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Effects of biochar on soil evaporation and moisture content and the associated mechanisms

Weiying Feng[1], Tengke Wang[1], Fang Yang[2*], Rui Cen[2*], Haiqing Liao[2] and Zhongyi Qu[3]

Abstract

High soil evaporation levels are a major contributor to loss of soil moisture in arid and semiarid regions globally. Therefore, it is important to use effective measures to slow the evaporation from farmland soils. We applied various amounts of straw biochar (BC) in a soil column experiment and a field experiment to study the influence of BC on soil evaporation and moisture content, respectively, to improve the water use efficiency of cultivated soil in arid areas. The addition of BC reduced soil evaporation and delayed water loss from the soil by evaporation. In the field experiment, cumulative evaporation in the treatments declined by 9.58% (Bo-10), 10.95% (Bo-30), and 4.2% (Bo-50) compared with that in the control group, demonstrating that 30 t/hm^2 BC is the most effective at suppressing soil evaporation. BC also delayed the time required for the soil moisture content to drop to field capacity and increased the upward transport of water from the deeper soil layers at night. Data from continuous monitoring of moisture content for 3 days during each growth period revealed that the increases in moisture replenishment were 18.52–79.62% at the seedling stage, 55.81–202.38% at the jointing stage, 270.83–587.5% at the tassel stage, and 6.66–61.64% at the maturation stage; hence, BC was shown to work best at the tassel stage.

Keywords Simulation, Field experiment, Crop, Growth period

Introduction

Soil is an essential natural resource and serves as a medium to produce food crops for human consumption [20, 25]; however, overuse and poor management have led to soil degradation, especially in arid and semiarid saline and alkaline soils [17]. Between 1950 and 2010, soil degradation negatively impacted soil ecosystem services by 60% [19]. Hence, only 11% of the world's soil can be used to grow crops without amendment [39]. The global population is gradually increasing and is expected to reach 9.6 billion by 2050 [1, 10]. To sustain this rapidly increasing population, it is vital to improve the soil health to safeguard agricultural production.

In recent years, biochar (BC) has been widely used in soil remediation processes around the globe. It has a large specific surface area and strong adsorption properties; furthermore, it can increase soil organic matter content, remove heavy metal pollutants in soil, and increase crop yields [2, 3, 16]. Long-term application of BC can improve soil fertility and contribute to the sustainability of soil agroecosystems [15, 16]. The application of BC has also been shown to increase peanut yields and improve soil properties in North Queensland, Australia [1], as well as to promote microbial activity and growth in temperate soils [12]. Although many studies on improving soil by

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*Correspondence:
Fang Yang
yang.fang@craes.org.cn
Rui Cen
qinr8168@emails.imau.edu.cn
[1] School of Materials Science and Engineering, Beihang University, Beijing 100191, China
[2] State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China
[3] College of Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University, Hohhot 010018, China

altering the BC content have been conducted [29, 33, 40] and some have explored the impact of various rates of BC on salinized soil in arid and semiarid regions, few studies have combined indoor soil column simulation and field experiments to cross-check the results. Hence, the influence of BC on soil evaporation and moisture content remains unclear.

Soil moisture is a major parameter in agroecosystems and a material necessity for the growth and development of crops. It affects not only the distribution of life on Earth but also the yields of agricultural crops [18, 28]. Under reduced irrigation conditions, BC has been shown to increase the yield and quality of tomatoes [2]. It can also increase grape yields and the plant available water content [3].

Soil water evaporation depends on internal factors such as soil structure, texture, moisture content, phreatic level, surface characteristics, capillarity, and pH; external meteorological conditions, such as temperature, humidity, and wind speed, also play a role [4, 13]. The addition of a certain amount of BC can help restrain soil cracking and reduce soil evaporation [5, 21, 36]. Some studies have shown that added BC not only inhibits the evaporation of soil water but also prevents the migration of salt in the soil and regulates the distribution of water [35, 37]. Therefore, the use of BC to reduce soil evaporation mainly inhibits soil cracking and controls soil salt distribution.

Studies on the effects of BC on soil evaporation have gained popularity in recent years. For example, BC has been shown to reduce soil evaporation when applied to sandy loam soil [14]; however, BC powder added to sandy soil does not reduce water loss through evaporation [38]. This indicates that evaporation is also related to the soil texture and particle size. BC has been shown to suppress soil evaporation when applied at low rates but promote soil evaporation when applied at high rates [34]. After adding BC, it is unclear whether the water holding capacity can be maintained throughout the evaporation process. The combined impact of BC addition and soil texture on soil evaporation is also unclear. As such, studying this effect on soil evaporation and soil moisture content will help to identify the optimal rate, which will play a vital role in reducing soil water evaporation in arid regions.

Materials and methods

Study area overview and soil properties

The study area was located in the Linhe District (107°23′12.01"E, 40°45′58.28"N), Bayannaoer City, Hetao Irrigation Area, China [7]. The soil was weakly alkaline [8]. The organic matter content was 2.93 g kg^{-1}. The soil particle size distributions were 43.09%, 50.50%, and 6.41% in the ranges of 0.05–2.00, 0.002–0.050, and < 0.002 mm, respectively. The soil bulk density was 1.48 ± 0.02 g cm^{-3}. The saturated soil conductivity was $(1.41 \pm 0.12) \times 10^{-4}$ mm min^{-1}.

Basic properties and experimental treatment of BC samples

The experiment used maize straw BC with a particle size of 0.002–2.0 mm. The pyrolysis temperature was 500–600 °C, and the pH was maintained at 7.84 (GB 15618–1995). The mass percentages of the nutrient elements were as follows: 39.72% carbon, 1.68% nitrogen, 0.82% phosphorus, and 1.55% potassium. A control group (CK; 0 t/hm^2) and three experimental groups were established in the soil column evaporation simulation experiment. The amount of BC applied in the experimental groups was 10, 30, and 50 t/hm^2, labeled as Bo-10, Bo-30, and Bo-50, respectively. In the field experiment, an additional treatment Bo-20 (20 t/hm^2) was included. The field soil samples were collected, mixed evenly with glass rods, dried naturally, and sieved through a 2-mm nylon sieve for the incubation experiment. After the incubation experiment, the samples were used for subsequent research after passing through a 0.149-mm nylon sieve. The water holding capacity was 24.91%, and the 0–40-cm porosity was 44.03% in bulk soil.

Design of the soil column evaporation simulation experiment

Different amounts of BC (0, 10, 20, 30, and 50 t/hm^2) were mixed with soil and added to the soil columns in 5-cm layers, for a total of 15 layers. The samples were weighed to ascertain daily evaporation (180 kg scales; accuracy, 0.005 kg), and the oven-drying method was used to ascertain soil moisture content. Infrared lamps were used to simulate evaporation at a temperature of 33 °C ± 0.5 °C [6]. Evaporating dishes were also established for real-time evaporation measurements. The evaporation observation period was 24 days, and the soil sampling frequency was once every 6 days. Soil samples were taken from three parallel sampling holes at each depth (2, 5, 15, 25, 35, 45, and 65 cm), with the oven-drying method used to ascertain the soil moisture content. The evaporation simulation test was used to monitor changes in soil evaporation after applying different amounts of BC, thus revealing the effect of BC on soil evaporation.

Field evaporation experiment design

To study the effect of BC application in actual field soil, BC was applied to a maize field at the same ratios used in the soil column experiment; further, the effect on field soil water evaporation during the different maize growth periods was studied. To facilitate an analysis of changes in water, the vertical 1-m soil range was divided into three sections: the first interval was the high-evaporation zone on the soil surface (0–20 cm), the second was the buffer zone (20–40 cm, with BC application at 0–40 cm), and the third was the replenishment zone (40–100 cm).

During the early stage of crop growth, lysimeters (Fig. 1) were placed between the membranes and rows, and daily soil evaporation was determined by weighing. In accordance with the randomized design for the study area, the lysimeters were placed in nine test fields; three replicates, which were placed between membranes to measure field evaporation, were used. We extracted undisturbed field soil of the same weight (2.5 kg ± 5 g), evenly mixed with the appropriate BC amounts, and placed them in the lysimeters. Initial weights were measured. The weights of the lysimeters were also taken before and 2 days after each irrigation event. The field was irrigated four times: 1,200 m^3/hm^2 on May 10, 2015; 1,500 m^3/hm^2 on June 1, 2015; 1,500 m^3/hm^2 on July 3, 2015; and 1,500 m^3/hm^2 on August 5, 2015.

Evaporation was measured at 10:00 AM every day. Given that iron conducts heat, rusts and decays quickly, and is difficult to modify, to reduce errors due to the instruments themselves, polyvinyl chloride was used, and a 10-cm-diameter qualitative filter paper was placed on the metal mesh (Fig. 2).

Data analyses

Field experiments were conducted in triplicates. One-way analysis of variance was conducted using SPSS statistical software (IBM, SPSS, Statistics 21). Statistical differences were considered significant when $p < 0.05$ [9]. The figures were processed using OriginPro 8.0 (OriginLab Corp.).

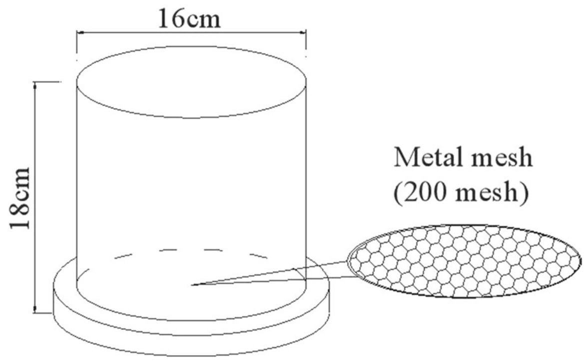

Fig. 2 Schematic diagram of the micro-lysimeter experimental device

Soil column evaporation was determined using the following formula:

Soil column evaporation (mm) = (the previous day's mass of the soil column − the next day's mass of the soil column) × water bulk density / ($\pi d^2/4$).

Results and analysis

Soil column simulation experiment

BC application suppressed soil evaporation in the application layers. The changes in soil evaporation over time at the different BC rates are shown in Fig. 3. Because of the consistently high indoor temperature, evaporation was high (average, 2.34 mm). Differences in evaporation between the various treatments became more notable over time. The overall trend was CK > Bo-10 > Bo-30 > Bo-50, indicating that BC application can suppress evaporation in the cultivated layer and improve the water holding capacity of soil in the field.

Fig. 1 Field diagram of the micro-lysimeter experimental device

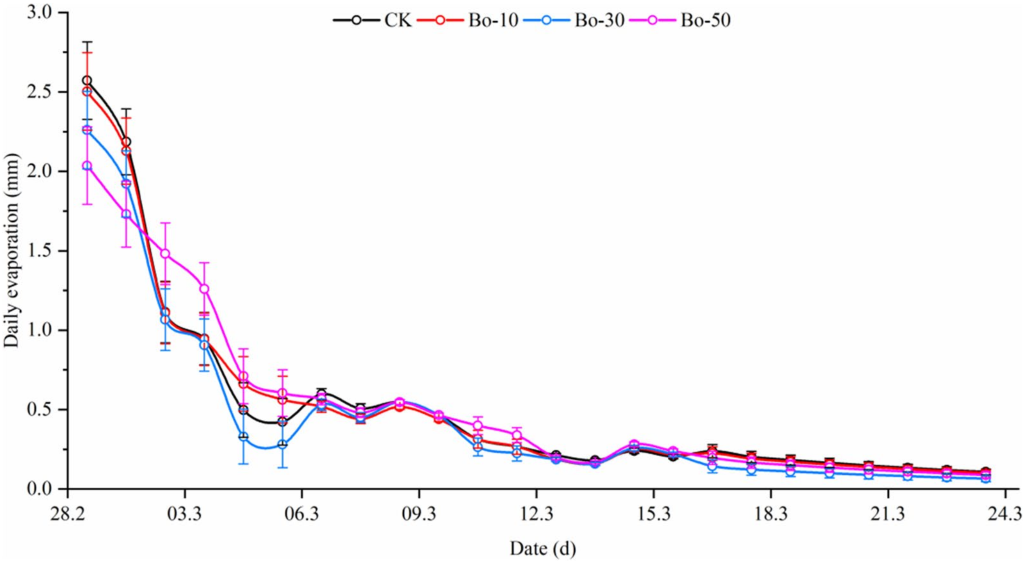

Fig. 3 Daily evaporation of soil column with biochar

The daily soil evaporation was negatively correlated with the BC application rate. For Bo-10, Bo-30, and Bo-50, the cumulative evaporation was 0.01%, 1.08%, and 13.67% lower, respectively, than that of the CK treatment over the entire experimental period (Fig. 4). The following are the main reasons for the reduced soil evaporation after BC application: (1) BC application changes the soil structure. Due to the low density of BC, soil density declines when BC is incorporated into the soil, thereby increasing soil porosity. Capillary water held in soil pores is one of the most effective forms of soil water. Increasing porosity also increases the capillary water content of soil, thereby increasing soil water storage capacity. (2) Increased capillary water extends the duration of the transition of soil moisture from the first stage of evaporation to the second stage, thereby reducing total water evaporation. The differences in the 2-day replenishment readings were averaged for a continuous measurement of nightly replenishment after daily evaporation for three consecutive days. BC application increased the upward transport of water from the lower soil layer at night to

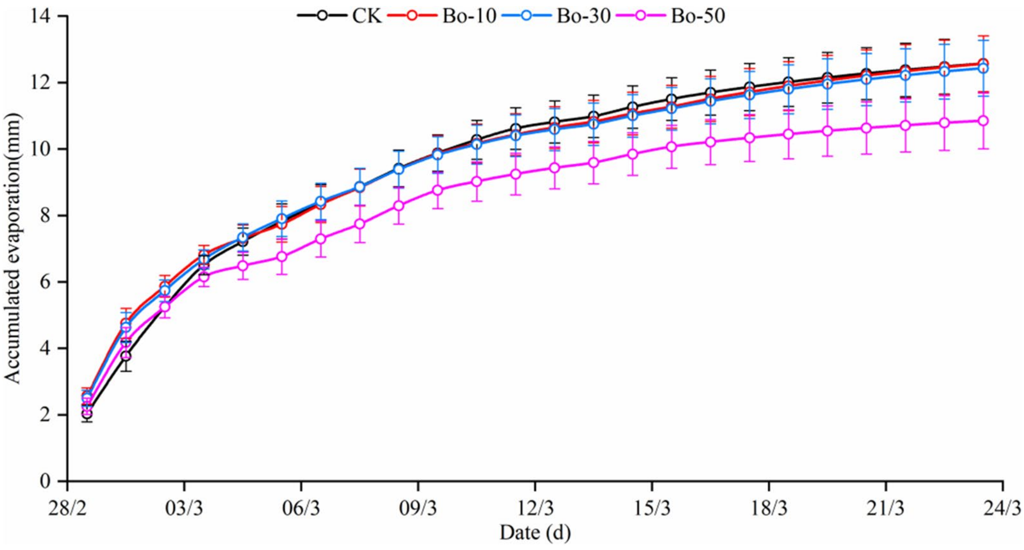

Fig. 4 Cumulative evaporation of biochar columns

Table 1 Variations in moisture content from 8:00 PM to 6:00 AM

Growth stage	**Measurement period (d)**	**Replenishment (mm)**				
		CK	**Bo-10**	**Bo-20**	**Bo-30**	**Bo-50**
Seedling	1–2	0.59	0.44	0.51	0.76	0.75
	2–3	−0.05	0.20	0.38	0.21	0.11
Jointing	1–2	0.67	0.11	0.87	0.95	0.40
	2–3	−0.24	0.17	0.31	0.35	0.27
Tassel	1–2	0.51	0.78	0.79	0.88	1.62
	2–3	−0.27	0.11	0.57	0.20	0.03
Maturation	1–2	0.59	0.44	0.51	0.76	0.75
	2–3	0.01	0.20	0.38	0.21	0.05

varying degrees (Table 1). The increase in replenishment was 18.52–79.62% at the seedling stage, 55.81–202.38% at the jointing stage, 270.83–587.5% at the tassel stage, and 6.66–61.64% at the maturation stage; replenishment increased at higher application rates, with the largest increase noted in the B-30 treatment. As time passes, the time required for the soil moisture in the surface layer (0–40 cm) to return to field capacity after an irrigation event declines. The soil moisture content reached field capacity on the 10th day after the first irrigation event, 12th day after the second irrigation event, 7th day after the third irrigation event, and 7th day after the fourth irrigation event.

Overall, the daily evaporation was low in the field experiment (Fig. 5) but was lower in the BC treatment groups than in the CK. Evaporation dropped sharply and stabilized from the 10th day after the irrigation events, and the daily evaporation gradually decreased. The evaporation volume of the various treatments from highest to lowest was as follows: CK > Bo-10 > Bo-20 > Bo-50 > Bo-30. By the second irrigation event, the maize had reached the jointing stage, and the difference in evaporation between treatments increased; however, the overall evaporation volumes were similar to those after the first irrigation event. By the third irrigation event, the maize had entered the tassel stage. The temperature and daily

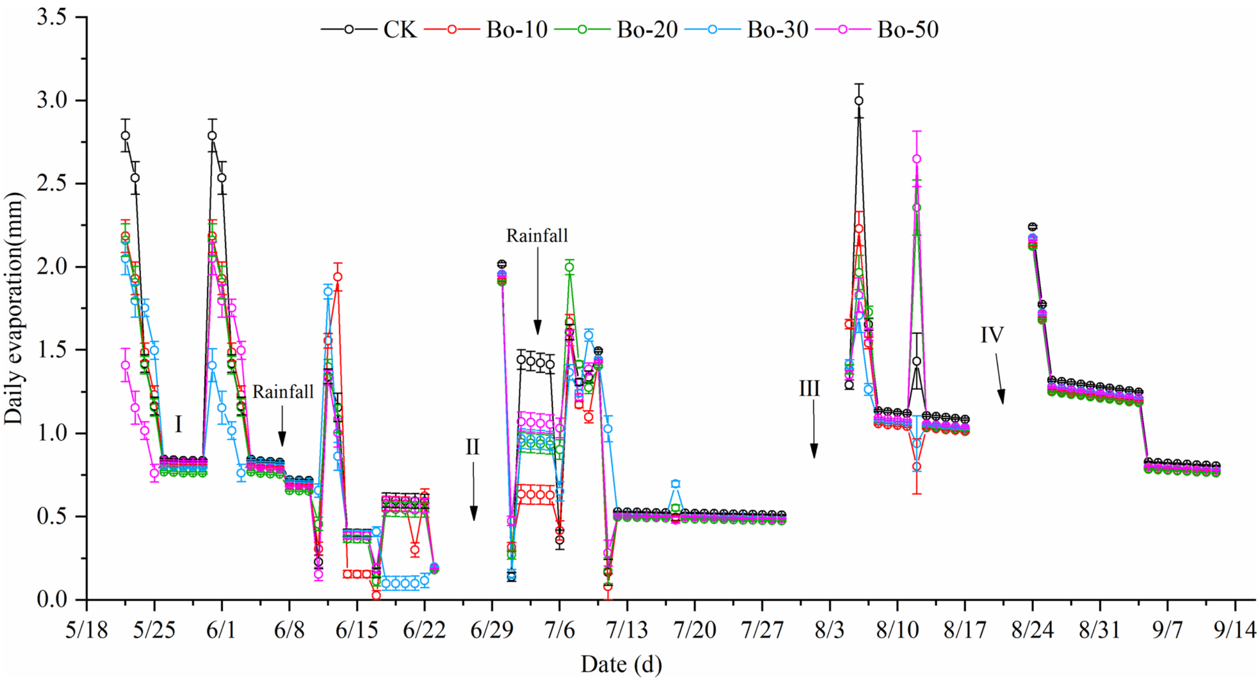

Fig. 5 Field cumulative soil evaporation using biochar

evaporation also gradually increased. The evaporation peak lasted from August 24 to September 2, 2015, and the evaporation gradually subsided afterward. The soil water holding capacity and resistance to evaporation were lower in the CK than in the BC treatment groups. The overall trend was CK > Bo-10 > Bo-20 > Bo-50 > Bo-30, which was consistent with the findings of the indoor experiment. The difference with the planted maize in the field experiment was that, in the later stages of maize growth, the height of the plant blocked most sunlight, and so evaporation was reduced. This did not occur in the soil column experiment, in which sunlight was a constant value. After BC application, the cumulative evaporation of the Bo-10, Bo-20, Bo-30, and Bo-50 treatments was reduced by 9.58%, 6.28%, 10.95%, and 4.20%, respectively, compared with that of CK, which was also consistent with the findings of the soil column experiment (Fig. 6).

Indoor BC soil column evaporation experiment

To understand the changes in soil moisture content under continuous soil evaporation conditions after BC addition, we conducted an indoor BC soil column evaporation experiment having an observation interval of 6 days (Fig. 7). Figure 5A shows the infiltration under gravity 2 days after irrigation, and the overall moisture content was at a relatively high level. The soil moisture content of the various BC application rates changed with depth, and the moisture content at the soil surface (0–15 cm) was higher in each BC treatment group than in the CK, most notably for the Bo-30 treatment. After 6 days of indoor evaporation, the moisture content readings at the surface layer (0–15 cm) for Bo-30 and Bo-50 were both higher than that for the CK. The reduction in soil moisture content compared with the first sampling was as follows: CK, 4.76%; Bo-10, 4.76%; Bo-30, 7.41%; and Bo-50, 4.78% (Fig. 5B). In the third sampling, beyond the application layer (0–20 cm), the soil column moisture content at each BC application rate was significantly higher than that in the CK. The rate of moisture reduction for each treatment in the third sampling compared with the second sampling was as follows: CK, 18.65%; Bo-10, 11.82%; Bo-30; 8.69%; and Bo-50, 9.57% (Fig. 5C). The monitoring results from the final sampling indicate that the moisture content of the BC treatment groups was significantly higher than that of the CK after 18 days of continuous evaporation. Using a depth of 25 cm as an observation point, the rates of reduction of the various application rates in the fourth sampling compared with the third sampling were as follows: CK, 4.93%; Bo-10, 5.00%; Bo-30, 6.66%; and Bo-50, 2.02%.

Diurnally, irrespective of growth stage, the soil evaporation at each growth stage initially increased, then decreased (Fig. 8). Evaporation occurs as the Earth's surface heats up from 8:00 AM; the amount of evaporation gradually increases, peaking at 2:00 PM and trending downward until it levels off from 6:00 PM until 6:00 AM the next day, when moisture content tends to rise.

After the first irrigation event, the moisture content of the topsoil was higher for Bo-30 and Bo-50; whereas, the moisture content of the other treatments was close to that of the CK (Fig. 9). After the second irrigation, the maize was in the jointing stage, and there was a notable increase in plant height, the crop

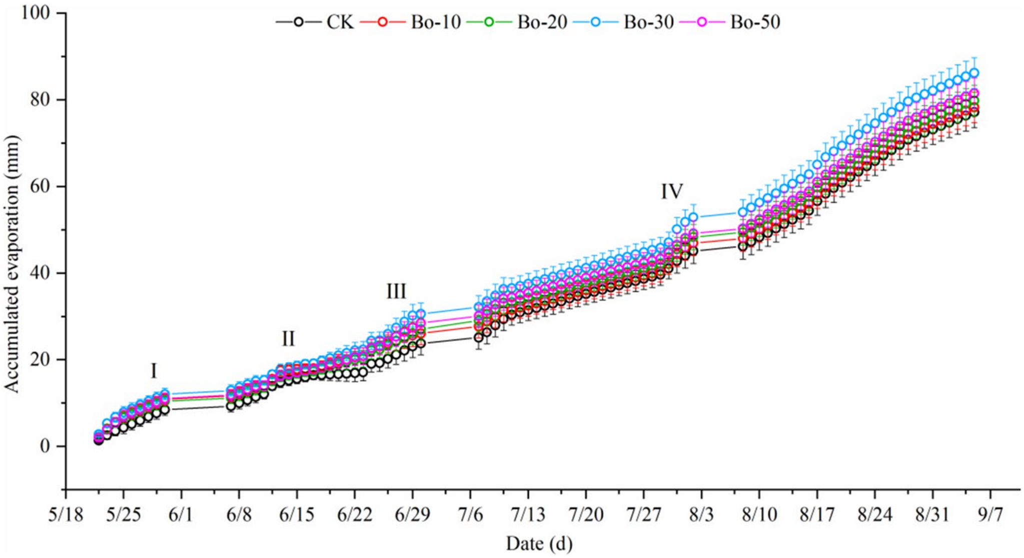

Fig. 6 Effect of evaporation of the biochar column on soil moisture content

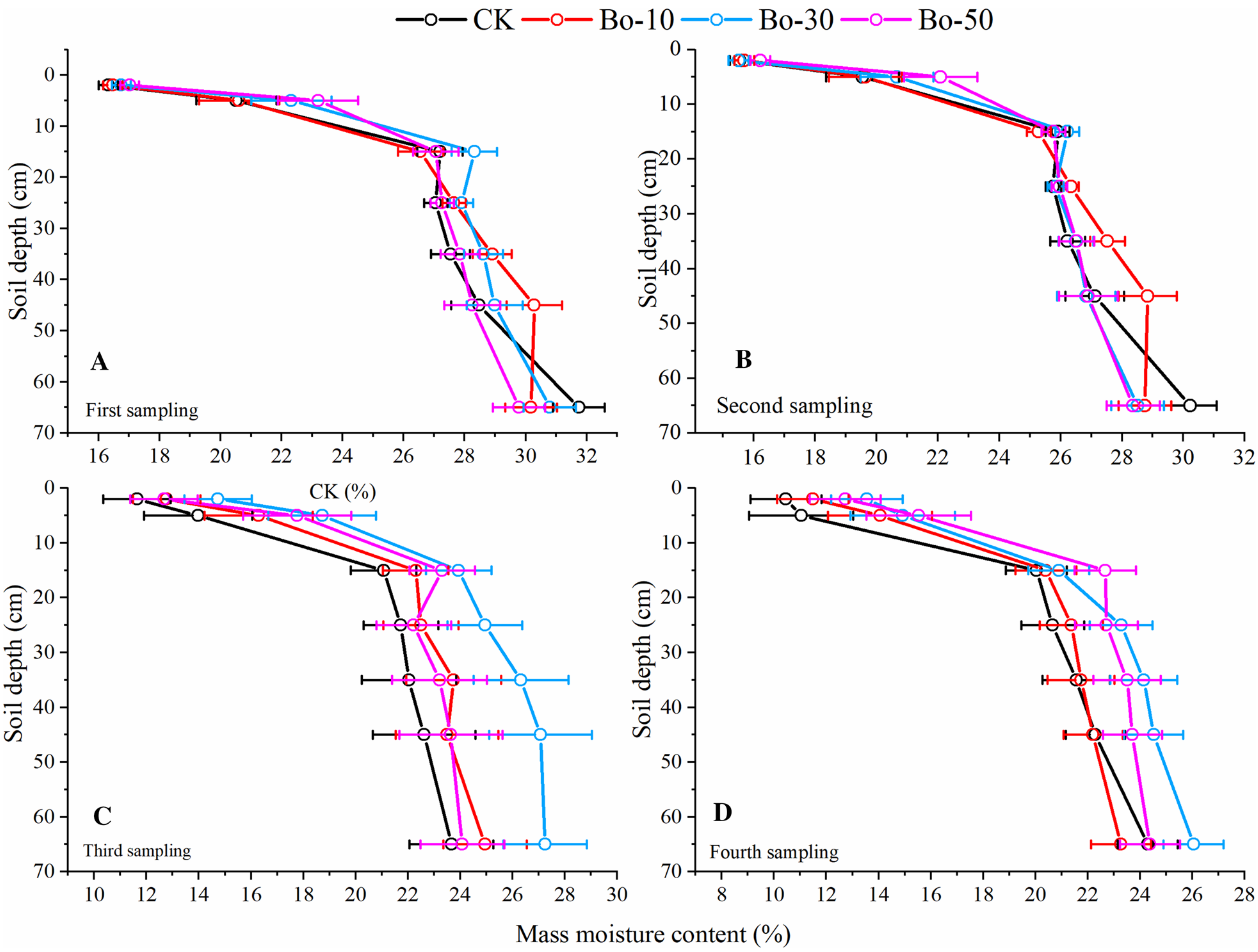

Fig. 7 Field daily soil evaporation using biochar

stems grew rapidly, and the leaf density increased. Soil moisture loss was mainly due to plant absorption and transpiration. The vegetation cover provided by the stems and leaves meant less direct sunlight on the soil and less soil evaporation. Therefore, at this stage, water loss due to each treatment and the differences in water reduction between treatments were small, but the moisture absorption for CK was notably lower than that for other treatments, which was consistent with the results of the soil column evaporation experiment. The order of the treatments by moisture content in the first interval was Bo-30 > Bo-50 > Bo-20 > CK > Bo-10 (Fig. 9).

At the plough pan (40–60 cm), the soil is compacted by repeated mechanical ploughing, sedimentation, and the accumulation of clay particles during rainfall or irrigation (Fig. 9).

Discussion

Effects of BC rates on soil moisture under evaporation conditions

As evaporation continued, the moisture content decreased; however, as the experiment progressed, the suppressive effect of BC on evaporation gradually emerged. BC application can reduce soil evaporation, prolonging the time required for water vapor in the drying surface layer to escape into the atmosphere, thereby reducing soil compaction and hardening caused by rapid evaporation. This was consistent with the findings of Wang [32], who found that BC from timber and locust bark can increase soil field capacity in semiarid areas. Similarly, Glaser et al. [11] highlighted that the water holding capacity of cultivated soil in the black carbon-rich Amazon basin is approximately 18% higher than that of surrounding soil not containing black carbon.

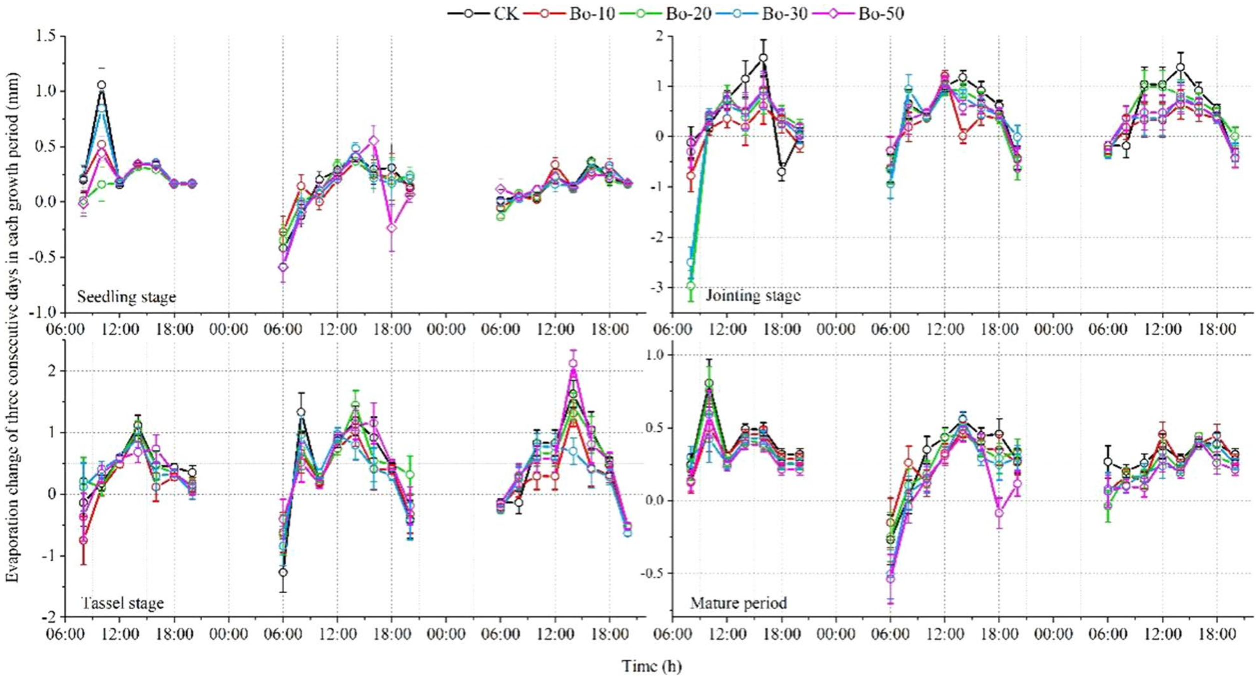

Fig. 8 Diurnal variation in soil evaporation at different growth stages upon application of biochar

From the application layer to the deep layer (0–65 cm), the moisture content of Bo-30 was higher than that of the other treatments at the end of the experiment, making it the preferred application rate.

Effect of BC on daily soil evaporation at different crop growth stages

According to the soil water energy principle, without considering the influence of the temperature and solutes, the movement of unsaturated soil water mainly depends on the gravitational and matric potentials. When the topsoil moisture content gradually decreases, the matric potential can vary from 0 to approximately − 10 units of atmospheric pressure. Due to surface evaporation during the day, soil moisture is lost and negative pressure suction increases; thus, water at deeper levels gradually rises to the surface through the capillary system, resulting in water replenishment.

The phenomenon of increased overnight water replenishment after BC application results from sunlight heating the soil during the day, thereby increasing evaporation; as the air temperature decreases at night, the temperature difference between the soil and air causes the soil to radiate heat and transport moisture to the upper soil layer surface in the form of evaporation to replenish its water content. This is the principle underlying the upward transport of water from the lower soil layer. The above conclusions further verify that BC application can increase soil capillary conductivity. Similar to the results of previous studies [22, 24, 25, 35], the incorporation of BC not only reduced the evaporation of soil water, but also optimized the distribution of soil salt and water.

Effect of BC on field soil moisture under evaporation conditions

This study showed that the soil was dense, which was not conducive to water transfer. Due to the interception of irrigation by the BC layer, the moisture content of this soil layer was similar to that of the CK. Studies have shown that BC can improve the crack resistance of soil by improving the tension stress between soil particles, thus reducing soil water evaporation. Therefore, the density of soil is also an important factor affecting water evaporation [27]. Below the plough pan (60–100 cm) was deep soil that received no BC application, but it was indirectly affected by the application layers and crop roots. The soil moisture content at this depth also varied according to the soil moisture content of the upper layers during the various stages of crop growth. Particularly after the third irrigation event, due to vegetation cover, the soil solar radiation decreased, resulting in a corresponding decrease in soil evaporation. In addition, the maize was transitioning from the jointing to the tassel stage, the daily crop water consumption was increasing, and the moisture variation below the plough pan was basically similar to that in the upper soil layer (0–20 cm).

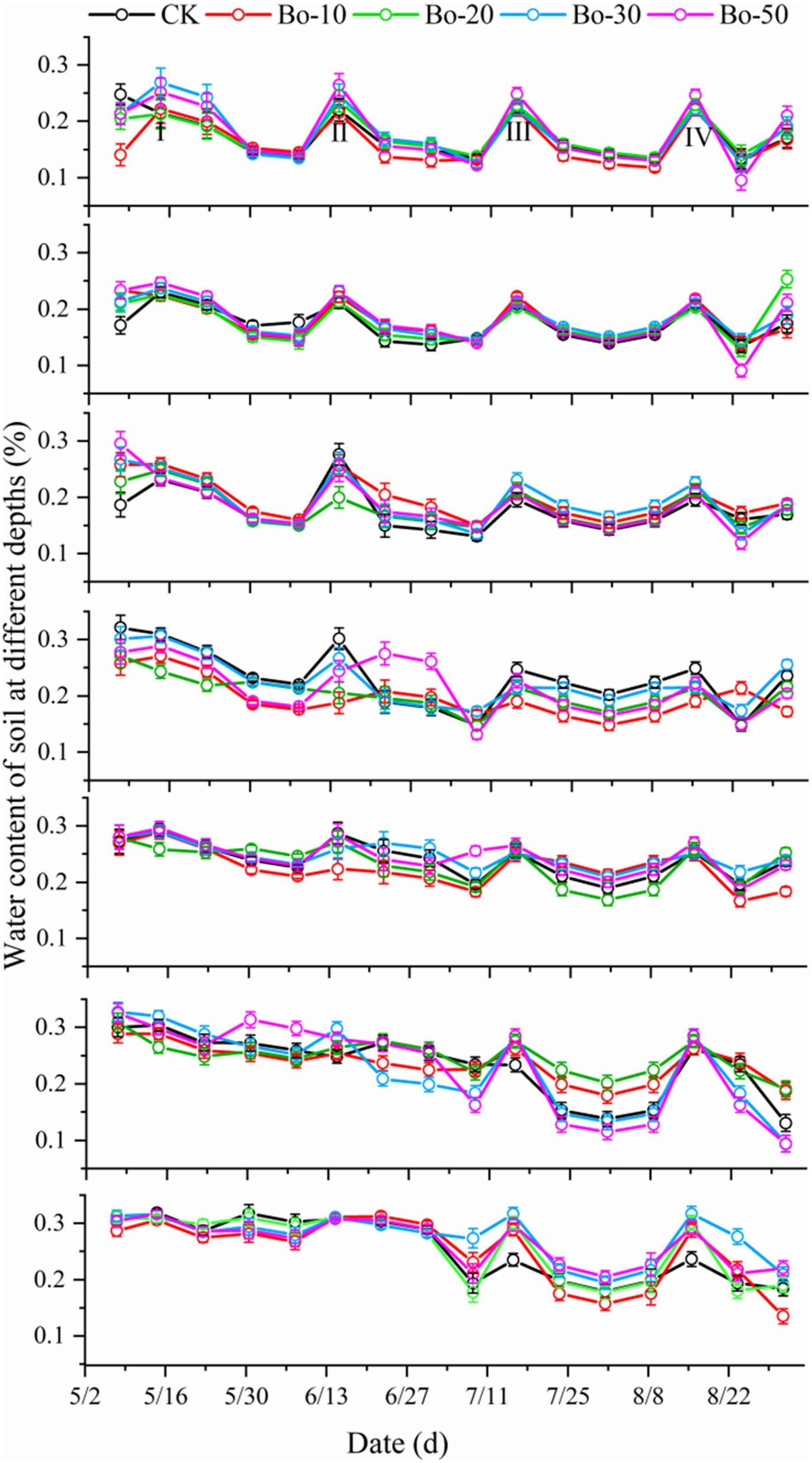

Fig. 9 Effect of soil evaporation with biochar on soil water content

Maize is a deep-rooted crop, with a root system that can extend 80–100 cm underground. For the root system to develop fully, soil moisture must be maintained within a range that can support growth during the seedling and jointing stages, i.e., close to the field capacity. Excessive irrigation will concentrate maize roots in the shallow layer, preventing water absorption at deeper layers. This will result in insufficient water supply during growth and a reduced yield. Thus, water supply plays an important role in the late-stage growth of maize.

Compared with the soil column evaporation experiment, the actual field presented more complex conditions that were not under human control. However, based on the real-time monitoring of changing soil moisture content at different depths throughout the maize growth period, we found that BC was effective at suppressing soil evaporation. The most effective treatment was Bo-30 (i.e., 30 t/hm^2), which had a cumulative evaporation that was 10.95% less than that of the CK, indicating that it effectively preserved the water in field soil.

Suppressive mechanism of BC on soil evaporation

BC adsorbs irrigation water or rainwater between soil particles owing to its strong adsorption. Applying BC can also reduce soil bulk density [26, 30]. Studies have shown that BC easily forms a microporous structure during the preparation process, and this structure creates many pores of various sizes when heated. If the pore surface is ablated, the structure is incomplete and the presence of ash will lead to the formation of oxygen-containing functional groups (hydroxyls, lactones, etc.). These microporous structures promote the capillary system of the soil, thereby increasing the soil moisture content.

The cumulative evaporation of each treatment in the BC soil column experiment was 0.01% (Bo-10), 1.08% (Bo-30), and 13.67% (Bo-50) less than that in the CK. The cumulative evaporation of each treatment in the BC field experiment was 9.58% (Bo-10), 6.28% (Bo-20), 10.95% (Bo-30), and 4.2% (Bo-50) less than that in the CK. We found that during the growth of the tested crop, BC had a good suppressive effect on actual field evaporation. Using average soil moisture in the soil amendment application layer (0–40 cm) after each irrigation event as the evaluation criterion and the time it took for the average moisture content to return to field capacity after irrigation as a reference, we compared the changes in the moisture content of each test group under evaporation conditions to determine which BC treatment rate more effectively reduced soil moisture loss. The Bo-30 BC treatment was observed to be the most effective because the 30 t/hm^2 application rate shortened the time it took for soil moisture content to reach field capacity after irrigation.

The capillary water volume in the soil voids plays an important role throughout the process of soil water evaporation. When the soil is rich in pores, the storage of capillary water increases and resistance to evaporation improves. Moreover, retaining a certain volume of water plays an important role in maintaining a constant soil temperature. Therefore, the application of 30 t/hm^2 BC can result in a prolonged delay in the loss of soil moisture, which is beneficial for growing crops.

Applying BC increases soil porosity, prolonging soil moisture retention in the field and stimulating increased soil microbial activity [5, 23, 31]. BC changes the soil's physical properties and the water evaporation kinetics. BC addition can increase the soil water content and effectively reduce soil evaporation, and as BC addition increases, the suppressive effect on soil evaporation increases. The amount of BC added reportedly changes the evaporation process significantly based on the soil type and BC particle size [22–25]. The addition of BC reduces capillary evaporation in the first stage of evaporation and increases evaporation in the second stage. Larger BC particles also reduce soil evaporation to a greater extent than smaller BC particles [38].

Conclusions

This study focused on the effects on soil evaporation and moisture content of adding different amounts of BC to soil. An indoor soil column evaporation simulation experiment and field experiment were conducted to observe the principles underlying daily evaporation changes, cumulative evaporation changes, and soil moisture changes. From these experiments, we drew the following conclusions:

1. Compared with the CK, the BC treatments in the field experiment reduced cumulative evaporation by the following percentages: Bo-10, 9.58%; Bo-20, 6.28%; Bo-30, 10.95%; and Bo-50, 4.2%. This indicated that BC effectively suppressed the soil evaporation in the cultivated land in the study area.
2. The most effective BC treatment was Bo-30 (application rate of 30 t/hm^2); the soil moisture content reached field capacity on the 10th day after the first irrigation event, 12th day after the second irrigation event, 7th day after the third irrigation event, and 7th day after the fourth irrigation event.

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Author contributions
WF: writing the original draft; TW: writing and reviewing; FY: writing, reviewing and editing; RC: data analysis and investigation; HL: writing and reviewing. ZQ: conceptualization, methodology, and supervision.

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Availability of data and materials
Not applicable.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All the authors agreed to publish the article.

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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