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Response of biochar to water infiltration in clayey raw soils

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Abstract

In order to investigate the response of biochar to water infiltration and water holding capacity of clayey raw soil, the infiltration rate, wetting front, cumulative infiltration and water holding capacity of soil with different biochar additions were investigated by using field experiments combined with indoor soil column simulation experiments. The results showed that with the increase of biochar addition, the initial infiltration rate, stable infiltration rate and cumulative infiltration rate decreased continuously, and the wetting front process showed a slowdown trend. The soil water infiltration process was simulated using Philip model, Horton model and Kostiakov model, and the Kostiakov model had the best result with R2 of 0.992. The study results verified that the addition of biochar significantly improved soil water holding and water retention, and the higher the amount of biochar added, the more obvious the improvement of soil water holding and water retention.

Keywords

Biochar, Soil moisture, Model Fitting, virgin soil.

1. Introduction

Raw soils generally have low fertility levels, stiff or too loose soils, and the infiltration rate of soil water is small, far from being able to meet the nutrients and water needed for crop growth(Zhang et al. 2013, Lim et al. 2016). Under natural conditions, the maturation process of raw soil is slow, making it difficult to meet the expectations of cultivators and the needs of agricultural development(Lu et al.2008). Therefore, the rapid improvement of the quality of new arable land and barren land through soil improvers is an inevitable choice for modern agricultural development(Githinji et al. 2014, Zhao et al. 2015, Pereirar et al. 2012, Gou et al.2013, Liu et al. 2018, Xiao et al. 2019). Water infiltration is an important part of the soil water cycle in agricultural fields, and the infiltration process determines the effective degree of soil acceptance of rainfall and irrigation water, and also affects surface runoff and soil water erosion processes(Ghulam et al. 2017). Take effective measures to improve soil infiltration characteristics is an effective way to improve the soil's ability to store water and retain moisture and promote high and stable crop yields(Ding et al. 2022, Ali et al. 2017, Alfred et al. 2020, Yu et al. 2019, Aliva et al. 2019, Tuana et al. 2019). Soil texture has a significant effect on the infiltration capacity of soil water(Li et al. 2021). Afrin et al.(Afrin et al. 2020) analyzed and discussed the soil texture on the infiltration capacity of field soil water based on the infiltration test data of field soil water accumulation under different soil texture conditions, and found that the infiltration rate of soil steadily decreases and the infiltration capacity decreases when the soil texture changes from light to heavy. The greater the clay particle content of the soil, the smaller the cumulative infiltration volume of the soil in the same infiltration time, i.e., the more viscous and heavy the soil is, the worse its infiltration capacity(Liu et al. 2020, Bharat et al.2019). For raw soils with relatively clayey texture and compact soil, the lack of agglomeration and low infiltration rate affects the acceptance of precipitation and irrigation water, and easily generates surface runoff, resulting in degradation of raw soil quality(Leila et al. 2019, Wang et al.2019). Therefore, how to improve its water storage capacity is the key to improve the quality of clayey raw soil.

Biochar has a highly developed pore structure and a huge specific surface area, and the surface contains a variety of organic functional groups, which has a strong ion adsorption and exchange capacity. These unique physicochemical properties allow it to be applied to the soil as a novel soil amendment(Sergio et al. 2019). However, the effect of biochar on soil water holding capacity is closely related to the soil texture and the properties of biochar itself (Angelaki et al.2021). Studies have shown that biochar can reduce the saturated hydraulic conductivity of sandy soils, but can improve the hydraulic conductivity of loamy and clayey soils(Cao et al.2019). Rafael et al.(Rafael et al. 2019)found that biochar can reduce the infiltration capacity of sandy soil but can significantly increase the infiltration capacity of small mound soil through soil column simulation tests. For clayey raw soils, the amount of biochar applied and the number of years of application will inevitably improve the soil structure, causing changes in soil capacitance and soil porosity(Haimanote et al. 2019), which leads to changes in the infiltration capacity and water holding capacity of the soil. However, there are relatively few studies on the effects of biochar application rates and application years on water infiltration in clayey raw soils. In this study, based on an indoor soil column simulation experiment, the effect of biochar application on soil capacity was considered. In the article, the effects of biochar application on soil water infiltration and its intrinsic mechanism were investigated around different biochar application rates and application years. Aiming to determine the application amount of biochar applied to improve soil hydraulic properties of clayey raw soils and the effect of continuous application of biochar on soil moisture infiltration performance, and to enrich the study of the effect of biochar addition on soil moisture effect of clayey raw soils.

2. Research Program

2.1. Overview of the test area

The test area is located at the Qinling Field Monitoring Center Station in Shangwang Village, Tangyu Town, Mei County, Baoji City, Shaanxi Province, which is situated at 107°39′-108° 00′E and 33°59′-34°19′N. It is located in the western part of Guanzhong Plain, Shaanxi Province, with the Qinling Mountains to the south and the Weishui to the north, and belongs to the middle reaches of the Yellow River in the Sichuan Plateau Gully Area.

2.2. Test materials

Biochar produced by Shaanxi Yixin Bioenergy Technology Development Co., Ltd. was used for the test, and the biochar was crushed and sieved through 2 mm sieve. The test crop was maize and the soil texture was clay. Soil water infiltration tests were conducted indoors with a homemade mason jar and a 10 cm inner diameter, 50 cm high Plexiglas cylinder.

2.3. Experimental design

2.3.1. Field experiments

In this study, a combination of simulated soil column and field test was used. Fifteen test plots were set up in the field test, with the plot size of 1.5*3 m^2 . The amount of biochar application was set up in 5 treatments according to 0, 5, 10, 15 and 20 t/hm^2 (hereafter labeled as B0, B5, B10, B15 and B20), and the plots were arranged in a randomized group design with 3 replications for each treatment. The biochar was spread evenly on the soil surface and mixed with the cultivated soil (20 cm) by hand, so that the color of the soil was uniform in all parts, and then the plots were set up. The same N, P, and K fertilization regimens were used in the test plots, which were consistent with local farmers' fertilization habits: N: 150 kg/hm^2; P_2O_5: 120 kg/hm^2; and K_2O: 90 kg/hm^2.

2.3.2. Soil column simulation experiment

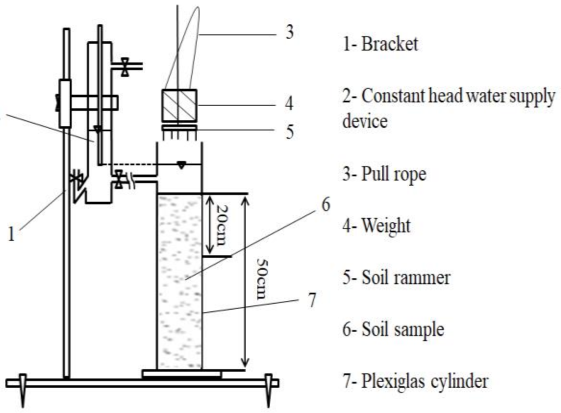

Fig.1 Schematic diagram of vertical soil column infiltration test setup

A clear Plexiglas column with an inner diameter of 10 cm and a height of 60 cm was selected for this purpose, and the soil was filled to a height of 50 cm. A layer of 300 mesh nylon mesh and filter paper was placed at the bottom of the soil column before filling. To reduce the wall effect, a layer of petroleum jelly was applied to the inside of the column.

Step 1: Open the inlet hole and water inlet of the Mars bottle, use the funnel to fill the Mars bottle with water until the Mars bottle is full of water, at this time, close the inlet hole and air inlet hole, and check whether it leaks, to ensure that the Mars bottle does not leak. In adjusting the position of the Mars bottle to make the Mars bottle of air inlet hole and the soil bucket designed to be flush with the water surface, to ensure zero head water supply, Mars bottle can be more accurate measurement of the amount of water into the soil body.

Step 2: Filling of soil sample. When starting to fill the soil, first weigh the weight of the soil to be filled in the layer, after each layer is filled with soil, it should be leveled first, and then hit with a stone batterer to make the filled soil flush with the pre-defined line of the layer, and then throw the hair with appropriate tools, and then proceed to fill the next layer of soil, when filling the soil, it should ensure good contact between the layer and the layer, and no obvious layering phenomenon should occur.

Step 3: System connection. After the soil sample is filled, place an asbestos net or qualitative filter paper on the top of the soil sample to prevent the water from washing over the surface of the sample when it is filled with water. Then use a rubber hose to connect the water outlet of the marsupial to the water inlet of the soil bucket.

Step 4: Observe and record the test data. Record the start time of the experiment, start infiltration, observe the depth of the wetting front and the water level of the marsupial, and record the transport depth and water level scale under the corresponding time according to the principle of dense in the front and sparse in the back. The infiltration process ended when the wetting front reached the bottom of the soil column.

2.4. Observation indicators and methods

Soil moisture content and soil capacity: The drying method was used to determine the soil moisture content of 0 ~ 20 cm, 20 ~ 40 cm and different soil layers of agricultural soils during the maturity of maize, and to determine the soil capacity of the corresponding soil layers.

Soil moisture infiltration performance parameters.

Soil moisture content calculation method: Using the drying method, the collected soil was dried at 100℃~105℃ for 12 hours until the weight no longer changed, and the dry soil weight was weighed and recorded.

$$W=(M-M_s)/\ M_s*100\% \quad (1)$$

Where W is the soil water content (%); M is the soil wet weight (g); Ms is the soil dry weight (g).

Soil capacity calculation method.

$$R=(G-G_0)/V \quad (2)$$

Where: R is the soil capacity (g/cm^3); G is the sum of ring knife and soil weight after drying (g); G_0 is the weight of ring knife (g); V is the volume of ring knife (cm^3).

2.5. Parameter Fitting Model

Philip infiltration model：

$$I(t)=0.5st^{-\frac{1}{2}}+i_c \quad (3)$$

The formula I(t) is the infiltration rate (cm/min), S is the soil moisture absorption rate (mm/min$^{1/2}$), Closely related to the properties of the soil itself. t is the infiltration time (min); i_c is the steady infiltration rate (mm/min); S and i_c can be measured by infiltration test.

Kostiakov infiltration model：

$$I(t)=kt^n \quad (4)$$

The equation: k is the accumulated infiltration volume of the first timing unit (cm), n is the empirical constant.

Horton infiltration model：

$$I(t)=i_c+(i_a-i_c)e^{-\alpha t} \quad (5)$$

The equation: ia is the assumed initial infiltration rate (cm/min), α is the decay index.

2.6. Data processing and analysis

All experimental data were averaged over three replications, plotted using Origin software, and simulated by R software for soil infiltration parameters and statistical analysis.

3. Results

3.1. Effect of different biochar addition methods on soil physical properties

Figure 2 depicts the changes in soil bulk, water content, and porosity at different treatments for soils with depths of 0-20 and 20-40, respectively. For soils in the 0-20 cm depth, the soil bulk weight decreased continuously with the increase of biochar application, the soil water content did not show obvious gradient characteristics, the soil porosity increased gradually with the increase of biochar application. For soils with 20-40 cm soil depth, there were no significant changes in soil bulk, water content, and porosity with the increase of biochar application.

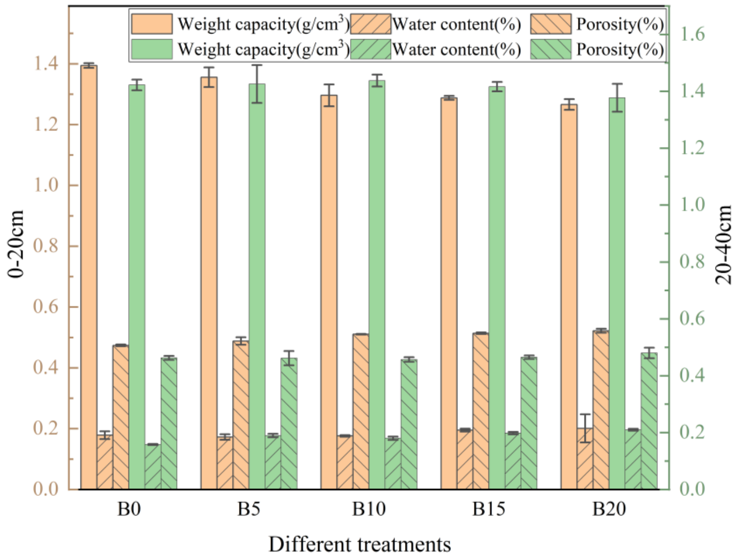

Fig.2 Soil physical properties under different treatments

The specific values can be viewed in Table 1.

Tab.1 Physical properties of soils with different treatments

Different treatments	Soil depth	Soil capacity	Soil water content	Soil porosity
B0	0-20	1.39431±0.0077	0.17871±0.01262	0.47384±0.00291
	20-40	1.42269±0.01892	0.15825±0.00183	0.46314±0.00714
B5	0-20	1.35578±0.03235	0.17266±0.00904	0.48839±0.01221
	20-40	1.42587±0.0665	0.18987±0.00611	0.46193±0.0251
B10	0-20	1.29648±0.0361	0.17633±0.00273	0.51076±0.00136
	20-40	1.43827±0.02102	0.18006±0.00594	0.45726±0.00793
B15	0-20	1.28809±0.00651	0.19525±0.00483	0.51393±0.00246
	20-40	1.41681±0.01652	0.19832±0.00458	0.46535±0.00623
B20	0-20	1.26649±0.01756	0.20095±0.0462	0.52208±0.00663
	20-40	1.37759±0.04909	0.20993±0.00342	0.48016±0.01853

3.2. Effect of biochar content on the wetting front process

Wetting front processes respond to soil moisture infiltration patterns. Figure 3 shows the variation of the wetting front with time. The trend of the wetting front process is similar for all treatments in the figure, i.e., the slope of the wetting front process curve decreases with infiltration time. The process of wetting front was significantly different among treatments with the same infiltration time, and the process of wetting front of B0 was significantly faster than that of adding biochar, and the more biochar was added, the slower the process of wetting front was. It can be seen from Figure 3 that the infiltration time of B0, B5, B10, B15 and B20 were 150, 175, 192, 223 and 298 min, respectively, which also indicates that the more biochar was added the slower the wetting front process.

3.3. Effect of biogenic carbon content on cumulative soil infiltration

Figure 4 shows the relationship between the cumulative infiltration amount and infiltration time for different biochar content. Cumulative infiltration increased with infiltration time for all treatments, but there were significant differences in the degree of increase of cumulative infiltration at different infiltration moments. Larger slope of the cumulative infiltration curve at the initial infiltration stage. The slope of the cumulative infiltration curve decreases after entering the stable infiltration stage, i.e., the cumulative infiltration is proportional to the infiltration time and inversely proportional to the amount of biochar added. The cumulative infiltration volume of 150 min was selected to quantify the soil water infiltration characteristics.

The cumulative infiltration amounts of B0, B5, B10, B15 and B20 at 120 min were 17 cm, 15.65 cm, 14.35 cm, 12.87 cm and 11.34 cm, respectively.

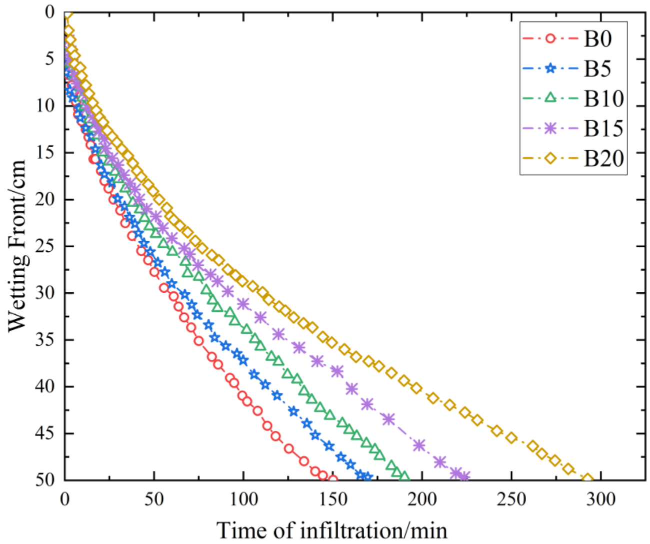

Fig.3 Dynamic changes of wetting fronts under different biochar application rates

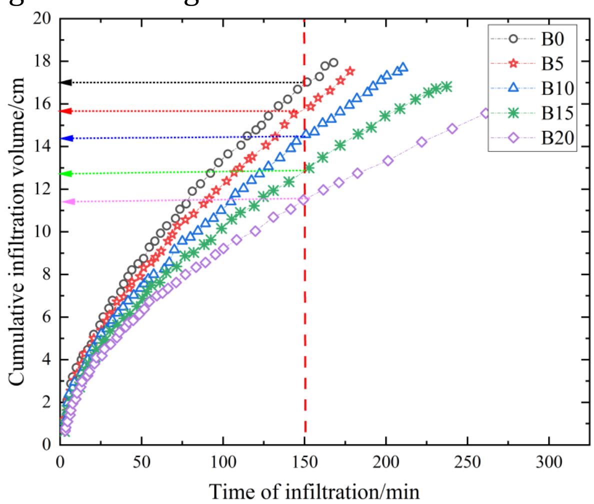

Fig.4 Effect of biochar application rate on cumulative infiltration

3.4. Soil water infiltration process fitting and infiltration performance analysis

To fully understand the effect of biochar addition on soil water infiltration and to determine the applicability of the infiltration model, three models, Philip, Kostiakov, and Horton, were used to fit the soil water infiltration process (Table 3). The s value in Philip's model ranges from 0.532 to 1.026 and s decreases with the increase of biochar content, while the larger the s, the larger the slope of the soil infiltration curve and the faster the instantaneous infiltration rate decays. The order of instantaneous infiltration rate is B0>B5>B10>B15>B20. *ic* range: 0.148~0.502 and increased significantly with the increase of biochar content, showing a significant positive correlation characteristic. Range of a values in Kostiakov model: 0.589~1.09, a increases with the increase of biochar content. The range of ic values in the Horton model: 0.825 ~ 12.99 and a positive correlation with biochar content. Alpha value range: 0.375 ~ 0.532 and negatively correlated with the amount of biochar added. Combining the fitting results of the three models, it can be found that the Kostiakov model has the best fitting effect.

Table 3 Fitting results of different infiltration model parameters

Model	Parameters	Different treatments

		B0	B5	B10	B15	B20
Philip	s	0.902±0.124	0.873±0.133	0.81±0.112	0.75±0.124	0.642±0.11
	i_c	0.176±0.028	0.213±0.0101	0.32±0.016	0.39±0.0012	0.49±0.012
	R^2	0.943	0.953	0.943	0.896	0.88
	RRMSE	0.0275	0.0264	0.0257	0.051	0.055
Kostiakov	a	0.980±0.111	0.896±0.017	0.812±0.135	0.73±0.032	0.71±0.121
	b	0.569±0.025	0.587±0.012	0.571±0.021	0.592±0.011	0.572±0.014
	R^2	0.988	0.992	0.976	0.986	0.986
	RRMSE	0.0136	0.0115	0.021	0.031	0.015
Horton	i_c	0.927±0.102	6.198±0.330	8.21±0.261	9.57±0.36	12.74±0.25
	α	0.495±0.037	0.438±0.013	0.412±0.011	0.411±0.019	0.396±0.021
	R^2	0.92	0.96	0.94	0.91	0.94
	RRMSE	0.0386	0.033	0.043	0.046	0.031

3.5. Effect of biochar content on soil moisture characteristic curve

Soil water characteristics curve reflects the relationship between soil water absorption and soil water content, which can be used to understand the water-holding and water-holding properties of the soil. Soil moisture characteristics curves differed significantly between treatments . When the soil water content was near 0.17, the slope order of the suction curves of different treatments of substrates produced a significant change, with the slope of the curve that originally had a large slope rapidly becoming smaller and the slope of the curve that originally had a small slope, rapidly becoming larger. The part circled by the red box in the figure is the most obvious (Figure 5).

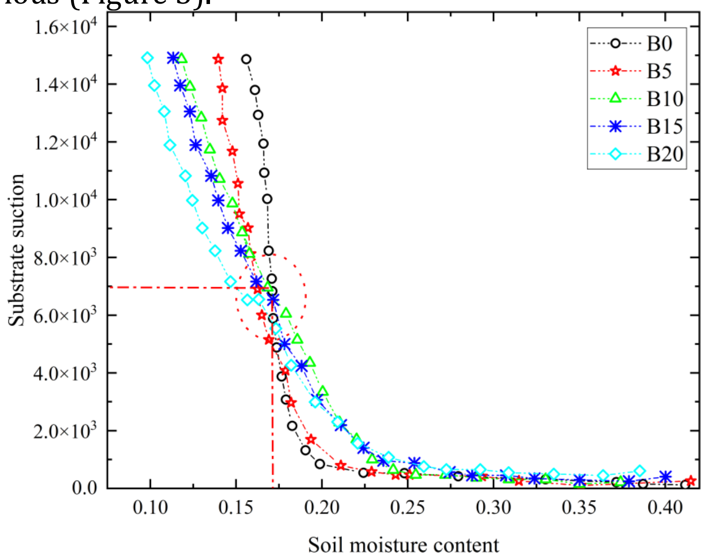

Fig.5 Soil moisture characteristic curves of different biochar treatments

4. Conclusion

(1) The initial infiltration rate, stable infiltration rate, average infiltration rate and cumulative infiltration amount decreased gradually with increasing the amount of biochar added to the soil, and the wetting front process slowed down.

(2) Comparing the three infiltration models with R2 values and model parameters, the simulated water infiltration processes of clayey soil with biochar addition were in the order of Kostiakov model, Philip model and Horton model.

(3) By fitting the soil water characteristics curve after biochar addition, it was found that the addition of biochar significantly improved soil water holding and water retention, and the higher the amount of biochar addition, the more obvious the improvement of soil water holding and water retention.

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