Effects of mixed-based biochar on water infiltration and evaporation in aeolian sand soil (Postprint)

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Abstract

Abstract: Aeolian sandy soil in mining areas is characterized by intense evaporation and poor water retention capacity. This study was designed to identify a suitable biochar application method to improve soil water infiltration and minimize soil water evaporation for aeolian sandy soil. Using an indoor soil column method, we investigated the effects of three application patterns (A (0–20 cm was a mixed sample of mixed-based biochar and soil), B (0–10 cm was a mixed sample of mixed-based biochar and soil and 10–20 cm was soil), and C (0–10 cm was soil and 10–20 cm was a mixed sample of mixed-based biochar and soil)), four application amounts (0% (control, CK), 1%, 2%, and 4% of mixed-based biochar in dry soil), and two particle sizes (0.05–0.25 mm (S1) and <0.05 mm (S2)) of mixed-based biochar on water infiltration and evaporation of aeolian sandy soil. Five infiltration models (the Philip, Kostiakov, Horton, USDA-NRCS [United States Department of Agriculture-Natural Resources Conservation Service], and Kostiakov-Lewis models) were used separately to fit the relationship between cumulative infiltration and time. Compared with CK, the application of mixed-based biochar significantly reduced cumulative soil water infiltration. Under application patterns A, B, and C, the higher the application amount and the finer the particle size, the lower the migration velocity of the wetting front. At the same application amount, cumulative soil water infiltration was lowest under application pattern A. Using 10-minute infiltration as an example, the reductions in cumulative soil water infiltration under treatments A2%(S2), A4%(S1), A4%(S2), A1%(S1), C2%(S1), and B1%(S1) exceeded 30%, which satisfied the hydraulic parameter requirements of loess soil suitable for plant growth. The five infiltration models fit well for treatments with application pattern C and S1 particle size (R2>0.980), but the R2 values of the Horton model exceeded 0.990 for all treatments (except for treatment B2%(S2)). All treatments reduced cumulative soil water infiltration compared with CK, except for B4%(S2). At the same application amount, the difference in cumulative soil water evaporation between application patterns A and B was small. Treatments with application pattern C and S1 particle size resulted in greater reductions in cumulative soil water evaporation. The reductions in cumulative soil water evaporation under treatments C4%(S1), C4%(S2), C2%(S1), and C2%(S2) exceeded 15.00%. Therefore, applying 2% of mixed-based biochar with S1 particle size to the underlying layer (10–20 cm) could improve soil water infiltration while minimizing soil water evaporation. Moreover, application pattern was the main factor affecting soil water infiltration and evaporation. Furthermore, there were interactions among the three influencing factors in the infiltration process (application amount×particle size with the most important interaction), while there were no interactions among them in the evaporation process. The results of this study may contribute to the rational application of mixed-based biochar in aeolian sandy soil and the resource utilization of urban and agricultural wastes in mining areas.

Full Text

Preamble

Effects of Mixed-Based Biochar on Water Infiltration and Evaporation in Aeolian Sandy Soil

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Abstract: Aeolian sandy soil in mining areas exhibits intense evaporation and poor water retention capacity. This study was designed to identify a suitable biochar application method to improve soil water infiltration while minimizing evaporation in aeolian sandy soil. Using indoor soil column experiments, we investigated the effects of three application patterns (A: 0–20 cm mixed layer of biochar and soil; B: 0–10 cm mixed layer with 10–20 cm pure soil; C: 0–10 cm pure soil with 10–20 cm mixed layer), four application amounts (0% [control, CK], 1%, 2%, and 4% biochar in dry soil), and two particle sizes (0.05–0.25 mm [S1] and <0.05 mm [S2]) of mixed-based biochar on water infiltration and evaporation. Five infiltration models (Philip, Kostiakov, Horton, USDA-NRCS, and Kostiakov-Lewis) were used to fit cumulative infiltration over time. Compared with CK, biochar application significantly reduced cumulative soil water infiltration.

Under patterns A, B, and C, higher application amounts and finer particle sizes resulted in slower wetting front migration. For a given application amount, pattern A produced the lowest cumulative infiltration. Using 10-minute infiltration as an example, treatments A2%(S1), A4%(S1), A4%(S2), A1%(S1), C2%(S1), and B1%(S1) reduced cumulative infiltration by more than 30%, meeting the hydraulic parameter requirements for loess soils suitable for plant growth. While all five models performed well for pattern C with S1 particle size ($R^2 > 0.980$), the Horton model achieved $R^2 > 0.990$ for all treatments except B2%(S2). Except for B4%(S2), all treatments reduced cumulative infiltration compared with CK. With the same application amount, the difference in cumulative evaporation between patterns A and B was small.

Treatments with pattern C and S1 particle size caused greater reductions in cumulative evaporation. The reductions under C4%(S1), C4%(S2), C2%(S1), and C2%(S2) exceeded 15.00%. Therefore, applying 2% mixed-based biochar with S1 particle size to the subsurface layer (10–20 cm) can improve infiltration while minimizing evaporation. Application pattern was the main factor affecting both processes. Significant interactions existed among the three factors during infiltration (application amount × particle size being the most important), whereas no interactions occurred during evaporation. These results contribute to rational biochar application in aeolian sandy soil and resource utilization of urban and agricultural wastes in mining areas.

Keywords: biochar; water infiltration; water evaporation; aeolian sand soil; mining areas

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1 Introduction

Soils in most arid and semi-arid regions worldwide are characterized by high sand content and low organic matter, which harm their physical and chemical properties. These soils feature high infiltration rates, low water holding capacity, intense evaporation, and low fertility and organic matter content, leading to poor water supply and utilization efficiency (Alaa et al., 2017). Low soil organic matter content generally results in weak water holding capacity and poor soil structure (Breus et al., 2014). Studies have shown that adding organic and inorganic amendments such as biochar can improve soil physical and chemical properties (Tang et al., 2015; Basanta et al., 2017; Zhou et al., 2020).

Recent research indicates that biochar produced from pyrolysis of organic waste offers an alternative amendment with porous structure, large specific surface area, and abundant functional groups (Wang et al., 2021a, b), which affect soil bulk density, porosity, aggregation, and hydraulic properties (Lehmann, 2007; Lehmann et al., 2011; Ahmad et al., 2012; Kinney et al., 2012; Li, 2019).

Biochar can reduce soil bulk density (Laird et al., 2010; Githinji, 2013), increase porosity (Tammeorg et al., 2014), alter aggregate number and stability (Mukherjee et al., 2014; Zhang et al., 2015), and influence hydraulic properties (Wang et al., 2015; Bao, 2020; Razzaghi et al., 2020). However, these effects depend on various factors including application pattern, amount, particle size, biochar type, and soil type (Qi et al., 2014; Xie et al., 2016; Wang et al., 2018; Wang et al., 2019). Current research focuses on how application patterns and amounts affect soil hydraulic properties, finding that appropriate biochar application can improve infiltration capacity and that different application patterns significantly impact water infiltration and evaporation (Burrell et al., 2016; Li et al., 2016, 2018; Lim et al., 2016; Liu et al., 2016). However, the effects of biochar particle size on soil hydraulic characteristics remain uncertain (Xie et al., 2016; Wang et al., 2019), with most studies focusing on sizes above 0.25 mm and few examining smaller particles (Wang et al., 2019; Kim et al., 2021). Consequently, the combined effects of application pattern, amount, and particle size on infiltration and evaporation are unclear. Moreover, in arid and semi-arid regions, it remains uncertain whether suitable combinations of these factors can significantly improve infiltration while effectively reducing evaporation from aeolian sandy soil, particularly in ecologically degraded mining areas. Exploring this issue is crucial for determining whether biochar can improve soil quality in water-scarce mining environments. Additionally, while biochar feedstocks are typically wood and straw, sewage sludge from urban wastewater treatment plants contains substantial organic matter and represents a suitable raw material. Pyrolytic thermal conversion reduces sludge volume, eliminates pathogens, and enables safe disposal and resource utilization (Sun et al., 2018).

This study prepared mixed-based biochar through co-pyrolysis of urban domestic sludge and agricultural straw. Using one-dimensional vertical infiltration experiments, we examined the effects of mixed-based biochar on water infiltration and evaporation characteristics of aeolian sandy soil from a Chinese mining area. We established three application patterns, four application amount gradients, and two particle size ranges in a full-factorial design with 19 treatments. Our objectives were to: (1) explore how application pattern, amount, and particle size of mixed-based biochar affect soil water infiltration and evaporation; and (2) identify the optimal combination to improve infiltration while minimizing evaporation in aeolian sandy soil. The results will contribute to rational biochar application in aeolian sandy soil and resource utilization of urban and agricultural wastes in mining areas.

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2 Materials and Methods

2.1 Study Area

Aeolian sandy soil was collected from the collapse area of Daliuta Coal Mine (110°26 N, 39°29 E) in Daliuta Town, Shenmu County, Shaanxi Province, China.

The mining area belongs to the Shendong mining region, located at the transition zone between the southern edge of the Mu Us Sandy Land and the northern edge of the Loess Plateau, with poor environmental conditions and fragile ecology. Annual precipitation ranges from 251.3 to 646.5 mm, while evaporation reaches 1788.4 mm. Precipitation is highly variable and concentrated in summer, with an average annual temperature of approximately 7.0°C.

2.2 Sample Collection

Soil samples were collected from 14 sampling points in the Shendong Central Coal Mine (including Shangwan, Daliuta, and Halagou) at 0–50 cm depths in July 2020 using the biological community sampling method. After removing impurities, samples were air-dried in darkness and ground through a 2-mm sieve for analysis. A laser particle size analyzer (Malvern 2000, Mettler Toledo, Malvern, USA) determined the mechanical composition: sand 85.52%, silt 14.44%, and clay 0.04%. Other physical and chemical properties are shown in Table 1.

Sludge was obtained from the Gaobeidian Sewage Treatment Plant in Beijing. After air-drying at room temperature, it was crushed, passed through a 60-mesh screen, and stored in a desiccator to prevent moisture adsorption. Corn stalks were collected from Beijing suburbs, sun-dried for 10 days, chopped, passed through a 60-mesh screen, and stored in a desiccator. Mixed-based biochar was prepared by mixing sludge and corn stalks at a 7:3 ratio (w/w) and carbonizing at 550°C with a 120-min residence time (Table 2).

Table 1. Physical and chemical properties of tested aeolian sandy soil

Property	Value
Electrical conductivity (S/cm)	[value]
Cation exchange capacity (cmol/kg)	[value]
Total carbon (g/kg)	[value]
Soil organic carbon (g/kg)	[value]
Total nitrogen (g/kg)	[value]
Available nitrogen (mg/kg)	[value]
Total phosphorus (g/kg)	[value]
Available phosphorus (mg/kg)	[value]
Number of microorganisms ($×10^{4}$/g)	[value]

Table 2. Physical and chemical properties of mixed-based biochar

Property	Value
Cation exchange capacity (cmol/kg)	[value]
BET surface area (m^2/g)	[value]
Carbon (g/kg)	[value]
Hydrogen (g/kg)	[value]

Property	Value
Nitrogen (g/kg)	[value]
Oxygen (g/kg)	[value]
Phosphorus (mg/kg)	[value]
Potassium (mg/kg)	[value]
Zinc (mg/kg)	[value]
Copper (mg/kg)	[value]
Chromium (mg/kg)	[value]
Average pore size (nm)	[value]
Pore volume (cm^3/g)	[value]

2.3 Experimental Design

The experiment employed a full-factorial design with three application patterns, four application amounts, and two particle sizes of mixed-based biochar, totaling 19 treatments (Table 3). Each treatment was replicated three times.

Application patterns: 1. **Pattern A:** 0–20 cm mixed layer of biochar and soil 2. **Pattern B:** 0–10 cm mixed layer with 10–20 cm pure soil 3. **Pattern C:** 0–10 cm pure soil with 10–20 cm mixed layer

Application amounts: 0% (CK), 1%, 2%, and 4% biochar in dry soil

Particle sizes: S1 (0.05–0.25 mm) and S2 (<0.05 mm)

Based on pre-filling tests, the bulk densities of soil and biochar were 1.56 and 0.40 g/cm^3, respectively. Since biochar reduces soil bulk density, we maintained constant filling volume. Bulk densities for soils with 1%, 2%, and 4% biochar were 1.52, 1.48, and 1.40 g/cm^3, respectively.

Table 3. Full-factorial design experiment

Treatment	Application Pattern	Application Amount	Particle Size
A1%(S1)	A	1%	S1
A1%(S2)	A	1%	S2
A2%(S1)	A	2%	S1
A2%(S2)	A	2%	S2
A4%(S1)	A	4%	S1
A4%(S2)	A	4%	S2
B1%(S1)	B	1%	S1
B1%(S2)	B	1%	S2
B2%(S1)	B	2%	S1
B2%(S2)	B	2%	S2
B4%(S1)	B	4%	S1
B4%(S2)	B	4%	S2
C1%(S1)	C	1%	S1

Treatment	Application Pattern	Application Amount	Particle Size
C1%(S2)	C	1%	S2
C2%(S1)	C	2%	S1
C2%(S2)	C	2%	S2
C4%(S1)	C	4%	S1
C4%(S2)	C	4%	S2
CK	-	0%	-

2.4 Experimental Procedures

2.4.1 Soil Column Preparation The soil column consisted of a transparent acrylic tube (7.0 cm inner diameter, 30.0 cm height). Three layers of gauze sand and one gravel layer were placed at the bottom to prevent soil particle loss. Vaseline was applied thinly and evenly to the inner wall to minimize wall effects. Soil was added in 5.0 cm increments, with each layer compacted separately. Biochar and soil samples were calculated, weighed, mixed uniformly, loaded into the column, and carefully "flashed" at layer interfaces to ensure close contact and avoid delamination. After assembly, the surface was smoothed with a scraper.

2.4.2 Determination of Soil Water Infiltration and Evaporation A one-dimensional constant-head vertical ponding infiltration method measured infiltration parameters using a Mariotte bottle connected to the soil column (Fig. 2). The head height was maintained at 2.5 cm. After infiltration began, the descending depth of the wetting front and water level in the Mariotte bottle were recorded continuously. Recording stopped when the wetting front reached the column bottom, but water supply continued until saturation. All columns were then placed indoors for evaporation testing under stable conditions (average temperature 23.4°C, relative humidity 22%). Daily evaporation losses were measured at 17:00 LST using an electronic scale for 53 days. Daily evaporation was calculated as:

$$E = \frac{10M_d}{\pi r^2}$$

where E is daily evaporation (mm), M_d is daily mass change (g), and r is the column' s inner radius (cm).

Fig. 2. Schematic diagram of the infiltration and evaporation measurement apparatus

2.5 Data Processing and Analysis

All data represent averages of replicate measurements. Excel 2016 processed the data, Origin 2018 created figures, and SPSS 20.0 simulated infiltration parameters and performed statistical analyses. Least significant difference (LSD) tests assessed significance at $P < 0.05$.

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3 Results

3.1 Effects on Wetting Front Migration

One-dimensional vertical wetting front movement increased gradually with infiltration time across all treatments, though times to reach the column bottom varied. Compared with CK, all treatments except C1%(S1) slowed wetting front migration. Under patterns A and B, higher application amounts and finer particle sizes reduced migration speed. The slowing effect decreased in the order: 4%(S2) > 2%(S2) > 4%(S1) > 1%(S2) > 2%(S1) > 1%(S1) > CK. The 4%(S2) treatment showed significantly greater mitigation than any other treatment (Fig. 3). Under pattern C, the descending order was: 4%(S2) > 2%(S2), 4%(S1), and 2%(S1) > 1%(S2) and CK > 1%(S1), with 4%(S2) remaining the most effective combination.

In summary, higher biochar amounts and finer particle sizes under patterns A, B, and C more pronouncedly slowed wetting front migration. At 1% application with S1 particle size, patterns A, B, and C all reduced migration speed in the order A > B > C. At 1% with S2, patterns A and B had similar slowing effects, while pattern C promoted migration. At 2% and 4% application, all patterns slowed migration, with patterns A and B showing significantly greater effects than pattern C.

Considering all factors, only C1%(S1) promoted infiltration at 10 minutes. All other treatments had smaller wetting front migration distances than CK (significant at $P < 0.05$), increasing water absorption and slowing downward water movement, particularly for A4%(S2).

The wetting front-time relationship followed a power function:

$$F = pt^v$$

where F is the wetting front depth, p and v are empirical parameters, and t is time. Fitting results (Table 4) showed good simulation of moisture peak migration across treatments ($R^2 > 0.911$, $P < 0.05$). No clear pattern emerged for patterns A and B, though all reduced migration compared with CK, with 4%(S2) showing the strongest effect. Under pattern C, p increased slowly then sharply with application amount, while power index v decreased significantly with increasing amount (except B4%(S2)), being lower for finer particle sizes. This indicates that application pattern, amount, and particle size significantly impacted the initial matrix potential-dominated infiltration process and attenuated the wetting front.

Table 4. Fitting results for wetting front and infiltration time

Treatment	Pattern A	Pattern B	Pattern C
	p	v	R^2
1%(S1)	[value]	[value]	[value]
1%(S2)	[value]	[value]	[value]
2%(S1)	[value]	[value]	[value]
2%(S2)	[value]	[value]	[value]
4%(S1)	[value]	[value]	[value]
4%(S2)	[value]	[value]	[value]

3.2 Effects on Cumulative Soil Water Infiltration

Cumulative infiltration represents the total water volume entering a unit surface area over time and integrates the infiltration rate function. Before stabilization, it characterizes infiltration capacity. Figure 4 shows that cumulative infiltration increased over time, but treatment effects varied. Except for B4%(S2), all treatments reduced cumulative infiltration compared with CK.

For S1 particle size under patterns A and C, the inhibitory effect first strengthened then weakened with increasing application amount. For S2 particle size, the effect remained unchanged then increased. The overall order was: 2%(S1) < 4%(S2) < 1%(S1) < 4%(S1) < 1%(S2) < 2%(S2) < CK. For S1 under pattern B, inhibition first weakened then stabilized, while for S2, it remained constant then weakened sharply. The 1%(S1) treatment showed the best inhibition, whereas 4%(S2) promoted rather than inhibited infiltration. Other treatments had minor effects following the order: 1%(S1) < 1%(S2) < 2%(S2) and 4%(S1) < 2%(S1) < CK < 4%(S2).

At the same application amount, patterns affected infiltration differently. At 1% application, the order was A < B < C, with S1 reducing cumulative infiltration. For any application amount, pattern A produced lower cumulative infiltration than patterns B and C, and S1 particle size yielded lower values than S2.

Using 10-minute infiltration as an example, only B4%(S2) showed higher infiltration (13.5 cm) than CK (10.4 cm) ($P < 0.05$), representing a 30% increase that promoted infiltration. The complete ranking was: A2%(S1) < A4%(S1) < A1%(S1) < A4%(S2) < C2%(S1) < B1%(S1) < A1%(S2) < C4%(S2) < B1%(S2) < C4%(S1) < C1%(S1) < A2%(S2) < C1%(S2) < B2%(S2) < B4%(S1) < B2%(S1) < C2%(S2) < CK. Treatments A2%(S1), A4%(S1), A1%(S1), A4%(S2), C2%(S1), and B1%(S1) achieved >30% reduction, meeting loess soil hydraulic requirements for plant growth.

Fig. 4. Effects of application patterns, amounts, and particle sizes on cumulative infiltration: (a) pattern A, (b) pattern B, (c) pattern C

3.3 Effects on Infiltration Parameters

Several theoretical and empirical models have been developed to simplify infiltration concepts for field applications (Table 5). Following Liu et al. (2010), we selected the Philip model as the sole theory-based model due to the implicit functional relationship in the Green-Ampt model that may introduce errors.

Table 5. Infiltration models used to determine biochar effects

Model	Equation	Parameters
Philip (1957)	$I = St^{0.5} + At$	S = sorptivity (cm/s$^{0}\cdot{}^{5}$), A = stable permeability (cm/s)
Kostiakov (1932)	$I = Kt^n$	$K > 0$, $0 < n < 1$ (dimensionless)
Horton (1941)	$I = a + (b - a)(1 - e^{-ct})$	a = initial rate, b = final rate (cm/s), c = empirical constant
USDA-NRCS (1974)	$I = a''t^{b''}$	a'', b'' = dimensionless constants
Kostiakov-Lewis (Mezencev, 1948)	$I = K't^{b'} + A't$	$K' > 0$, $0 < b' < 1$, $A' > 0$

Table 6 presents estimated parameter values. Different infiltration modes existed for the five models across treatments. Parameters K (saturated hydraulic conductivity), b (final infiltration rate), a'', and K' were very similar, sharing physical meanings comparable to Philip' s sorptivity. K and K' were more significant than a'', consistent with Wang et al. (2017).

Ninety-five percent of R^2 values exceeded 0.900, indicating excellent model performance. The Horton model performed best ($R^2 > 0.990$ for all treatments except B2%(S2)), matching Duan et al. (2011). Fitting degrees were higher for S1 than S2, and pattern C was significantly better than patterns A and B.

Using pattern C as an example, the Kostiakov model' s K values were less than CK for all biochar treatments, indicating that biochar amount and particle size inhibited initial infiltration. However, K values first decreased then increased with application amount, showing that excessive biochar negatively affected infiltration capacity. No consistent pattern emerged for particle size effects.

Philip model fitting revealed that sorptivity and stable infiltration rates differed significantly from CK across treatments, confirming that amount and particle size affected the infiltration process. All biochar treatments had lower sorptivity than CK, indicating reduced capillary suction and weaker liquid absorption/release capacity. The influence patterns varied inconsistently with application amount and particle size. However, amount and particle size significantly increased infiltration rate and improved performance, with C1%(S2) and C2%(S2) being most effective.

Table 6. Parameters for the five infiltration models

Treatment	Philip	Kostiakov	Horton	USDA-NRCS	Kostiakov-Lewis
	S	A	R^2	K	n
A1%(S1)	1.481	0.145	0.976	1.145	0.730
A1%(S2)	1.684	0.149	0.969	1.164	0.760
A2%(S1)	1.621	0.042	0.957	1.072	0.700
A2%(S2)	2.148	0.010	0.928	1.683	0.600

Note: Figure translations are in progress. See original paper for figures.

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