 \times 365 \times 10^{-6} \times \Delta CO_{2e} \div (44R \times C) = -0.0001\Delta CO_{2e} \div (R \times C) \tag{5}$$

where k is the emission reduction coefficient, R is the amount of biochar added and ΔCO_{2e} is the net change value of greenhouse gas emission reduction converted into CO_2 content after biochar application in soil. In this study, the biochar was medium temperature biochar, and the greenhouse gas emission reduction induced by biochar was about 18.7 μg/g.

Microsoft Excel 2019 was used to organize and process the data, Origin Pro2021 software was used for plotting, and SPSS 19.0 was used for statistical analysis. The data are expressed as the mean ± standard deviation. Pearson's correlation analysis was used to determine correlations in the data obtained from the normality tests.

Results
Effects of biochar and bentonite on soil physical properties
Effects of biochar and bentonite on soil moisture content and bulk density
The changes of soil bulk density under different amendment treatments are shown in Fig. 1, and there was no significant difference between the soil bulk density obtained under different treatments in two years($P > 0.05$). The application of biochar and bentonite significantly reduced the soil bulk density (Fig. S5). The soil bulk density decreased with the progression of maize growth and decreased with increasing amendment amount. In 2021, the combined application of 1.9 t/hm² bamboo charcoal and 12 t/hm² bentonite at the jointing stage, silking stage and maturity stage (T22) resulted in the most obvious decrease in soil bulk density, which was 3.2%, 5.3% and 5.6%, respectively, compared with that in the T2 treatment. In 2022, the soil bulk density under the T2 treatment at the jointing stage, silking stage and maturity stage was 1.474 g/cm³, 1.453 g/cm³ and 1.392 g/cm³, respectively. The ranges of the soil bulk density under the biochar and bentonite treatments were 1.469–1.449 g/cm³, 1.448–1.414 g/cm³, and 1.374–1.340 g/cm³, respectively. The effect of the mixed application of 1.9 t/hm² corn stalk biochar and 12 t/hm² bentonite was most significant on soil bulk density.

As shown in Fig. 2, soil moisture content of biochar and bentonite applied in 2021 showed an increasing trend with the growth period of maize, and there was a significant difference in soil moisture content between T1 treatment and T22 treatment ($P < 0.05$), while no significant difference in soil moisture value obtained from other treatments ($P > 0.05$). In 2022, the soil moisture content in order from high to low is at maturity stage, silking stage and jointing stage, and there was no significant difference in soil moisture content among each treatment ($P > 0.05$). At the jointing stage, silking stage and maturity stage in 2022, the mixed application of 1.9 t/hm² corn stalk biochar and 12 t/hm² bentonite (2T18) resulted in the highest soil moisture content, and the soil moisture at the jointing stage in 2022 was greater than that in the same treatment in 2021, which was largely related to rainfall conditions.
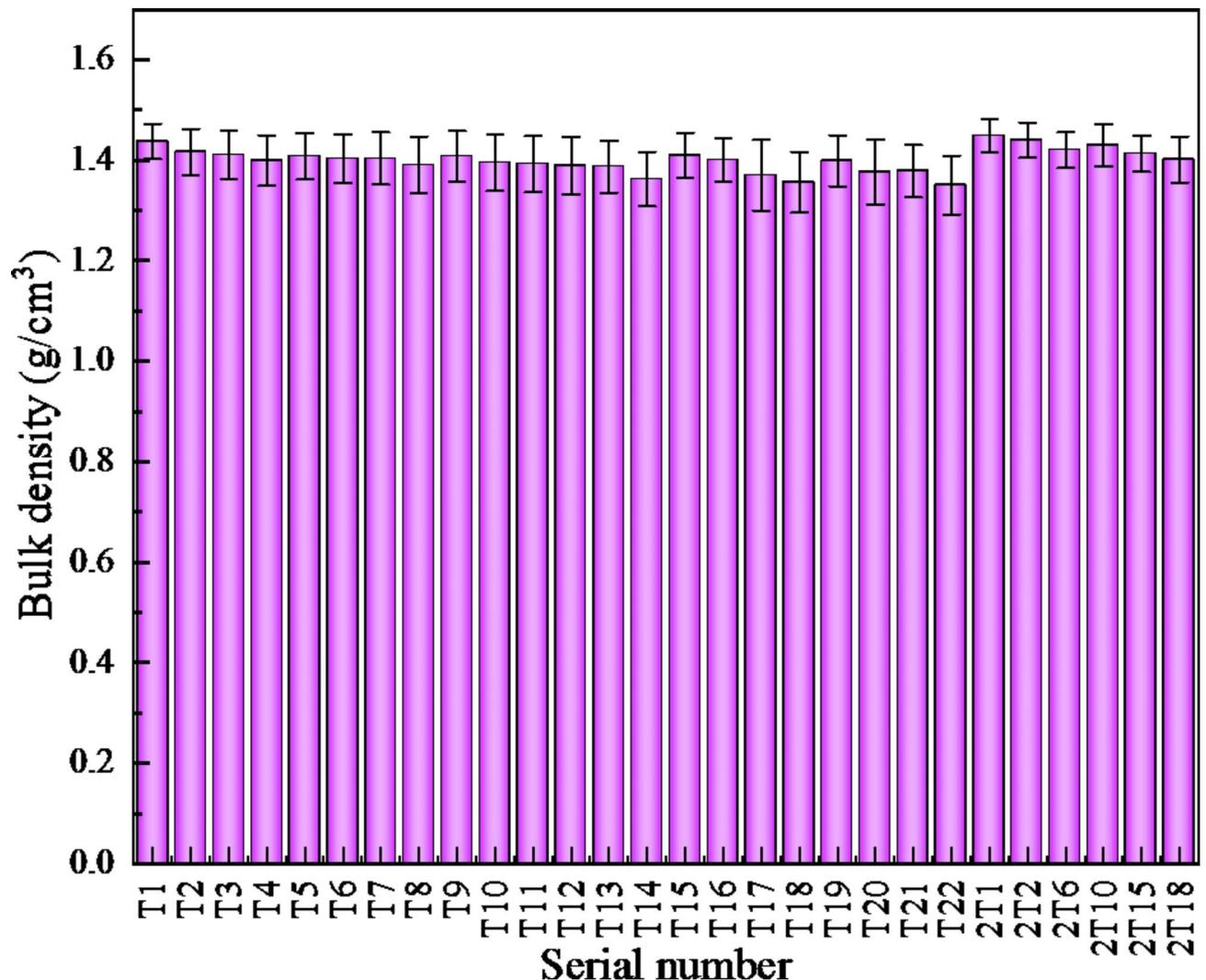
Fig. 1. Changes in the bulk density of soils treated with different modifiers.

Effects of biochar and bentonite on soil aggregates

Different types and amounts of biochar had certain effects on soil aggregates (Table 2). Compared with the control treatment, the treatments in 2021 and 2022 had significant effects on the $WR_{>0.25\,mm}$ content ($P < 0.05$). In 2021, the mixed application of 1.9 t/hm² bamboo charcoal and 12 t/hm² bentonite obviously increased the $WR_{>0.25\,mm}$, and the mass fraction at silking stage and maturity stage increased by 30.2% and 16.0%, respectively, compared with that of the fertilization treatment. In 2022, the 2T18 treatment resulted in the most obvious change in the $WR_{>0.25\,mm}$ content, which was greater than that in the same treatment in 2021. Compared with those in the T18 treatment, the $WR_{>0.25\,mm}$ content increased by 1.5%, 2.5% and 4.1%, respectively. In addition, the MWD (mean weight diameter) of each treated soil was affected by the type and amount of biochar added. The MWD of the aggregates treated with T22 at the jointing stage and silking stage in 2021 was obviously greater than that of the other treatments. The changes in the MWD of aggregates treated with mixed corn stalk biochar and bentonite in the three stages in 2022 were obvious and greater than those with the same treatment in 2021, among which the MWD of aggregates treated with 2T18 at silking increased by 11.6% compared with that of those treated with T18. The water-stable aggregate GMD (geometric mean diameter) increased obviously with the growth of maize. In 2021, the GMD values of the T22, T17 and T7 treatments were the highest at the jointing stage, increasing by 10.0% compared with those of the T2 treatment. The GMDs of the T14, T18, T20 and T22 treatments were the highest in the silking stage, and the GMD markedly changed with the mixed application of bamboo charcoal and bentonite. The GMD value treated with 1.9 t/hm² corn stalk biochar and 12 t/hm² bentonite was the highest at maturity, and the GMD increased by 18.9% compared with that in the T2 treatment. The GMD of the 2T18 treatment at the jointing stage, silking stage and maturity stage of corn in 2022 was obviously greater than that of the other treatments.
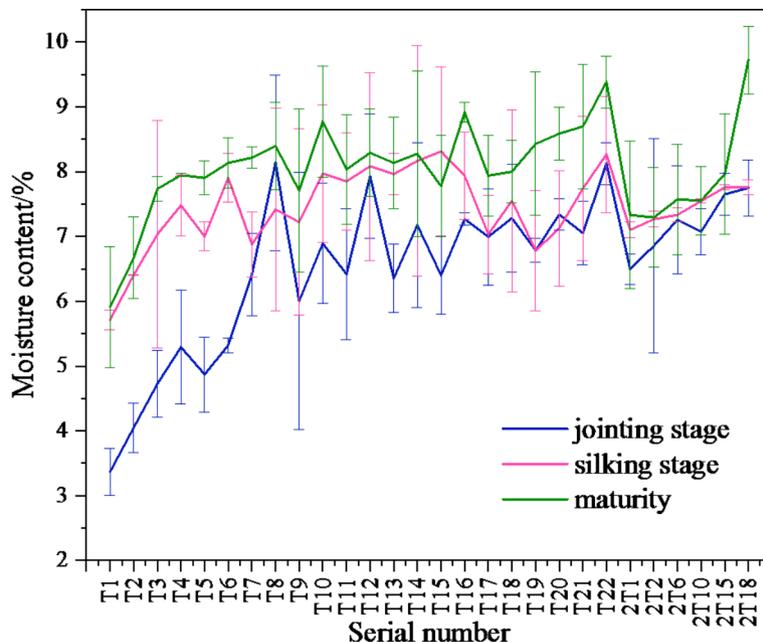
Fig. 2. Changes in the moisture of soils treated with different modifiers.

Treatment	WR > $_{0.25\ mm}$			MWD			GMD		
	jointing stage	silking stage	maturity	jointing stage	silking stage	maturity	jointing stage	silking stage	maturity
T1	18.23 ± 1.47^g	19.98 ± 1.00^g	38.61 ± 5.39^c	0.30 ± 0.01^f	0.31 ± 0.01^e	0.36 ± 0.05^b	0.28 ± 0.01^c	0.29 ± 0.01^f	0.33 ± 0.01^b
T2	22.41 ± 5.28^{ef}	27.88 ± 0.91^f	45.48 ± 1.84^b	0.35 ± 0.02^e	0.37 ± 0.02^d	0.43 ± 0.04^{ab}	0.30 ± 0.01^{bc}	0.31 ± 0.01^e	0.37 ± 0.04^{ab}
T3	22.96 ± 2.35^f	29.03 ± 1.31^{ef}	50.09 ± 0.81^{ab}	0.36 ± 0.03^{de}	0.38 ± 0.02^{bcd}	0.55 ± 0.06^{ab}	0.30 ± 0.01^{bc}	0.32 ± 0.01^{cde}	0.39 ± 0.06^{ab}
T4	24.90 ± 0.76^{ef}	29.90 ± 0.79^{ef}	51.55 ± 2.59^{ab}	0.37 ± 0.01^{bcde}	0.41 ± 0.01^{bcd}	0.60 ± 0.05^{ab}	0.30 ± 0.01^{abc}	0.32 ± 0.02^{de}	0.41 ± 0.07^{ab}
T5	25.59 ± 3.55^{bcde}	29.58 ± 1.15^{def}	48.83 ± 1.40^{ab}	0.38 ± 0.06^{abcde}	0.41 ± 0.02^{abcd}	0.55 ± 0.07^{ab}	0.31 ± 0.02^{ab}	0.32 ± 0.01^{bcde}	0.38 ± 0.04^{ab}
T6	26.24 ± 1.57^{cde}	30.72 ± 0.29^{cdef}	52.74 ± 1.48^{ab}	0.39 ± 0.03^{abcde}	0.41 ± 0.03^{abcd}	0.62 ± 0.07^{ab}	0.31 ± 0.01^{abc}	0.32 ± 0.01^{bcde}	0.41 ± 0.03^{ab}
T7	26.50 ± 3.14^{bcde}	29.72 ± 0.70^{def}	50.32 ± 1.72^{ab}	0.37 ± 0.02^{cde}	0.39 ± 0.01^{bcd}	0.54 ± 0.06^{ab}	0.33 ± 0.05^a	0.32 ± 0.01^{cde}	0.39 ± 0.05^{ab}
T8	27.12 ± 1.56^{bcde}	31.57 ± 1.47^{bcde}	51.41 ± 2.42^{ab}	0.42 ± 0.04^{ab}	0.44 ± 0.02^{ab}	0.58 ± 0.06^{ab}	0.32 ± 0.01^{ab}	0.33 ± 0.01^{abc}	0.41 ± 0.04^{ab}
T9	26.00 ± 2.25^{de}	30.93 ± 0.84^{cdef}	51.44 ± 3.81^{ab}	0.37 ± 0.03^{de}	0.39 ± 0.02^{bcd}	0.56 ± 0.04^{ab}	0.30 ± 0.01^{abc}	0.32 ± 0.01^{cde}	0.39 ± 0.02^{ab}
T10	27.59 ± 1.01^{bcde}	30.85 ± 1.37^{ef}	50.24 ± 1.83^{ab}	0.39 ± 0.03^{abcde}	0.39 ± 0.04^{cd}	0.60 ± 0.07^{ab}	0.31 ± 0.01^{ab}	0.31 ± 0.01^e	0.40 ± 0.05^{ab}
T11	27.42 ± 0.92^{bcde}	31.19 ± 1.82^{cde}	51.14 ± 1.22^{ab}	0.40 ± 0.02^{abcd}	0.42 ± 0.01^{abcd}	0.57 ± 0.06^{ab}	0.32 ± 0.01^{ab}	0.33 ± 0.01^{abcde}	0.39 ± 0.03^{ab}
T12	30.09 ± 1.22^{bc}	32.17 ± 1.49^{bcde}	51.03 ± 0.63^{ab}	0.42 ± 0.05^{abcd}	0.41 ± 0.04^{abcd}	0.60 ± 0.06^{ab}	0.32 ± 0.01^{ab}	0.32 ± 0.02^{bcde}	0.41 ± 0.05^{ab}
T13	29.23 ± 0.78^{abcd}	33.37 ± 1.26^{bce}	49.32 ± 0.83^{ab}	0.40 ± 0.01^{abcd}	0.42 ± 0.03^{abcd}	0.57 ± 0.10^{ab}	0.32 ± 0.01^{ab}	0.34 ± 0.01^{abc}	0.40 ± 0.03^{ab}
T14	30.81 ± 2.03^{abcd}	33.96 ± 1.47^{bc}	51.24 ± 2.16^{ab}	0.40 ± 0.01^{abcde}	0.43 ± 0.04^{abcd}	0.66 ± 0.15^{ab}	0.32 ± 0.01^{ab}	0.35 ± 0.02^{abcde}	0.42 ± 0.05^a
T15	29.54 ± 0.74^{bcd}	31.78 ± 0.74^{bcde}	50.72 ± 1.63^{ab}	0.40 ± 0.01^{abcd}	0.41 ± 0.06^{abcd}	0.58 ± 0.05^{ab}	0.32 ± 0.01^{ab}	0.33 ± 0.01^{abcde}	0.39 ± 0.03^{ab}
T16	29.89 ± 0.38	33.36 ± 3.35^{bcd}	51.00 ± 2.91^{ab}	0.42 ± 0.04^{abcde}	0.42 ± 0.01^{abcd}	0.60 ± 0.05^{ab}	0.32 ± 0.01^{ab}	0.33 ± 0.01^{abcde}	0.41 ± 0.02^{ab}
T17	29.67 ± 0.85^{ab}	34.42 ± 1.06^{ab}	50.26 ± 3.91^{ab}	0.41 ± 0.02^{abc}	0.43 ± 0.04^{ab}	0.66 ± 0.13^{ab}	0.33 ± 0.01^{ab}	0.33 ± 0.02^{abc}	0.42 ± 0.06^a
T18	30.14 ± 1.12^{abc}	35.10 ± 0.93^{abc}	52.49 ± 2.24^a	0.41 ± 0.05^{abcd}	0.43 ± 0.04^{ab}	0.70 ± 0.11^{ab}	0.32 ± 0.01^{ab}	0.35 ± 0.01^{ab}	0.44 ± 0.07^a
T19	29.05 ± 0.99^{bcd}	31.09 ± 0.80^{acd}	49.08 ± 4.18^{ab}	0.39 ± 0.02^{abcde}	0.41 ± 0.02^{abcd}	0.50 ± 0.05^{ab}	0.32 ± 0.01^{ab}	0.33 ± 0.01^{abcde}	0.39 ± 0.02^{ab}
T20	29.25 ± 1.2^{bcd}	32.43 ± 0.7^{abcd}	52.06 ± 1.94^{ab}	0.39 ± 0.01^{abcde}	0.42 ± 0.02^{abcd}	0.56 ± 0.07^{ab}	0.32 ± 0.01^{ab}	0.35 ± 0.02^{abcde}	0.41 ± 0.02^{ab}
T21	28.82 ± 0.93^{abcd}	33.58 ± 1.06^{abc}	51.50 ± 2.65^{ab}	0.40 ± 0.02^{abcd}	0.43 ± 0.03^{abc}	0.65 ± 0.16^{ab}	0.32 ± 0.01^{ab}	0.33 ± 0.01^{abcd}	0.42 ± 0.05^a
T22	29.58 ± 0.48^{abc}	36.30 ± 2.93^a	52.77 ± 0.72^a	0.42 ± 0.02^a	0.45 ± 0.02^a	0.69 ± 0.13^a	0.33 ± 0.01^{ab}	0.35 ± 0.01^a	0.43 ± 0.04^a
2T1	18.95 ± 0.75^d	20.05 ± 0.01^e	38.39 ± 0.91^b	0.30 ± 0.00^b	0.30 ± 0.00^d	0.39 ± 0.01^d	0.28 ± 0.00^b	0.29 ± 0.00^d	0.33 ± 0.00^c
2T2	24.98 ± 0.11^c	28.46 ± 0.34^d	41.49 ± 3.76^b	0.35 ± 0.00^{ab}	0.39 ± 0.01^c	0.48 ± 0.01^c	0.30 ± 0.00^a	0.31 ± 0.00^c	0.37 ± 0.00^b
2T6	26.15 ± 0.39^{bc}	30.93 ± 0.09^c	50.18 ± 0.44^a	0.39 ± 0.00^a	0.40 ± 0.01^c	0.57 ± 0.00^b	0.31 ± 0.01^a	0.32 ± 0.00^{bc}	0.39 ± 0.00^b
2T10	27.50 ± 0.27^b	30.85 ± 0.00^c	52.75 ± 0.84^a	0.39 ± 0.03^a	0.39 ± 0.00^{bc}	0.52 ± 0.03^{bc}	0.31 ± 0.01^a	0.32 ± 0.00^{bc}	0.39 ± 0.00^b
2T15	29.90 ± 0.40^a	32.38 ± 0.15^b	52.46 ± 0.94^a	0.41 ± 0.02^a	0.45 ± 0.02^{ab}	0.57 ± 0.00^b	0.32 ± 0.00^a	0.34 ± 0.01^{ab}	0.39 ± 0.01^b
2T18	30.58 ± 0.44^a	35.96 ± 0.48^a	54.62 ± 0.43^a	0.42 ± 0.00^a	0.48 ± 0.01^a	0.71 ± 0.02^a	0.33 ± 0.00^a	0.35 ± 0.00^a	0.44 ± 0.00^a

Table 2. Changes in soil aggregates under different soil amendments. Note: Different letters in the same column in the same year indicate significant differences between treatments at $P < 0.05$. The data after addition or subtraction is (s.d.).

Effects of biochar and bentonite on soil chemical properties

Effects of biochar and bentonite on soil pH, organic matter and cation exchange capacity

The changes of soil pH value under different amendment treatments are shown in Fig. 3A and there were significant differences in soil pH between T2 treatment and T22 treatment in 2021 ($P < 0.05$). In 2022, there was a significant difference in soil pH value between 2T2 and 2T18 treatments($P < 0.05$). The variation of soil pH value in different periods is shown in Figure S6A. In 2021, the pH values in the jointing stage, silking stage
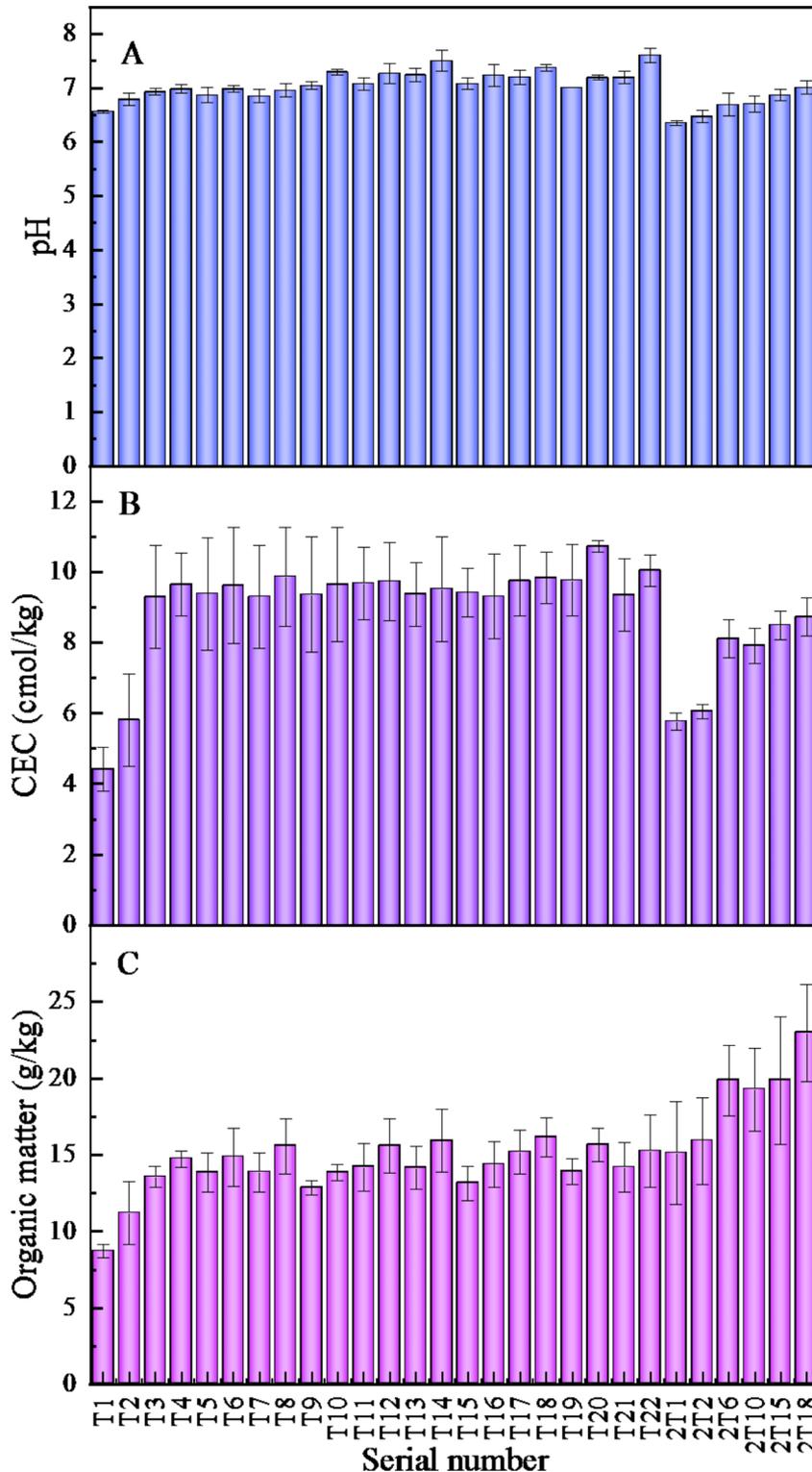
Fig. 3. Changes in soil Organic matter, pH and CEC after treatment with different amendments. Note：The letters A, B and C stand for pH, CEC and Organic matter, respectively

and maturity stage were 6.540–7.760, 6.560–7.683 and 6.60–7.437, respectively, and the pH value in the T22 treatment was the highest in jointing stage and maturity stage, with unit increases of 1.10 and 0.50, respectively, compared with the T2 treatment. In 2022, the pH of the mixed treatment was greater than that of the individual treatment and was greater than that of the no-biochar-application treatment, and the pH of the 2T18 treatment at maturity increased by 0.73 units compared with the 2T2 treatment.

The overall change trend of soil CEC is shown in Fig. 3B. Except for T1 treatment, there were significant differences between T2 treatment and other treatments ($P < 0.05$); there were significant differences between T1 and T2 treatment and other treatments in 2022, respectively ($P < 0.05$), but there were no significant differences between T1 and T2 ($P > 0.05$). During each growth cycle of maize, the soil CEC in each treatment tended to increase, and the soil CEC increased significantly from the jointing stage to the silking stage (Fig. S6B). At the jointing stage in 2021, compared with the T2 treatment, the T20 treatment increased the soil CEC by 150.4%. The CEC in the T8 treatment group at the silking stage was the highest, increasing by 94.5% compared with the T2 treatment. The concentration of CEC in the T6 treatment at the maturity stage was obviously greater than that in the other treatments. In 2022, the CEC in the 2T18 treatment group was obviously greater than that in the other treatment groups, and the CEC in the 2T18 treatment group increased by 41.0% than that in the 2T2 treatment group at the jointing stage.

The overall change trend of soil organic matter content is shown in Fig. 3C. In 2021, there were significant differences between T1 treatment and T14, T18 and T22 treatment ($P < 0.05$). There was no significant difference in soil organic matter content in 2022. The organic matter content showed an overall upward trend with the growth of maize (Fig. S6C). The average ranges of the organic matter content at the jointing stage, silking stage and maturity stage in 2021 and 2022 were 8.083–18.573 g/kg, 8.856–24.488 g/kg and 9.114–25.864 g/kg, respectively. The content of organic matter in the T20 treatment at the 2021 jointing stage was the highest. Compared with the T2 treatment, the increase was 79.2%. In 2022, the organic matter content of the 2T18 treatment at the jointing stage was the highest, increasing by 54.3% compared with the 2T2 treatment. The organic matter content in the 2T18 treatment in 2022 was obviously greater than that in the T18 treatment in 2021 and increased by 28.6%, 49.1% and 47.4% in the three stages.

Effects of biochar and bentonite on soil available phosphorus, available potassium and alkali-hydrolyzable nitrogen

The changes in the soil available phosphorus content are shown in Fig. 4A. There was no significant difference in soil available phosphorus content among all treatments in 2021($P > 0.05$), and there were significant differences between 2T1 treatment and 2T15 and 2T18 treatment in 2022, respectively ($P < 0.05$). In Fig. S7A, the results showed that when the dose of the same amendment increased, the available phosphorus content in the soil also increased. The content of soil available phosphorus in the T14 treatment group was the highest at the jointing stage in 2021, with an increase of 2.6 times compared with the T2 treatment. The T16 treatment at the silking stage had the most obvious effect on the change in soil available phosphorus, and compared with that in T2, the available phosphorus content increased by 2.4 times. The available phosphorus content in the T22 treatment group at maturity was the highest and increased by 2.6 times compared with the T2 treatment. In 2022, the 2T18 treatment had the most obvious effect on the available phosphorus content among the three stages of maize growth. Compared with that in the 2T2 treatment group, the AP content in the jointing stage increased by 2.4 times, the AP content in the silking stage and maturity stage increased by 2.1 times, and the AP content in the mixed treatment group in the three stages showed an increasing trend compared with that in the same treatment group in 2021. The available phosphorus content in the 2T18 treatment group at the maturity stage was 1.4 times higher than that in the T18 treatment group.

The overall changes of soil available potassium content under different amendments are shown in Fig. 4B. There was no significant difference in soil available potassium content among all treatments in 2021($P > 0.05$), and significant difference between 2T18 treatment and 2T2 treatment in 2022 ($P < 0.05$). The content of soil available potassium also increased with the addition of amendments and showed a downward trend with the growth of maize (Fig. S7B). At the jointing stage in 2021, the soil available potassium content under the T20 treatment was the highest, increasing by 40.2% compared with that under the T2 treatment. The content of available potassium in the soil treated with T22 at the silking stage increased by 40.0% compared with that in the soil treated with T2. The soil available potassium content in the T16 treatment at maturity stage was significantly greater than that in the other treatments and increased by 43.5% compared with that in the T2 treatment. In 2022, the content of available phosphorus in the 2T18 treatment was the highest, and the content of available potassium in the soil at the jointing stage increased the most. The available potassium content in the 2T18 treatment increased by 54.0% compared with that in the 2T2 treatment.

The overall changes of soil alkali-hydrolyzed nitrogen content under different amendments are shown in Fig. 4C. In 2021, there were significant differences between T1 treatment and T21 treatment and T22 treatment, respectively ($P < 0.05$). In 2022, except for 2T1 treatment, there were significant differences in soil alkali-hydrolyzed nitrogen content between 2T2 treatment and other treatments ($P < 0.05$). The soil alkali-hydrolyzable nitrogen content showed a decreasing trend with maize development (Fig. S7C). In 2021, the soil alkali-hydrolyzable nitrogen content at the jointing stage, silking stage and maturity stage under T22 was the highest and increased by 185.0%, 125.6% and 211.5%, respectively, compared with that under the T2 treatment. In 2022, the effect of 2T18 treatment on alkali-hydrolyzable nitrogen was the most obvious, especially in the jointing stage, and the content of alkali-hydrolyzable nitrogen increased by 182.6% compared with that in the 2T2 treatment.
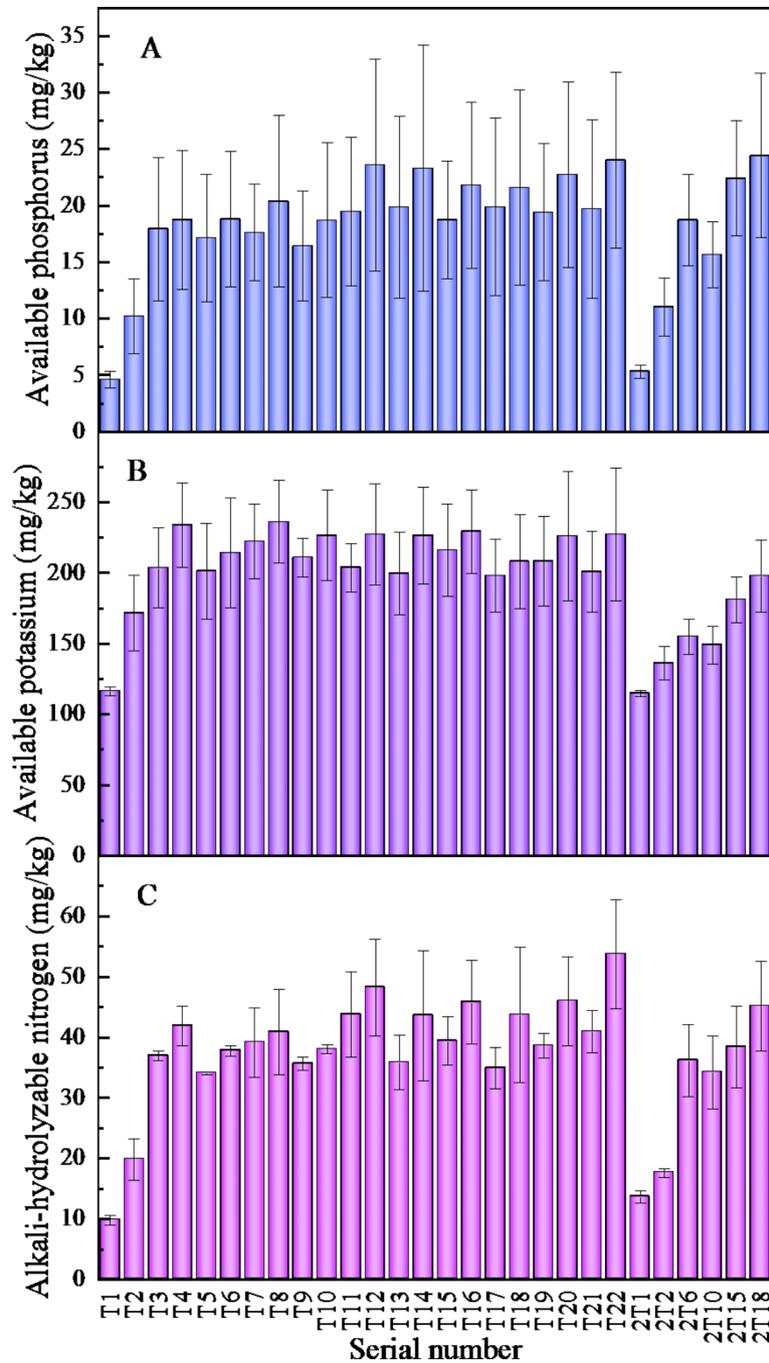
Fig. 4. Changes in soil nutrients after treatment with different amendments. Note：The letters A, B and C stand for Available phosphorus, Available potassium and Alkali-hydrolyzed nitrogen, respectively

Effects of biochar and bentonite on soil biological properties

Effects of biochar and bentonite on soil catalase activity

The changes of soil catalase activity under different amendments were shown in Fig. 5A, and there was no significant change in soil catalase activity between different treatments in two years ($P > 0.05$). The application of biochar and bentonite increased the catalase activity of the soil. With the growth of maize, the catalase activity showed a downward trend; that is, the catalase activity first increased and then decreased (Fig. S8A). At the jointing stage in 2021, the catalase activity of soil treated with 12 t/hm^2 bentonite (T10) changed obviously, with an increase of 19.0% compared with that in the T2 treatment. The activity of catalase in soil treated with 0.94 t/hm^2 corn stalk biochar (T5) at the silking stage increased by 34.0% compared with that in soil treated with T2. From planting to maturity, the change in soil catalase activity under the T10 treatment was the most obvious in 2021, increasing by 37.0% compared with that under the T2 treatment. In 2022, the 2T18 treatment at the jointing stage, silking stage and maturity stage resulted in obvious changes in catalase activity, which
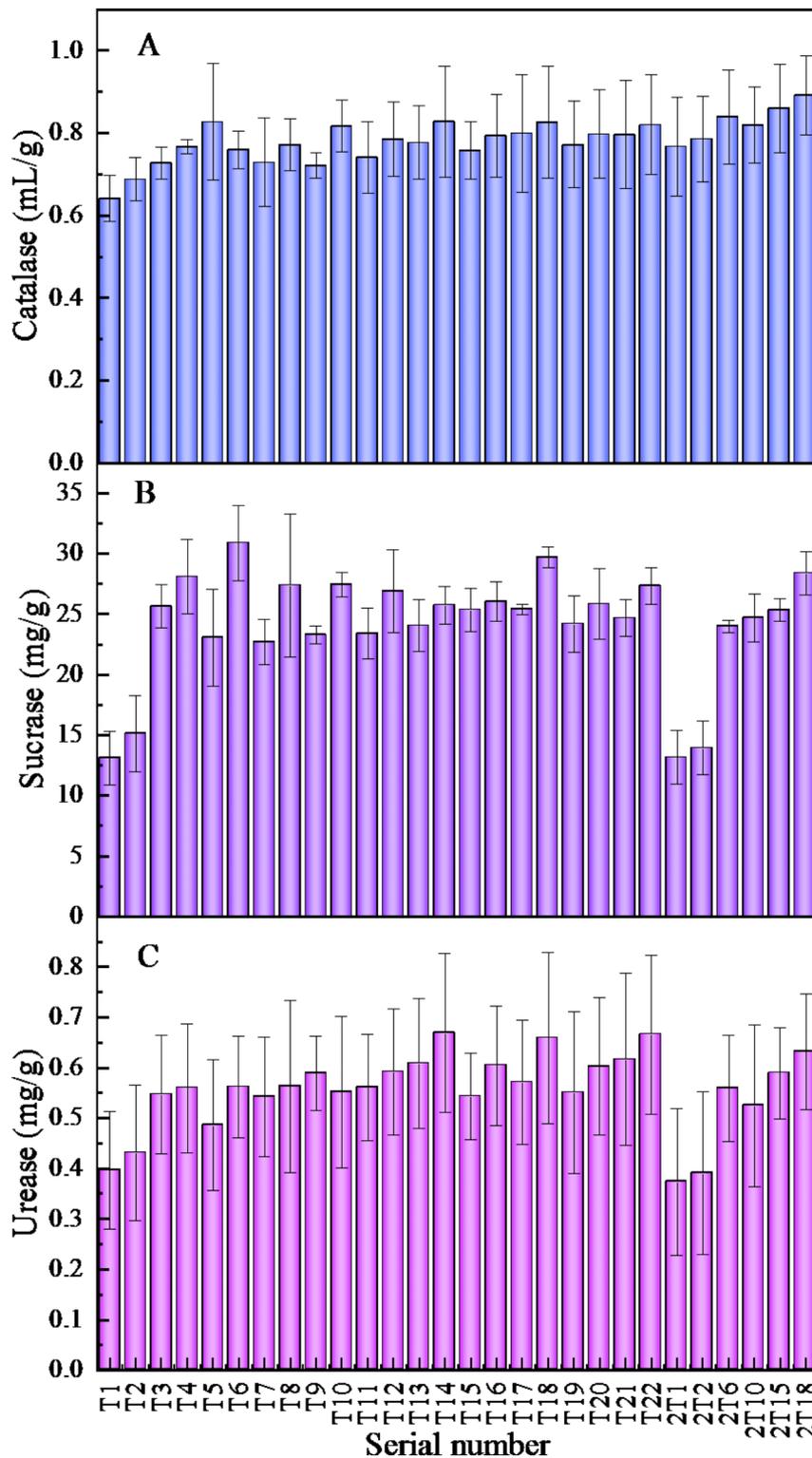
Fig. 5. Effects of different amendments on enzyme activity. Note：the letters A, B and C represent Catalase, Sucrase and Urease, respectively

increased by 18.8%, 12.1% and 10.8%, respectively, compared with that in the 2T2 treatment, and the effect of the combined application of corn stalk biochar and bentonite in the three periods was greater than that in the same treatment in the same period in 2021.

Effects of biochar and bentonite on soil sucrase
The changes of soil sucrase activity under different treatments are shown in Fig. 5B. In 2021, there were significant differences between T2 treatment and T14, T18, and T22 treatment ($P < 0.05$). In 2022, there were significant differences between 2T1 and 2T2 treatment and other treatments, respectively ($P < 0.05$). The application of biochar and bentonite significantly increased the activity of soil sucrase, and the activity of soil sucrase first increased and then decreased with the growth of maize (Fig. S8B). In 2021, the 1.9 t/hm^2 corn stalk biochar (T6) treatment at the jointing stage and silking stage had the most obvious effect on soil sucrase activity, which increased by 149.8% and 69.9% compared with that in the T2 treatment, respectively. When 1.9 t/hm^2 of bamboo charcoal (T8) was applied alone at maturity, the soil sucrase activity increased by 159.6% compared with that in T2. In 2022, mixed application of 1.9 t/hm^2 corn stalk biochar and 12 t/hm^2 bentonite at the jointing stage, silking stage and maturity stage resulted in the most obvious changes in soil sucrase activity. Compared with the same treatment in 2021, the sucrase activity showed an increasing trend.

Effects of biochar and bentonite on soil urease
The changes of soil urease activity under different treatments are shown in Fig. 5C, and there was no significant change in soil urease activity between different treatments in two years ($P > 0.05$). The changes in soil urease activity in different periods after the application of biochar and bentonite are shown in Fig. S8C. Soil urease activity first increased and then decreased with the growth of maize. At the jointing stage in 2021, the urease activity of soil treated with 1.9 t/hm^2 bamboo charcoal and 12 t/hm^2 bentonite (T22) was the most obvious, increasing by 1.7 times that in the T2 treatment. Compared with that in the T2 treatment, the urease activity in the 1.9 t/hm^2 corn stalk biochar and 12 t/hm^2 bentonite treatment (T18) groups at silking stage increased by 1.4 times. The urease activity of the soil treated with 1.9 t/hm^2 rice husk biochar and 12 t/hm^2 bentonite was obviously greater than that of the other treatments at maturity and increased by 1.7 times that of T2. In 2022, the 2T18 treatment resulted in the most significant changes in soil urease activity in all three periods, among which the 2T18 treatment increased the soil urease activity by 2.6 times compared with that in the 2T2 treatment at the maturity stage, and the soil urease activity achieved by the mixed application of 1.9 t/hm^2 corn stalk biochar and 12 t/hm^2 bentonite was greater in 2022 than that in 2021.

Effects of biochar and bentonite on soil microbial biomass
The changes of soil microbial biomass carbon content under different amendments are shown in Fig. 6, and there were significant differences between T1 treatment and T14, T18 and T22 treatment respectively in 2021 ($P < 0.05$). In 2022, there was a significant difference between 2T2 treatment and 2T18 treatment ($P < 0.05$). Biochar and bentonite significantly affected the soil microbial biomass carbon content, and the soil microbial biomass carbon increased with increasing amount of amendment and tended to first increase and then decrease during the maize growth period (Fig. S9). At the jointing stage in 2021, the mixed application of 1.9 t/hm^2 rice husk biochar and 12 t/hm^2 bentonite (T14) obviously improved soil microbial biomass carbon content, which increased by 2.0 times compared with that of the control T2. Compared with that of T2, the soil microbial biomass carbon content of T18 with mixed 12 t/hm^2 bentonite and 0.94 t/hm^2 corn stalk biochar at the silking stage increased 2.3 times. The mixed application of 1.9 t/hm^2 bamboo charcoal and 12 t/hm^2 bentonite at maturity obviously increased the soil microbial biomass carbon content. The mixed application of 1.9 t/hm^2 corn stalk biochar and 12 t/hm^2 bentonite at the jointing stage, silking stage and maturity stage in 2022 obviously increased the soil microbial biomass carbon content compared with the 2T2 treatment, and there were obvious differences between 2T15 treatment and 2T18 treatment and the fertilization treatment (2T2) in the three periods. Compared with that in the 2T2 treatment at the maturity stage, the microbial biomass carbon content in the 2T18 treatment increased by 2.4 times, and compared with that in the same treatment in 2021, the soil microbial biomass carbon content increased by 1.1 times.

Effects of biochar and bentonite on the agronomic traits of maize
In general, the application of biochar and bentonite improved maize field dry matter quality (Fig. 7a), and there was no significant difference among treatments in the same year. In 2021, the mixed application of 1.9 t/hm^2 bamboo charcoal and 12 t/hm^2 bentonite (T22) had a more obvious effect on dry matter quality, and the dry matter quality increased by 5.3% compared with that in the T2 (555.158 g) treatment. In 2022, the effect of mixed treatment was greater than that of the individual treatment, the increase in the 2T18 treatment was more obvious than that in the 2T2 treatment, and the dry matter quality increased by 40.7%.

The application of biochar and bentonite increased the leaf area index of maize (Fig. 7b). In 2021, the leaf area index of the T10 treatment was significantly greater than that of the other treatments. In the mixed treatment, the leaf area index of maize increased with increasing biochar addition when the bentonite addition level was constant, and the mixed application of 0.94 t/hm^2 bamboo charcoal and 12 t/hm^2 bentonite (T20) had the most obvious effect. Compared with that in the T2 (4.33) treatment, the leaf area index of maize increased by 33.0%. The leaf area index of the 2022 2T18 treatment (mixed application of high-concentration corn stalk biochar and bentonite) was obviously greater than that of the other treatments.

Maize plant height increased due to the application of biochar and bentonite, and there was a significant difference between T1 treatment and T22 treatment in 2021, while there was no significant difference between each treatment in 2022 (Fig. 7c). In 2021, the plant height of rice husk biochar (T4) and bamboo charcoal (T8) treated with 1.9 t/hm^2 single application was the highest, both 294 cm. In 2022, the effect of the mixed application
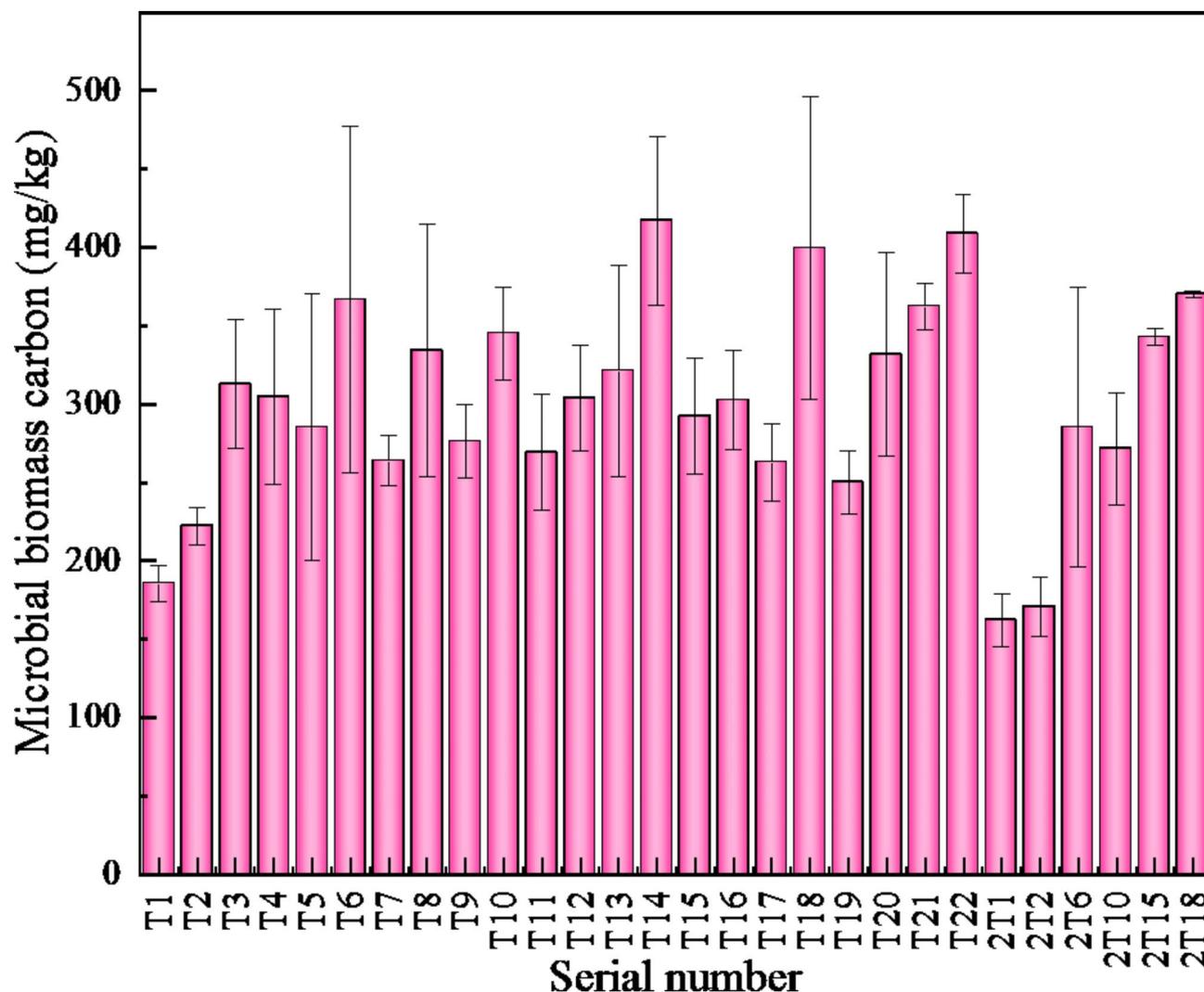
Fig. 6. Effects of different amendments on the microbial biomass carbon content.

treatment was greater than that of the single application treatment. Compared with the 2T2 treatment, the 2T18 treatment (mixed application of 1.9 t/hm^2 corn stalk biochar and 12 t/hm^2 bentonite) increased the maize plant height by 45.5 cm.

Corn yield was significantly affected by the type and amount of biochar added (Fig. 7d). The application of biochar and bentonite alone or in combination significantly and consistently increased corn yield. Specifically, in 2021, the corn yield under the mixed application of 1.9 t/hm^2 rice husk biochar and 12 t/hm^2 bentonite (T14) treatment (14970.01 kg/hm^2) was obviously greater than that under the fertilizer treatment (T2), and the corn yield increased by 36.6% than that under the T2 treatment (10956.37 kg/hm^2). In 2022, the yield under mixed application of 1.9 t/hm^2 corn stalk biochar and 12 t/hm^2 bentonite (4286.99 kg/hm^2) was obviously greater than that under the other treatments, and the corn yield increased by 25.8% compared with that under 2T2 (3406.74 kg/hm^2). However, compared with the same treatment in 2021, the corn yield showed a decreasing trend. This may be related to soil bulk density, and may also be related to climatic conditions and environmental factors.

Estimation of the carbon sequestration and emission reduction potential of biochar

In the past two decades, Chinese scholars have conducted much research in the field of greenhouse gas emission reduction in food production, established a series of effective emission reduction measures, and confirmed that biochar has great potential for long-term carbon sequestration and emission reduction. Biochar application to soil can not only improve soil properties but also directly or indirectly reduce CO$_2$ emissions and improve the soil carbon sequestration capacity. At present, it is important to take carbon conversion and resource utilization measures, improve the carbon sequestration potential of farmland and bring about carbon neutrality. This study estimated the total carbon sequestration and emission reduction potential of biochar after improving aeolian sand soil, mainly including two processes of carbon sequestration and emission reduction, that is, the carbon sequestration potential realized by the annual production of biochar in China and the effect of the application of
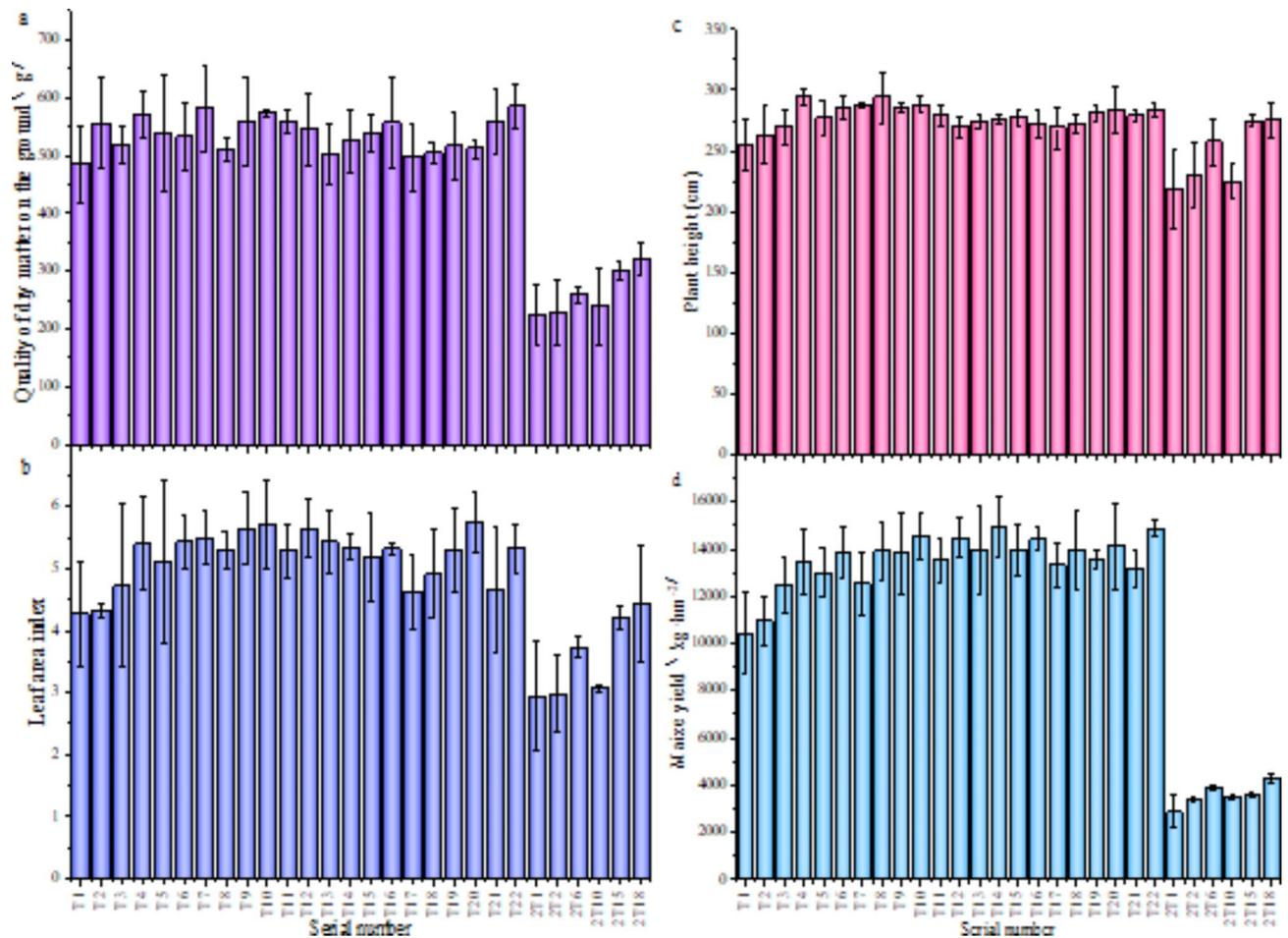
Fig. 7. Changes in maize agronomic traits after the application of biochar and bentonite.

these biochar on greenhouse gas emissions (Fig. 8). The greenhouse gas emission reduction induced by biochar was 18.7 µg/g with medium-temperature biochar. The carbon sequestration and emission reduction potential of biochar was estimated as follows:

$K = -0.0001 \times (-18.7) \div (1\% \times 65\%) = 28.77\%$.

$P_1 = 0.2275$ million tons $C \times 3.7 = 0.8418$ million tons CO_{2e} (calculated as 1% biochar applied to aeolian sand).

$P = 0.8418 \times (1 + 0.2877) = 108$ million tons of CO_{2e}.

According to calculations, approximately 100 million tons of CO_2 emissions can be offset in each year.

Correlation analysis between crop indexes and soil physicochemical properties

Correlations among the soil physicochemical properties (Fig. 9), and relationships between corn yield and agronomic traits and soil physical and chemical properties(Fig. 10). Except for available phosphorus, available potassium and alkali-hydrolyzed nitrogen, soil bulk density was negatively correlated with other soil indexes ($P > 0.05$), indicating that the increase of soil bulk density may have adverse effects on other physical and chemical properties of soil. Similarly, available phosphorus, available potassium and urease activity were negatively correlated with content of water-stable aggregates with particle size greater than 0.25 mm ($WR_{>0.25\,mm}$), mean weight diameter (MWD) and geometric mean diameter (GMD) ($P > 0.05$). This may reflect the effect of soil structure on nutrient availability and microbial activity. On the other hand, soil moisture content, pH value, soil organic matter content, sucrase activity and microbial biomass carbon were positively correlated with other soil indexes except soil bulk density ($P < 0.05$). These positive correlations indicate that soil water status, pH, organic matter richness and biological activity promote each other and jointly affect soil health and fertility. In particular, the positive correlation between microbial biomass carbon and most other soil properties underscores the important role of soil microorganisms in maintaining soil function and promoting nutrient cycling.

Soil bulk density, CEC and catalase activity showed significant negative correlation with corn yield, quality of dry matter, leaf area index and plant height ($P > 0.001$), and other soil indexes showed positive correlation with these growth parameters ($P < 0.05$). Specifically, soil bulk density was significantly negatively correlated with corn yield, above-ground dry matter quality and plant height ($P > 0.01$). Soil pH, organic matter content, available potassium content and alkali-hydrolytic nitrogen content were significantly positively correlated with corn yield, dry matter quality, leaf area index and plant height ($P < 0.001$). These findings show that the physical and chemical properties of the soil have a profound effect on the growth and yield of maize. The increase of soil
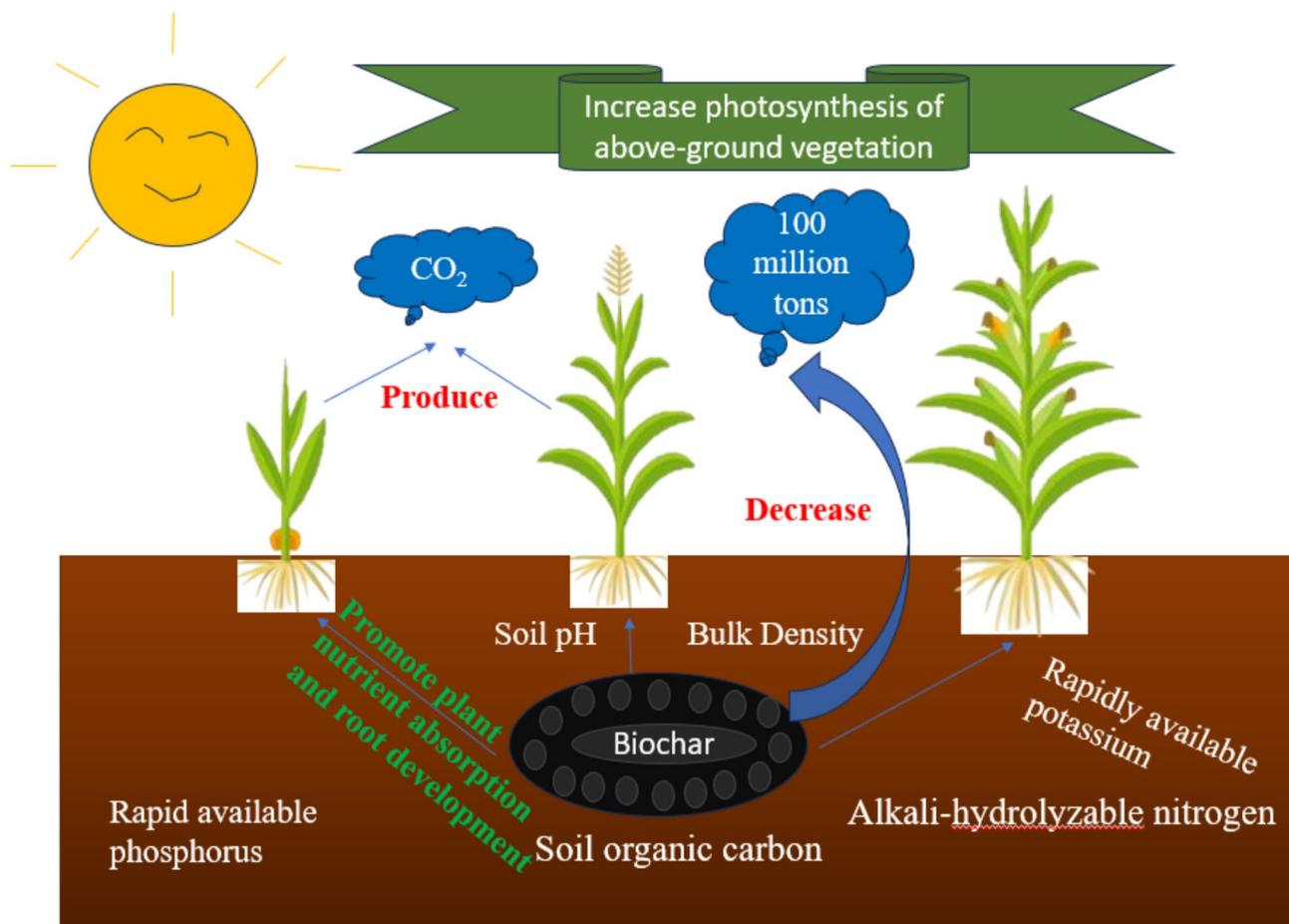
Fig. 8. Schematic of the routes by which biochar promotes carbon sequestration and greenhouse gas emission reduction.

bulk density may limit the growth space and water retention capacity of the root system, thus negatively affecting the growth performance of maize. In contrast, suitable pH, adequate organic matter, available potassium and alkali-hydrolyzed nitrogen directly support the nutrient requirements of plants, promoting their healthy growth and high yield.

Discussion
Biochar and bentonite application and soil physical properties
Soil bulk density is important indicator for measuring soil structure, and aeolian sand is characterized by high bulk density, which is not conducive to the exchange and regulation of water, gas, fertilizer, heat or other elements in the soil[31]. The application of biochar and bentonite reduced soil bulk density. Compared with soil with no biochar applied, biochar application reduced the soil bulk density of the 0–20 cm layer, and the greater the applied amount of biochar was, the more significant the decrease in bulk density, which is in agreement with the results of Liu Xianghong[32] and Laird et al.[33]. Biochar typically reduces soil bulk density through mixing and dilution, as well as by increasing soil aggregation and porosity. The addition of biochar and bentonite increased the soil water content because biochar is a porous material that can effectively store soil water and nutrients. Bentonite, on the other hand, is an absorbent material; its volume can expand 30 times, and it can absorb 8–15 times its own volume of water[34], so it has good water storage capacity. The addition of biochar and bentonite changed the content and structure of aeolian agglomerates, and with increasing amount added, the MWD, GMD and $WR_{> 0.25 \text{ mm}}$ showed an increasing trend. Compared with that in the T18 treatment, the content of $WR_{> 0.25 \text{ mm}}$ increased by 4.1% during the maturity stage. Compared with that in the T18 treatment, the MWD increase in the 2T18 treatment at maturity was 11.6%, and the effect of the addition of medium- and high-concentration bentonite in all the treatments was more significant than that of mixed biochar and bentonite addition because bentonite has strong cohesion and adsorption capacity. The application of bentonite to soil can promote the aggregation of microaggregates to form large aggregates, thus improving the aggregate structure of aeolian sandy soil[35]. In addition, the application of biochar may lead to the increase of soil microbial activity and the enhancement of agglomeration performance, thus improving the soil structure[36].
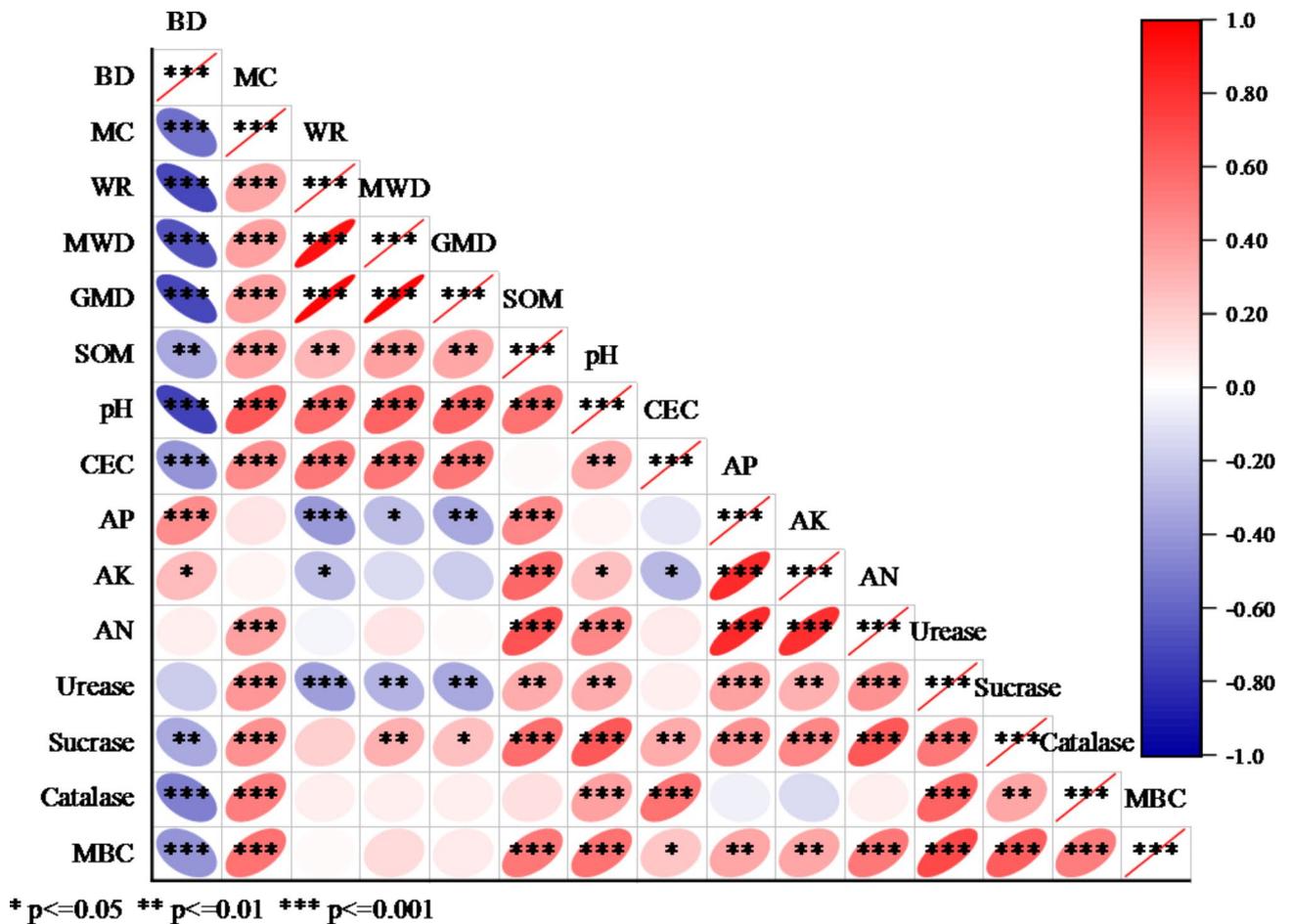
Fig. 9. Correlations among the soil physicochemical properties. Note: BD is the soil bulk density, MC is the moisture content, WR is the content of water-stable aggregates with a particle size greater than 0.25mm, SOM is the organic matter, AP is the rapidly available phosphorus, AK is the rapidly available potassium, AN is the alkali-hydrolable nitrogen, MBC is the microbial biomass carbon, the same below

Biochar and bentonite application and soil chemistry

In this study, the soil pH increased in response to the application of biochar and bentonite, with a maximum increase of 1.1 units, because alkaline cations in the raw biomass materials formed alkaline substances such as oxides, hydroxides and carbonates during pyrolysis, which can increase the pH of soil and pore water. The application of biochar and bentonite significantly increased the soil CEC because the pyrogenic organic residues in biochar provided oxygen-containing functional groups (carboxyl, carbonyl and hydroxyl)[37]. In a natural environment, more oxygen-containing functional groups can form on the surface of biochar due to the oxidation and adsorption of organic matter. Thus, the negative charge on the biochar surface increases, which in turn increases the CEC of soils[38]. Soil organic matter and nutrient content play important roles in the determination of soil fertility and can improve soil structure and soil permeability, enhance the ability of soils to retain fertilizer and water, and provide nutrients for plants[39]. In this study, the soil organic matter content showed an increasing trend, and the organic matter content increased by 49.1% in the second year compared with that in the first year after the mixed application of high-concentration corn stalk biochar and bentonite. Biochar can significantly increase soil organic matter and nutrient content due to its abundance of organic carbon, nitrogen, phosphorus, potassium and other nutrients[40], and the content of soil organic matter is also affected by the change of soil water content, because the increase helps to promote the activity of microorganisms, accelerate the decomposition and transformation of organic matter, and thus increase the content of soil organic carbon. The content of available phosphorus in 2022 increased by 38.4% compared with that in the same treatment in the first year, this is consistent with the conclusion of Gu Meiying's research[41].

Biochar and bentonite application and soil biological properties

Soil enzyme activity is a very important index for measuring soil fertility and biological activity. It reflects the suitability of planting areas and the nutrient content of soils. Soil enzymes mediate the decomposition and transformation of organic matter, making it easier for plants to absorb nutrients. The results of this study showed that biochar could significantly improve the activity of soil sucrase, and the maximum increase of sucrase activity was 159.6% compared with the application of chemical fertilizer alone, which was consistent
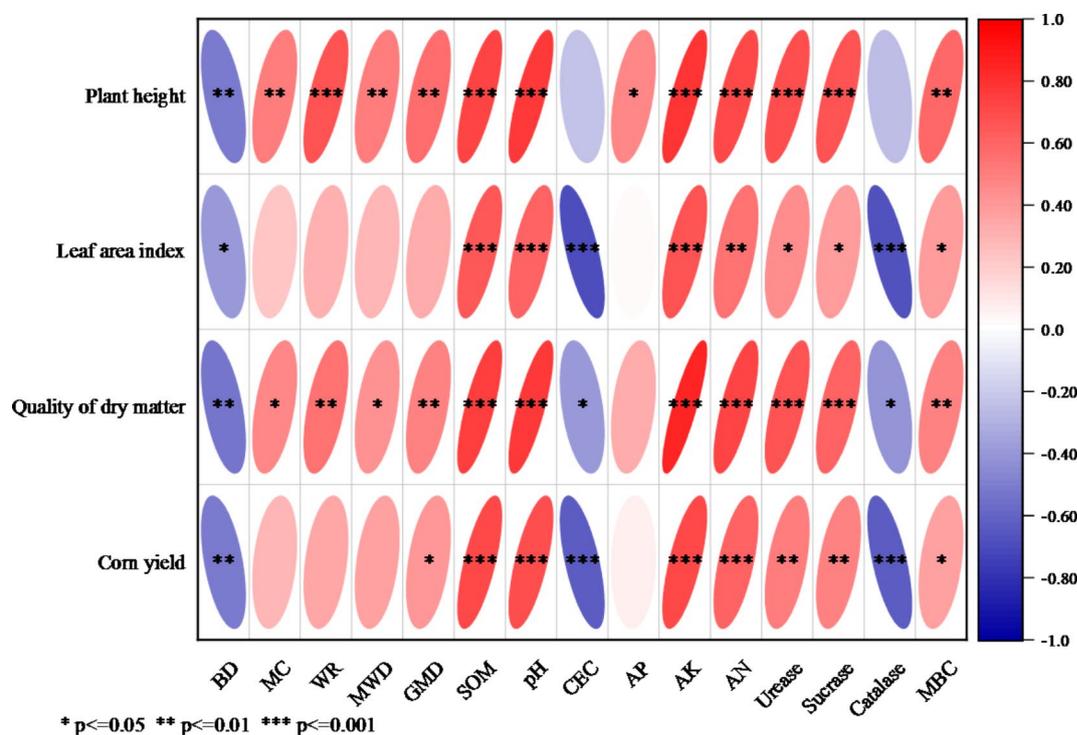
Fig. 10. Correlations between the maize yield, agronomic traits and soil physical and chemical properties.

with the change trend of soil organic matter, because biochar provided abundant available carbon sources for soil microorganisms, thus promoting the activity of sucrase. This finding is consistent with the findings of Huang Jian[42] and Chen Xinxiang et al.[43].The addition of biochar and bentonite can improve soil enzyme activity, and the greater the amount of biochar added is, the greater the impact on enzyme activity, which is similar to the conclusions of Wang Zhihui et al.[44], who showed that the application of different amounts of corn stalk biochar could promote the activities of urease, sucrase and catalase in soil, and a high application treatment had more obvious promoting effects on urease. The application of bentonite can also improve soil enzyme activity because bentonite can improve the soil environment of sandy lands, especially the water conditions, thus promoting the growth of corn roots and contributing to the secretion of various enzymes[45]. Microbial biomass carbon (MBC) in soil is closely related to the absorption and decomposition of carbon, nitrogen, phosphorus, sulfur and other elements in soil, and it is the driving force for nutrient decomposition in soil and promotes nitrogen mineralization in fertilizers applied to soil. In this study, when biochar and bentonite were applied, the MBC content in the soil increased significantly, and the MBC content in 2022 increased 2.4 times compared with that in 2021. This finding is similar to the results of Pan et al.[46]. Biochar applied to soil can provide soil media and external sources of carbon and nitrogen suitable for microbial survival, promote microbial growth and reproduction, and improve soil microbial quality.

Application of biochar and bentonite and agronomic traits of maize
Soil type, soil pH, fertilizer, biochar type, biochar application amount and crop variety are key factors in improving crop yield[47]. In this study, the plant height, leaf area index and aboveground dry matter quality improved relative to those of the only fertilization after the amendments were added. Studies have shown that biochar application reduces soil bulk density and promotes plant root growth and nutrient absorption[48], thus increasing the above-ground dry matter quality of maize crops. The increase of maize yield is closely related to soil properties. Nutrients, enzymes and microorganisms in soil are indispensable factors in the growth and development of plants, and each factor plays a very important role in the growth and development stage of corn. Under the synergistic action of all factors, corn can yield high quality[49]. For example, alkali-hydrolyzed nitrogen is one of the nitrogen forms in soil that can be directly absorbed and utilized by plants, providing the necessary nitrogen source for maize. Sucrase is involved in the decomposition of carbohydrates, and its activity directly affects the supply of readily available carbon in the soil, thus affecting the growth and development of crops[50]. Bentonite can reduce water loss, prevent nutrient leaching, and increase macronutrients at root sites, thereby improving the ability of plant roots to absorb nutrients[51] and increasing the overall agronomic performance of crops growing on sandy soils. After the application of biochar and bentonite over two years, the corn yield increased by 36.6%. In conclusion, soil quality was effectively improved after the application of amendments, which promoted the absorption and utilization of maize nutrients and was conducive to the increase of maize yield. However, compared with the same treatment in 2021, it was found that the corn yield showed a decreasing trend. Because the soil bulk density value in 2022 was higher than that in 2021, the corn

rhizomes could not effectively absorb nutrients and water, so the corn yield was reduced. It may also be affected by climatic conditions and environmental factors.

Carbon sequestration and emission reduction potential of biochar

Over the life cycle of biochar applied to soil, "carbon sequestration" can effectively increase the total soil carbon pool by 64.3% [52], and the conversion of biomass to biochar can increase carbon sequestration by 30–40% compared with the decomposition and sequestration of biomass in its natural state[53]. Biochar can also directly or indirectly affect the carbon sequestration and emission reduction potential of treated soil by changing the physical and chemical properties of soil and affecting the growth and development of soil microorganisms and aboveground vegetation[54]. Woolf et al.[55] estimated the carbon sequestration potential of biochar under the premise that it would have no impact on food security and ecosystems and reported that biochar could fix 1.8 Pg of CO_2-C per year, which is equivalent to 12% of the annual anthropogenic greenhouse gas emissions. In this study, we estimate that the carbon sequestration potential of biochar is equivalent to offsetting CO_2 emissions by about 100 million tonnes per year.

Conclusions

Through two-year experiments, it was found that the mixed application of biochar and bentonite reduced soil bulk density, increased soil moisture content and improved the content and structure of soil aggregates. The mixed application of 12 t/hm^2 bentonite and 1.9 t/hm^2 corn stalk biochar in 2022 resulted in higher MWD values, GMD values and WR$_{>0.25}$ mm contents than did the same treatment in 2021. Biochar and bentonite increased soil organic matter content, pH, CEC and available nitrogen, phosphorus and potassium contents. CEC in the 12 t/hm^2 bentonite mixed with 0.94 t/hm^2 bamboo charcoal treatment increased by 150.4%. The contents of available nitrogen, phosphorus and potassium in the soil increased with increasing modifier amount. The mixed application of bentonite and 1.9 t/hm^2 biochar was superior to the other treatments, and the maximum available phosphorus increased by 2.6 times compared with that in the fertilizer treatment. The maximum increases in available potassium and alkali-hydrolyzable nitrogen were 54.0% and 211.5%, respectively. The activities of urease, sucrase and catalase in soil all increased first and then decreased with the growth of maize. The maximum increases in soil sucrase in 2021 was 159.6% compared with only fertilizer treatment, and the maximum increases in soil urease in 2022 was 2.6 times compared with only fertilizer treatment. The application of biochar and bentonite increased corn yield, plant height, the leaf area index and dry matter quality and increased the amount of modifier. The mixed application of 12 t/hm^2 bentonite and 1.9 t/hm^2 corn stalk biochar increased the corn yield by 36.6% compared with the fertilizer treatment. Biochar and bentonite offset approximately 100 million tons of CO_2 emissions per year in which the experiment was conducted. In conclusion, biochar and bentonite have the potential to improve soil quality, increase plant nutrient utilization efficiency and promote crop growth.

Data availability

All data generated or analyzed during this study are included in this article.

References

1. D'Odorico, P., Bhattachan, A., Davis, K. F., Ravi, S. & Runyan, C. W. Global desertification: drivers and feedbacks. *Adv. Water Resour.* **51**, 326–344 (2013).
2. Zhang, K. F., Li, X. W., Zhou, W. H., Zhang, D. X. & Yu, Z. R. Land resource degradation in China: analysis of status, trends and strategy. *Int. J. Sustain. Dev. World Ecol.* **13**, 397–408 (2006).
3. Zhang, Z. H. & Huisingh, D. Combating desertification in China: monitoring, control, management and revegetation,Journal. *Clean. Prod.* **182**, 765–775 (2018).
4. Zhang, N. N., Yan, J. & K,Liu, P. L. Effect of bacterial manure on the properties of Complex. *Soil. Growth Ryegrass Agron.* **568**, 11030568–11030580 (2021).
5. Wei Ying, J. et al. Research and application progress of biochar in amelioration of saline-alkali soil [J/OL]. *Environ. Sci.* **45**, 940–951 (2024).
6. Blanco-Canqui, H., Laird, D. A., Heaton, E. A., Rathke, S. & Acharya, B. S. Soil carbon increased by twice the amount of biochar carbon applied after 6 years: field evidence of negative priming. *GCB Bioenergy*. **12**, 240–251 (2020).
7. Park, J. et al. Three years of biochar and straw application could reduce greenhouse gas and improve rice productivity. *Soil. Sci. Plant. Nutr.* **70**, 2–10 (2024).
8. Zhang, Y. et al. Biochar as construction materials for achieving carbon neutrality. *Biochar* **4**, 59–83 (2022).
9. Liu, Q. et al. Biochar application in remediating salt-affected soil to achieve carbon neutrality and abate climate change. *Biochar* **5**, 45–69 (2023).
10. Lehmann, J. et al. Biochar in climate change mitigation[J]. *Nat. Geosci.* **14**, 883–901 (2021).
11. Liang, B., Lehmann, J. & Sohi, S. P. Black carbon affects the cycling of non-black carbon in soil. *Org. Geochem.* **41**, 206–213 (2010).
12. Bohara, H. et al. Influence of poultry litter and biochar on soil water dynamics and nutrient leaching from a very fine sandy loam soil. *Soil. Tillage Res.* **189**, 44–51 (2019).
13. Matovic, D. Biochar as a viable carbon sequestration option: global and Canadian perspective. *Energy* **36**, 2011–2016 (2011).
14. Schlesinger, W. H. Evidence from chronosequence studies for a low carbon-storage potential of soils. *Nature* **348**, 232–234 (1990).
15. Scharlemann, J. P. W., Tanner, E. V. J., Hiederer, R. & Kapos, V. Global soil carbon: understanding and managing the largest terrestrial carbon pool. *Carbon Manag.* **5**, 81–91 (2014).
16. Windeatt, J. H. et al. Characteristics of biochars from crop residues: potential for carbon sequestration and soil amendment. *J. Environ. Manag.* **146**, 189–197 (2014).
17. Yang, J. et al. High-performance composite phase change materials for energy conversion based on macroscopically threedimensional structural materials. *Mater. Horizons.* **6**, 250–273 (2019).
18. Zhang, Y., Li, P., Liu, X. & Xiao, L. Changes in soil aggregate fractions, stability, and associated organic carbon and nitrogen in different land use types in the Loess Plateau. *China Sustain.* **14**, 3963–3975 (2022).

19. Wang, J., Xiong, Z. & Kuzyakov Biochar stability in soil: meta-analysis of decomposition and priming effects. *GCB Bioenergy*. **8**, 512–523 (2015).
20. Maxim, L. D., Niebo, R. & McConnell, E. E. Bentonite toxicology and epidemiology - A review Inhal. *Toxicol* **28**, 591–617 (2016).
21. Belousov, P. Carboniferous bentonites from 10th Khutor deposit (Russia): composition, properties and features of genesis. *Appl. Clay Sci.* **215**, 106308–106321 (2021).
22. Wang & Wenting Wang Yunhai. Research progress of bentonite soil improvement technology [J]. *Environ. Sci. Technol.* **24**, 66–68 (2011).
23. Mohammadifard, F., Tarakemeh, A., Moghaddam, M. & Zim, M. Bentonite mitigates the adverse effects of drought stress in fenugreek (Trigonella foenum-graecum L.)J. Soil Sci. *Plant. Nutr.* **22**, 1098–1111 (2022).
24. Mi, J., Gregorich, E. G., Xu, S., McLaughlin, N. B. & Liu, J. Effects of a one-time application of bentonite on soil enzymes in a semi-arid region.Can. *J. Soil. Sci.* **98**, 542–555 (2018).
25. Mi, J. et al. Changes in soil biochemical properties following application of bentonite as a soil amendment.Eur. *J. Soil. Biol.* **102**, 103251–103264 (2021).
26. Lv Yizhong, L. Baoguo. *Soil Science experiment* [M]. *China Agric. Press.* 44–50. (Lv Yizhong, Li Baoguo,2010).
27. Bao & Shidan *Soil Agrochemical Analysis* [M]. Beijing: China Agricultural Science and Technology. 25–158 .(Bao Shidan,2000).
28. Guan Songyin *Soil Enzymes and Their Research methods* [M]. Agricultural Press. Beijing.247–338Guan Songyin,. (1991).
29. Li, Y. et al. Effects of biochar and bentonite on physicochemical properties of aeolian sand soil and its effects on agronomic characters of maize [J]. Resources and environment in arid areas. **5**: 164–174 (2023).
30. Wang, L. Influencing factors and potential estimation of the carbon sequestration and emission reduction from farmland soil with biochar amendment [D]. Zhejiang University.67–90(Wang Lin,2021).
31. Xi et al. Experimental study on the improvement of aeolian sand by soil conditioner [J]. *Arid Zone Res.* **35**, 1075–1083. https://doi.org/10.13866/j.azr.2018.05.09 (2018).
32. Liu, X. H. *Effects of Biochar Application on soil Improvement on the Loess plateau[D]* (Research Center for Eco-Environmental Sciences, 2013).
33. Laird, D. A. et al. Impact of biochar amendments on the quality of a typical midwestern agricultural soil[J]. *Geoderma* **158**, 443–449 (2010).
34. Das, S. K. & Mukherjee, I. Flubendiamide transport through packed soil columns. *Bull. Environ. Contam. Toxicol.* **88**, 229–233 (2012).
35. Zhang, H. et al. Sandy soils amended with bentonite induced changes in soil microbiota and fungistasis in maize fields [J]. *Appl. Soil. Ecol.* **146**, 103378–103389 (2020).
36. Wang, N. et al. Effects of biochar and fertilization on Soil Environment and Yield, Quality of Sorghum [J]. *Shanxi Agricultural Sci.* **44**, 1633–1637 (2016).
37. Uchimiya, M., Lima, I. M., Klasson, K. T. & Wartelle, L. H. Contaminant immobilization and nutrient release by biochar soil amendment: roles of natural organic matter. *Chemosphere* **80**, 935–940 (2010).
38. Li, H. B. et al. Research progress on mechanism and application of biochar in remediation of farmland soil contaminated by heavy metals [J]. *Trans. Chin. Soc. Agricultural Eng.* **36**, 173–185 (2020).
39. Du et al. Effects of mixed application of biochar, zeolite and bentonite on growth and absorption of cd, pb and zn in maize [J]. *J. Ecol. Environ.* **28**, 190–198 (2019).
40. Ding, Y. et al. Biochar to improve soil fertility. *review[J] Agron. Sustain. Dev.* **36**, 1–18 (2016).
41. Gu et al. Impact of biochar application on soil nutrients and microbial diversities in continuous cultivated cotton fields in Xinjiang [J]. *Chin. J. Agricultural Sci.* **47**, 4128–4138 (2014).
42. Huang, J. *Study on Effects of Biochar on soil Microbial Biomass and soil Enzymes [D]* (Chinese Academy of Agricultural Sciences, 2012).
43. Chen, X. X. et al. Effects of biochar amendment on microbial biomass and enzyme activities in loess soil [J]. *J. Agro-Environ. Sci.* **33**, 751–757 (2014).
44. Wang, Z. et al. Effects of different amounts of biochar applied on soil nutrient, soil enzyme activity and maize yield [J]. *Jilin Agricultural Sci.* **44**, 14–19 (2019).
45. Zhou, L. et al. Effect of bentonite humic acid application on the improvement of soil structure and maize yield in a sandy soil of as emiarid region [. *J] Geoderma.* **338**, 269–280 (2019).
46. Pan Zhenzhen. Effects of biochar on soil microbial biomass carbon [J]. *Rural Sci. Technol.* **128**, 64–72 (2016).
47. Jeffery, S., Verheijen, F. G. A., van der Velde, M. & Bastos, A. C. A quantitative review of the effects of biochar application to soils on crop productivity using meta–analysis. *Agric. Ecosyst. Environ.* **144**, 175–187 (2011).
48. Cheng, X. Y. et al. Effect of biochar on root growth, absorption of nitrogen and maize yield [J]. *J. Shengyang Agricultural Univ.* **47**, 218–223 (2016).
49. Zhang, C., Mu, P. & Shang, J. M. Effects of continuous returning corn straw on soil chemical properties, enzyme activities and yield trait[J]. *Res. Soil. Water Conserv.* **25**, 92–98 (2018).
50. Cheng, M., Xie, W. Y., Yang, Z. X. & Zhou, H. P. Effects of long-term straw return on corn yield, soil nutrient contents and en-zyme activities in dryland of the Loess Plateau, China[J]. *Chin. J. Eco-Agriculture.* **27**, 1528–1536 (2019).
51. El-Nagar, D. A. Synthesis and characterization of nano bentonite and its effect on some properties of sandy soils[J]. *Soil Tillage. Res.* **208**, 104872 (2021).
52. Chagas, J. K. M., de Figueiredo, C. C. & Ramos, M. L. G. Biochar increases soil carbon pools: evidence from a global meta-analysis[J]. *J. Environ. Manage.* **305**, 12–35 (2022).
53. Lehmann, J. et al. Biochar effects on soil biota— a review. *Soil. Biol. Biochem.* **43**, 1812–1836 (2011).
54. Smith, P. Soil carbon sequestration and biochar as negative emission technologies[J]. *Glob. Change Biol.* **22**, 1315–1324 (2016).
55. Woolf, D., Amonette, J. E., Perrott, A. S., Lehmann, J. & Joseph, S. Sustainable biochar to mitigate global climate change. *Nat. Commun.* **1**, 56–64 (2010).

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Author contributions

J.T. acquired the funding for the study, supervised the formation of the manusctipt, and designed the experiments. W.L. wrote the manuscript, per-formed the experiments, and analyzed the data. S.T. & Y.L. assist with experiments and proofreading manuscripts. M.H. & L.H. statistical analysis and revision of manuscript format.

S.S. & X.J. assisted with the statistical analysis and graphing of figures.

Declarations

Competing interests
The authors declare no competing interests.

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