Evaluating the effects of biochar on the hydraulic properties of acidified soil in China

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Abstract

Purpose The increased human activities have significantly promoted the acidification of cultivated soils decreasing the soil water retention properties. This study investigated the improvement effect and mechanism of biochar on water retention properties of acidic soils.

Materials and methods Biochar was mixed with acidified and molded soils in different amounts (0, 2, 5, 8, and 10%), and then soil hydrological and water infiltration characteristics were analyzed.

Results and discussion The soil application of biochar, improved acidified soil capacity and porosity, and the effects were directly proportional to the applied amount of biochar. Compared to the control group, the application of 10%, biochar improved the average soil water content by 2.1–2.2 times and reduced the soil vertical infiltration rate by 41–43%. The soil vertical infiltration was 23–25% of that in the control group. Moreover, biochar-mediated improvement of soil aggregate agglomerates was found to be associated with the adsorption of soil microaggregates and the formation of water-stable macroaggregates.

Conclusion This study found that applying biochar to acidified soils can relieve the problems of poor water retention with a clear improvement mechanism. Large-scale soil application of biochar preventing migration of soil ions can contribute to environmental protection and natural resources recycling.

Keywords Application of biochar · Acidified soil improvement · Water retention · Molded soil

1 Introduction

Statistical data suggest that about 2.5 billion square kilometers of cultivated and potentially arable lands are under the influence of soil acidification, accounting for almost 50% of the total cultivated land (Jin et al. 2020). Soil acidification–mediated changes in soil structure of arable land leading to a significant reduction in their water retention capacity have become a serious threat to crop yields and food security. This not only reduces the profitability of farmers, but also increases the problem of environmental pollution. Therefore, it is particularly important to find an environment friendly method that can improve the water retention capacity of acidic soils (Gluba et al. 2021). In recent years, the developed traditional acidic soil amendments (such as slaked lime, minerals, and industrial by-products) are prone to cause problems such as soil re-acidification, compaction, lack of organic matter, and secondary pollution (Mohammadi

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and Vanclooster 2011). To solve these problems, experts and scholars have turned their attention to biochar (Fidel et al. 2018).

Biochar, a renewable resource, can replace fossil raw materials as a green soil conditioner improving soil properties (Ahmad et al. 2016). Biochar with sufficient pore structure has a large specific surface area. The soil porosity can be improved after continuous application of biochar, which reduces soil bulk density by adsorbing tiny soil aggregates (Chintala et al. 2014). However, the application of biochar to arable soils may have some negative effects, such as the reduced effectiveness of certain nutrients (Guszek et al. 2019). Therefore, the effectiveness and usage of biochar for acidic soil amendment enhancing soil water retention capacity have attracted the serious attention of experts worldwide. Recent studies found that pyrolysis temperature and type of feedstock can affect the physical and chemical properties of biochar through the staged decomposition of its structural and chemical bonds (Huang et al. 2021). Plant biochar has a greater potential to enhance soil water retention properties (Kameyama et al. 2019). Biochar particle size affects soil water storage by altering the interpore space between soil particles and adding new pores of the biochar (intrapore) (Liu et al. 2017). Compared to untreated soil, the addition of biochar increases soil water availability by 30% significantly improving water availability for crops (Fischer et al. 2019; Gluba et al. 2021). A study found that the addition of 10% biochar showed the best improvement in soil water retention capacity (Edeh et al. 2020). Therefore, considering biochar as a green acidic soil amendment is highly feasible and has a certain practical basis. Especially, biochar may have a better effect on water retention properties of acidic soils.

In this study, to simplify the analysis of acidified soil improvement, the concept of modal soil was proposed. This is beneficial to exclude factors in the soil that may interfere with the improvement effect of biochar, such as humus, plant roots, and microorganisms (Guo et al. 2019). The changes of soil volumetric water content and vertical infiltration parameters with biochar application were analyzed by simulation experiments, and the potential of biochar to improve acidic soil and water retention capacity was evaluated. The effect of biochar on acid soil bulk density, porosity, and aggregates was explored. Our research provides practical theoretical basis and data support for the large-scale application of biochar to improve acidic soil (Lu et al. 2020; Moradi et al. 2019).

2 Experimental materials and methods

2.1 Soils and biochar

This study used bio-carbon from peanut shell (BC) that was purchased from Shandong Huanba Environmental Protection and Energy Saving Equipment Technology Company. The basic physical and chemical properties of biochar are listed in Table 1, and the scanning electron microscope image is shown in Fig. 1. The molded soil was collected from 30 to 50 cm depth of an uncultivated soil in Huai'an City, Jiangsu Province. The acidified soil (AS) was sampled from the 0- to 20-cm layer of soil in Qingdao City, Shandong Province. The collected soil sample was naturally air-dried after removing impurities and screened with a 2-mm sieve. The soil moisture content was measured by a moisture meter (METTLER V10S, Mettler Toledo, Switzerland) and the soil was stored at 4 °C for later use. Diluted concentrated hydrochloric acid (analytical grade) and deionized water were sprayed into the experimental molded soil at 20% water content. The process was repeated many times, each time pH change was within 0.05, to finally obtain the acidified molded soil (MS). The basic physical and chemical properties of the two kinds of soil samples are listed in Table 2.

2.2 Column model

The simulated soil column container was a PVC plastic pipe with a height of 40 cm and a diameter of 10 cm. Five sampling holes with a diameter of 10 mm were opened at intervals of 5 cm from the top to the bottom. The bottom was sealed with the same material, and four leachate sampling holes with a diameter of 5 mm were opened, and the sampling holes were distributed on a 6-cm circle concentric with the bottom. Before usage, the soil column container was repeatedly washed with 1 mol/L hydrochloric acid solution and deionized water. Also, Vaseline was evenly coated on the inner wall to prevent water from sticking to the wall and infiltration reducing the edge effect.

2.3 Experiment and sampling

The two acidified soil samples were air-dried and ground before mixing with 2-mm sieved BC. In total, five treatment groups were set up: treatment 1 was the control group with no biochar (MS CK, AS CK); treatment 2 was 20 g of peanut

Table 1 Basic physical and chemical properties of biochar

	$C_{ar}{}^{*}$ (%)	H_{ar} (%)	O_{ar} (%)	N_{ar} (%)	S_{ar} (%)	pH	Specific surface area (m²/g)
Biochar	53.36	1.33	3.02	0.87	0.20	8.76	30.1180

*ar as-received basis

Fig. 1 The scanning electron microscope images of peanut shell biochar
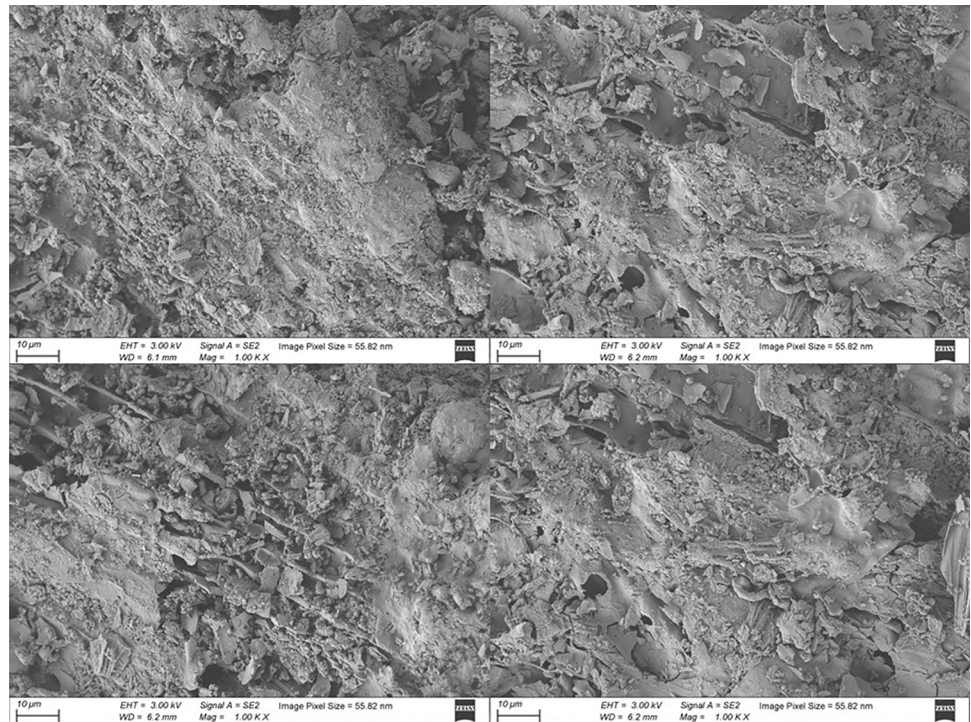
shell biochar added to each kilogram of soil sample (MS 2%, AS 2%); treatment 3 was 50 g of peanut shell biochar added to each kilogram of soil sample (MS 5%, AS 5%); treatment 4 was 80 g of peanut shell biochar added to each kilogram of soil sample (MS 8%, AS 8%); and treatment 5 was 1000 g of peanut shell biochar added to each kilogram of soil sample (MS 10%, AS 10%). All treatments were replicated three times.

Bulk density and porosity were determined by evenly applying petroleum jelly to the inner wall of the ring knife, of which the mass was weighed. Using a standard hand-held compaction apparatus, CK was uniformly loaded into the ring knife in two parts according to the set capacity of 1.38 g/cm³. The other treatment groups were also operated similarly. The mass of each treatment was measured and the corresponding index was calculated according to Eqs. (1) and (2).

$$\text{Bulk density} = \frac{m_1 - m_0}{V} \tag{1}$$

$$\text{Porosity} = \left(1 - \frac{\text{Bulk density}}{\rho}\right) \times 100\% \tag{2}$$

In the formula, m_0 denotes the weight of the ring knife (g), m_1 denotes the weight of the ring knife after filling (g), V denotes the volume of the ring knife (cm³), and ρ denotes the soil bulk density (g/cm³).

Soil moisture characteristic curves The soil samples from different treatment groups, in separate layers and uniformly packed in a ring knife, were saturated with water for 24 h. Soil moisture characteristic curves were obtained using a pressure film meter (NLYLM-15, Nanjing Nanlin Electronic Technology Co., Ltd., China). Different suction forces were applied at 0.02, 0.04, 0.06, 0.08, 0.10, 0.50, 0.80, 1.0, 3.0, 5.0, 7.0, 10.0, and 12.0 bar, and the weight of each sample was recorded after reaching equilibrium. Then the samples were placed at 105 °C and dried to a constant weight. Equation (3) was used to plot the soil moisture characteristic curve.

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha P)^n\right]^m} \tag{3}$$

In the formula, θ denotes the volume moisture content of acidified soil (cm³/cm³). P denotes soil water suction pressure (bar). θ_s and θ_r are the saturated and residual water content of acidified soil, respectively (cm³/cm³). α, m, and n are parameters of the Van Genuchten model.

Table 2 Basic physical and chemical properties of soil samples

	pH	Volume weight of soil (g/cm³)	Porosity (%)	Electrical conductivity (µS/cm)	Textural classification of soils[*]
MS[*]	5.20	1.38	48.54	206	Inceptisols
AS[*]	5.23	1.32	49.36	624	Inceptisols

[*]*MS* means the molded soil, *AS* means the acidified soil; textural classification of soil according to the US Soil Taxonomy system

Vertical infiltration of soil water The experimental equipment consisted of a 10-cm-wide and 40-cm-high soil column and a 6-cm-wide and 60-cm-high Marten's bottle. Soil samples from each treatment group were uniformly filled into the column in 4 batches, and water was continuously supplied to the column using the marsupial. The vertical infiltration and infiltrating rate of the soil in each treatment group were measured within 120 min and the curve was plotted using Eqs. (4) and (5).

$$K_i = kt^a \tag{4}$$

$$W_t = At^2 + Bt + C \tag{5}$$

In these formulas, K_i denotes the infiltration of the acidified soil (mm/min). k denotes the infiltration coefficient of acidified soil (mm/min). a denotes the infiltration index of acidified soil. W_t is the cumulative infiltration amount of acidified soil (cm); t is the infiltration time (min). A, B, and C are empirical constants of the Kostiakov infiltration model.

2.4 Data processing and analysis

The experimental data were summarized and plotted by Excel 2019 and Origin 2017, linearly fitted by MATLAB 2018 and Origin 2017, and analyzed by SPSS 25.0 statistical software using one-way ANOVA between and within groups, respectively. The significance level was set to 0.05.

3 Results and discussion

3.1 Effect of biochar on soil bulk density and porosity

Soil bulk density directly correlates to the soil conditions (Ola et al. 2019). A change in soil bulk density generally means a change in the soil structure affecting soil porosity. The changes in soil bulk density and porosity of the two soil samples mixed with biochar with different carbon-soil ratios are shown in Fig. 2. Compared with the control group, soil bulk density of AS decreased by 2, 6, 10, and 16%, and soil porosity increased by 3, 6, 12, and 19% respectively. Soil bulk density of MS decreased by 2, 6, 11, and 16%, and soil porosity increased by, 6, 13, and 19% respectively, showing significant differences among the treatment groups ($p < 0.05$). The increase of biochar application in acidified soil gradually decreased the soil bulk density and increased soil porosity, which could be attributed to the formation of pore structure by volatile organic components in biochar during pyrolysis and carbonization (Zhang et al. 2019). Biochar, with a better pore structure and large specific surface area, adsorbs tiny soil aggregate particles reducing soil bulk density and increasing porosity. This change improves the exchange of soil moisture and gas (Boostani et al. 2020). Notably, the 10% treatment group showed the most prominent effect with MS soil bulk density of 1.15 g/cm^3 and soil porosity of 58.03%; the AS soil bulk density was 1.18 g/cm^3 with soil porosity of 56.73%. Compared with AS, MS

Fig. 2 Change in soil bulk density and soil porosity under different carbon ratios. MS means the molded soil; AS means the acidified soil
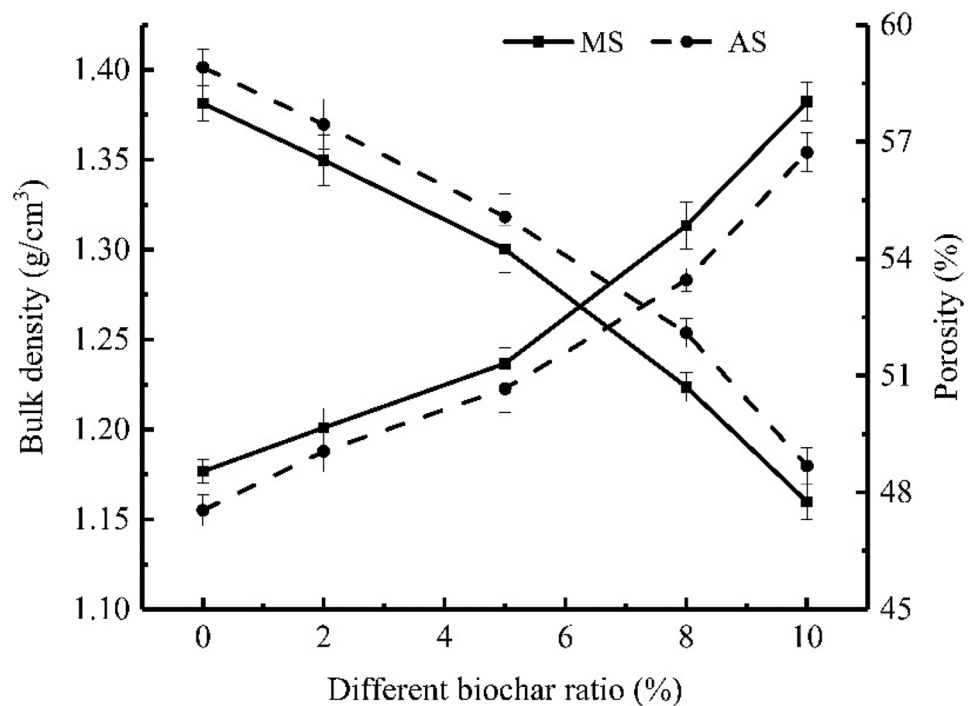
Table 3 Parameters of Van Genuchten model of acidified soil under different carbon ratios

Treatment groups[*]	Parameters of Van Genuchten model		R^2
	α	n	
MS CK	0.0223a	1.4383a	0.9857
MS 2%	0.0220a	1.4419a	0.9526
MS 5%	0.0219a	1.4398a	0.9447
MS 8%	0.0215a	1.4305a	0.9567
MS 10%	0.0211a	1.4407a	0.9325
AS CK	0.0217a	1.4158a	0.9876
AS 2%	0.0213a	1.4264a	0.9523
AS 5%	0.0208a	1.4193a	0.9412
AS 8%	0.0204a	1.4359a	0.9551
AS 10%	0.0201a	1.4225a	0.9294

[*]CK means the control group with no biochar; 2% means 20 g of peanut shell biochar added to each kilogram of soil sample; 5% means 50 g of peanut shell biochar added to each kilogram of soil sample; 8% means 80 g of peanut shell biochar added to each kilogram of soil sample; 10% means 100 g of peanut shell biochar added to each kilogram of soil sample

showed lower soil bulk density and higher soil porosity, which mainly depends on the soil characteristics before improvement.

3.2 Effect of biochar on soil moisture

Soil moisture characteristic curves are used to study soil hydrodynamics (Oliveira et al. 2017). MATLAB was applied to achieve curve fitting between experimental results of 10 treatment groups using the Van Genuchten model.

As shown in Eq. (3), "$m = 1 - 1/n$" was selected, and "α," "n," and correlation coefficient R^2 are shown in Table 3. θ_s and θ_r were selected 0.374 and 0.051, respectively, according to soil type. R^2 in different treatment groups was > 0.92 indicating a good fit of the experimental data to the model. The soil moisture characteristic curves are shown in Fig. 3.

As shown in Fig. 3, the overall volume of water content in the MS group was slightly higher than in the AS group but the difference was not significant ($p > 0.05$). However, the overall trend of change in soil moisture characteristics under different treatments was the same. Specifically, in the range of 0–1 bar soil water suction, the soil moisture content dropped rapidly; a higher carbon ratio led to a slower drop in water content. After that, with the increase of soil water suction, the soil water characteristic curve became stable. Under the same soil suction condition, the soil volume water content among different treatments increased with the increase in carbon ratio showing a trend of CK < 2% < 5% < 8% < 10%. The average moisture content of MS 2%, MS 5%, MS 8%, and MS 10% was 1.4, 1.7, 2.0, and 2.1 times compared to that of MS CK. Likewise, the average moisture content of AS 2%, AS 5%, AS 8%, and AS 10% was 1.4, 1.7, 2.0, and 2.2 times compared to that of AS CK. With the increase in pressure, the soil moisture content in the respective treatment group was generally higher than that of the control group. In the range of 0.02–0.06 bar, the average soil moisture content of MS 2% and AS 2% treatment groups increased by 18% and 19% compared with their respective control groups. In the range of 0.08–3.0 bar, the
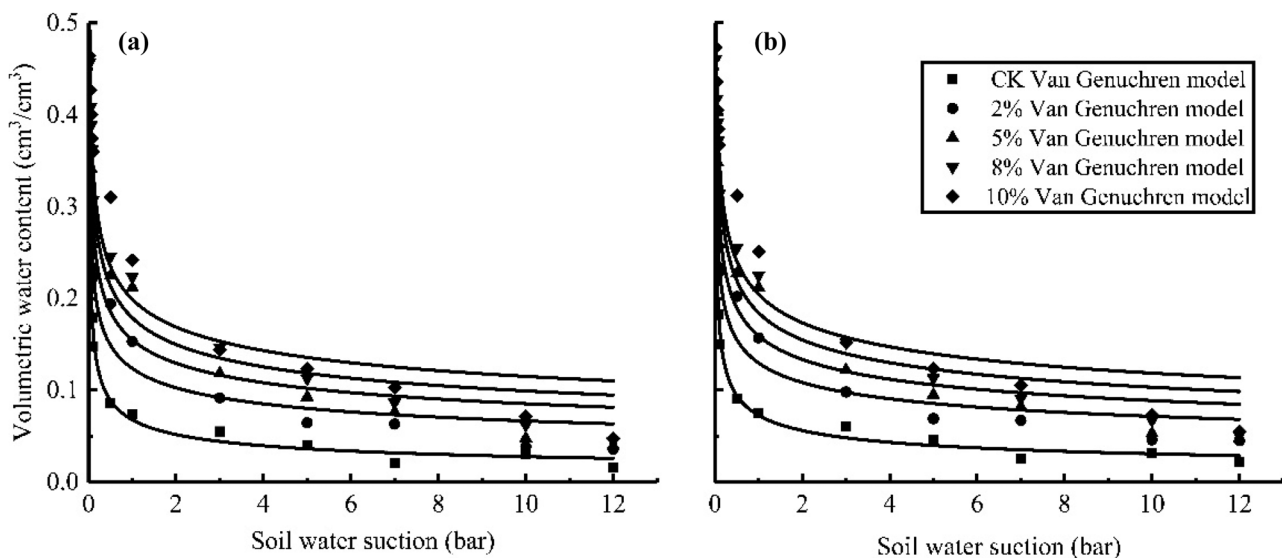

Fig. 3 Soil moisture characteristic curves under different carbon ratios. **a** The molded soil; **b** The acidified soil

increase was 64% and 66%, and in the range of 5.0–12.0 bar, the increase was 82 and 88%, respectively. These results showed that under the same soil water suction pressure, the addition of biochar to the soil effectively increased the soil water content indicating the good water retention characteristics of biochar. With the increase in soil water suction, the biochar treatment group always remained better than the control group. This can be attributed to the physical structure of biochar. Rich pore structure and high specific surface area of biochar strongly improve soil adsorption inhibiting water loss that effectively maintains the soil moisture (Sorrenti et al. 2016).

3.3 Effect of biochar on vertical infiltration of soil

The vertical infiltration of acidified soil water is an important part of water circulation and transfer (Su et al. 2018). The data for vertical infiltration rate and infiltration time of acidified soil were fitted with the Kostiakov infiltration model by Origin software, as in Eq. (4); the correlation coefficient R^2 of the fitting is 0.94. The cumulative infiltration amount and infiltration time showed a quadratic polynomial relationship, and Eq. (5) was fitted by Origin software with an average correlation coefficient R^2 of 0.97. The experimental results are shown in Table 4.

The data chart of vertical water infiltration rate of acidified soil with infiltration time is shown in Fig. 4. It can be seen that the changing trend of each treatment is almost the same. In the first 10 min of infiltration time, the infiltration rate dropped rapidly and then decreased slowly until became stable. In the end, both soil samples showed that a higher carbon ratio led to a lower infiltration rate, that is, 10% < 8% < 5% < 2% < CK. MS showed a decrease by 43, 38, 32, and 26%, and AS showed a decrease by 41, 38, 30, and 27%, showing significant differences between groups ($p < 0.05$). Compared with AS, the overall soil vertical infiltration rate was lower for MS; the proportion of decrease in infiltration rate after adding biochar was more prominent.

The change in vertical infiltration of soil with infiltration time is shown in Fig. 5. With the extension of infiltration time, the vertical infiltration of acidified soil increased continuously. The increase was inversely proportional to the amount of biochar. At the end of the infiltration experiment, the vertical infiltration of MS 2%, MS 5%, MS 8%, and MS 10% was 48, 33, 28, and 23% of MS CK, and that of AS 2%, AS 5%, AS 8%, and AS 10% was 50, 34, 29, and 25% of AS CK ($p < 0.05$). Biochar addition remarkably improved the vertical infiltration rate and infiltration amount of the soil. It seems that biochar reduced the vertical infiltration rate and infiltration rate of soil by increasing the soil water content. This is consistent with the water characteristic curve of soil showing great potential for water and fertilizer retention. Barrios et al. (2019) also confirmed through experiments that a higher carbon content increases this effect. Meanwhile, considering the soil bulk density, porosity, volume water content, vertical infiltration rate, and infiltration amount, the influence of biochar on MS characteristics was obvious and representative of real acidic soils, suggesting MS suitability for indoor small-scale exploratory experiments.

To explore the influence of biochar addition on the structure of acidified soil water retention capacity, two kinds of soils before and after improvement for the 10% treatment groups were collected to compare the changes in soil aggregates by soil agglomerate structure analyzer (LBF-100, DEAUPOS SCIENTIFIC, China). Soil aggregates are the basic constituent units of soil, and their content and stability play an important role in the soil's ability to retain water and fertilizer. Due to the porous structure, large specific surface area, and abundant organic carbon content of biochar, the formation of soil macroaggregates was promoted, which further improved soil structural stability and physical properties (Shah et al. 2017). To investigate the effect

Table 4 Water vertical permeability parameters of acidified soil at any time under different carbon ratios

| Treatment groups	Kostiakov infiltrating model		R^2	Quadratic polynomial			R^2
	k	a		A	B	C	
MS CK	14.7098a	−0.5737a	0.9398	−0.0031a	0.6977a	6.0791a	0.9736
MS 2%	11.5382b	−0.5983a	0.9407	−0.0013a	0.2967b	5.0695b	0.9532
MS 5%	10.2477c	−0.5924a	0.9397	−0.0009a	0.2161c	3.7561c	0.9544
MS 8%	9.3776d	−0.5734a	0.9385	−0.0004a	0.1347d	3.0310d	0.9526
MS 10%	8.5931e	−0.5662a	0.9411	−0.0004a	0.1288e	2.0787e	0.9629
AS CK	15.0793a	−0.5470bc	0.9576	−0.0031a	0.7187a	5.5358a	0.9871
AS 2%	9.0597b	−0.5697c	0.9472	−0.0013a	0.3133b	4.6392b	0.9699
AS 5%	5.5730c	−0.4202abc	0.9464	−0.0010a	0.2284c	3.4376c	0.9676
AS 8%	3.4544d	−0.2928ab	0.9332	−0.0004a	0.1445d	2.7771d	0.9672
AS 10%	2.4123e	−0.2075a	0.9538	−0.0004a	0.1357e	1.9016e	0.9799
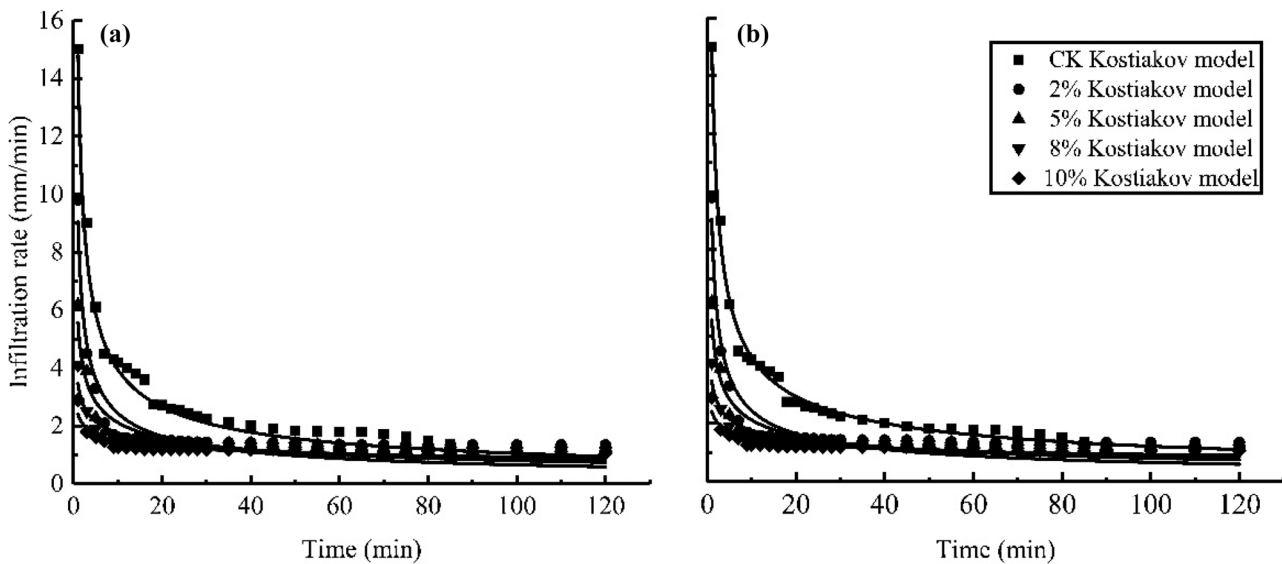
Fig. 4 Effect of biochar on vertical infiltration rate of soil under different carbon ratios. **a** The molded soil; **b** The acidified soil

of biochar on acidified soil aggregation, the 10% treatment groups were selected for showing the best improvement effect. The changes in the contents of water-stable aggregates and microaggregates are shown in Fig. 6. Before the biochar addition, the large water-stable aggregates were mostly of small size (< 0.5 mm); MS and AS accounted for 86 and 63% of the total aggregates. The microaggregates were mostly large in size (0.05–0.25 mm), 175 and 541 g/kg in MS and AS, respectively. Biochar mixing into the two soils made the obvious structural change to the soil after improvement. The

proportion of water-stable macroaggregates with particle size > 1 mm increased by 7.1% in MS. In AS, water-stable macroaggregates with particle size > 0.25 mm increased by 35%. The content of microaggregates with different particle sizes increased in both soils, with an overall increase of 332 and 218 g/kg, respectively. This change enhanced the soil water adsorption capacity improving the water retention capacity. In general, microaggregation affects the physical properties of the soil improving microbial proliferation, ion fixation, and nutrient release.
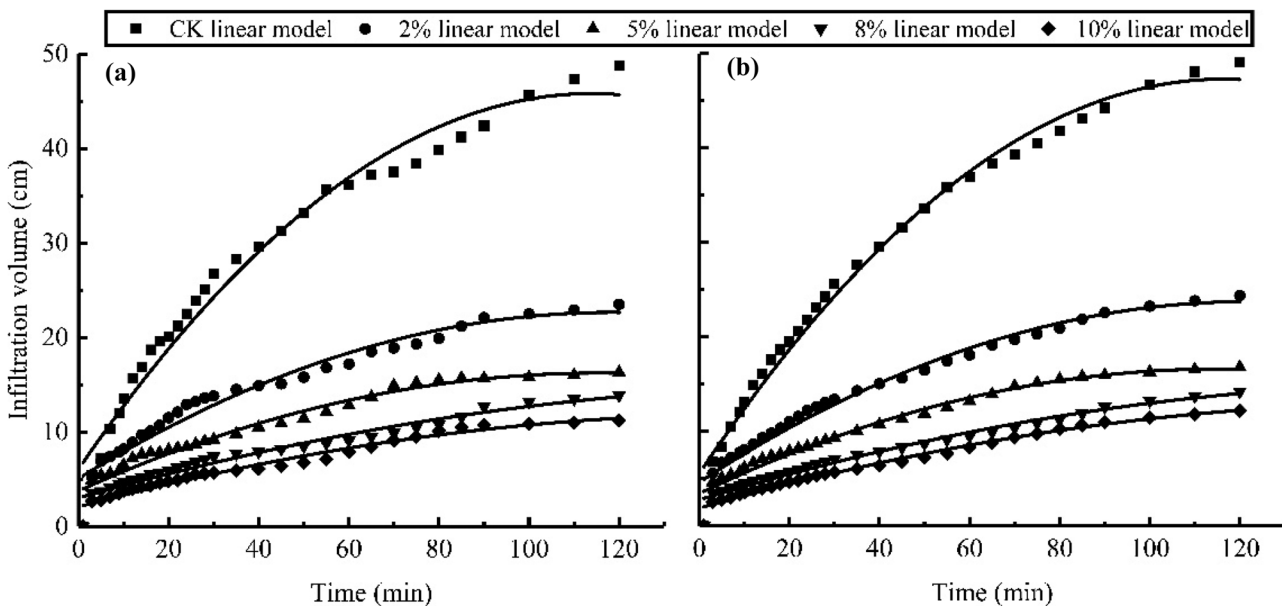

Fig. 5 Effect of biochar on vertical infiltration of soil under different carbon ratios. **a** The molded soil; **b** The acidified soil
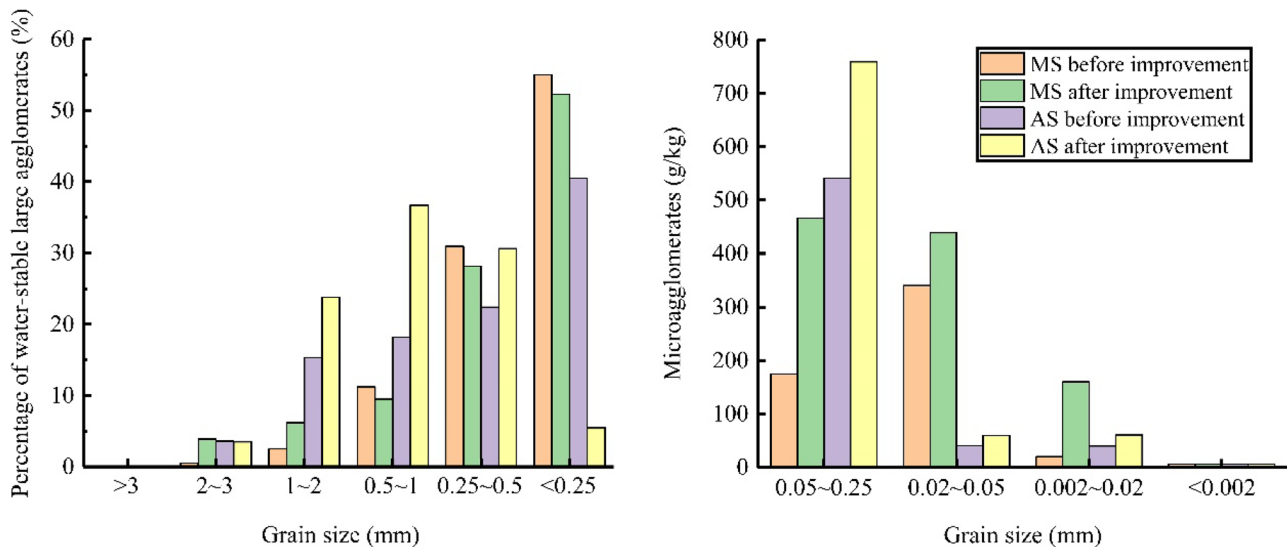
Fig. 6 Change in the proportion of water-stable macroaggregates and microaggregates before and after the addition of biochar. MS means the molded soil; AS means the acidified soil

4 Conclusions

The biochar addition improved the bulk density and porosity of acidified soil. This effect showed a positive correlation with the applied amount of biochar. Soil moisture characteristic curves showed a rapid decrease in soil moisture content in the range of low soil water suction and then became stable at soil water suction > 1 bar. Higher carbon ratios lead to higher soil moisture. We found no significant difference between MS and AS at the same soil water suction.

The rich oxygen-containing functional groups, strong hydrophilicity, and the high specific surface area of biochar provide good water retention capacity to acidified soil, and improve the physicochemical properties of acidified soil. Experiments showed that the vertical infiltration rate and infiltration volume decreased with an increase in biochar dosage and infiltration time. Meanwhile, biochar treatment increased the content of water-stable macroaggregates and microaggregates. Biochar acts as a soil binder. In addition, we found only small differences between the prepared MS and AS, indicating its suitability for small-scale, routine indoor exploratory experiments.

Mechanistically, the application of biochar to acidified soils effectively improved the soil's internal structure and in turn soil water retention capacity. These results provide a basis for further research into the effects of biochar on ion migration in acidified soils in the leached state.

Declarations

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