Land Degradation & Development

WILEY

RESEARCH ARTICLE OPEN ACCESS

Effects of Biochar on Freezing Temperature and Unfrozen Water Content in Pb-Contaminated Seasonally Frozen Soils: Implications for Mitigating Land Degradation

Shanbo Han[1] | Yaling Chou[1] | Wei Cao[2] | Fupeng Yang[1] | Yu Wang[1] | Xunkun Guo[1]

[1]School of Civil Engineering, Lanzhou University of Technology, Lanzhou, Gansu, China | [2]School of Spatial Planning and Design, Hangzhou City University, Hangzhou, China

Correspondence: Wei Cao (caowei@hzcu.edu.cn)

Received: 21 February 2026 | **Revised:** 28 July 2026 | **Accepted:** 29 July 2026

Keywords: biochar | freezing temperature | lead contamination | seasonally frozen soil | unfrozen water content

ABSTRACT

Freeze–thaw processes are important drivers of land degradation in cold regions, and soil freezing temperature and unfrozen water content are key parameters for characterizing soil hydrothermal conditions and water phase transitions during freezing. However, in the context of heavy metal pollution, there remains a lack of systematic understanding regarding biochar's (BC) regulatory role in the freezing behavior of seasonally frozen soil and the dynamic changes in unfrozen water content. Based on freezing and freeze–thaw experiments, this study investigated the effects of biochar on soil freezing temperature and unfrozen water content under various conditions, with the results subjected to statistical analysis. The findings showed that dry density and Pb content exert bidirectional regulatory effects on the freezing temperature and unfrozen water content of biochar-amended soils. Under low initial water conditions, the biochar addition ratio is the primary factor affecting soil unfrozen water content. Specifically, 1% and 3% biochar additions significantly increase soil unfrozen water content; however, as biochar content increases further, its enhancing effect gradually diminishes. Under high initial water content, soil unfrozen water content is jointly regulated by biochar content, initial water content, and lead content. Correlation analysis indicated that lead content and initial water content exhibited significant positive correlations with unfrozen water content, while biochar content showed a weak negative correlation. ANOVA further revealed a significant interaction between biochar content and initial water content, indicating a synergistic regulatory effect, whereas the interaction between biochar and lead content was not significant. These findings reveal the influence patterns of biochar under multifactor coupling on the freezing processes of seasonally frozen soil and changes in moisture status. The results provide a theoretical basis for biochar-assisted remediation of Pb-contaminated soils and the mitigation of land degradation in seasonally frozen regions.

1 | Introduction

Seasonally frozen soil experiences repeated freeze–thaw cycles over extended periods, which represent a key driving factor of land degradation in cold regions (Liu et al. 2024). During these cycles, the repeated phase transitions of soil water between freezing and thawing drive water migration, ice crystal growth, and soil particle rearrangement within the soil matrix. These processes weaken soil structural stability, alter pore characteristics, and reduce soil resistance to erosion (Zhang et al. 2024; He et al. 2023). Long-term freeze–thaw disturbances not only accelerate the decomposition of soil organic matter, intensify soil

Shanbo Han and Wei Cao contributed to the work equally and should be regarded as co-first authors.

erosion, and degrade soil quality, but also modify the chemical forms and migration-transformation processes of contaminants in soils. In particular, freeze–thaw processes can promote the mobilization of heavy metals, thereby increasing their ecological risks and further exacerbating land degradation and ecosystem vulnerability in cold regions (Zhang et al. 2026; Wang et al. 2021). Therefore, a comprehensive understanding of the effects of freeze–thaw processes on soil hydrothermal state and contaminant environmental behavior is essential for the restoration of degraded land and the maintenance of ecosystem functions in cold regions.

Soil freezing temperature is a critical parameter that characterizes the phase transition of soil water during freezing and thawing processes. It serves as an essential indicator for assessing changes in soil hydrothermal state and the degree of soil freezing (Bing and Ma 2011). However, soil freezing does not result in the complete conversion of liquid water into ice. Owing to the adsorption of soil particle surfaces, capillary effects, and interfacial energy interactions, a certain amount of water remains in a liquid state within frozen soils, which is defined as unfrozen water (Cui et al. 2024). The unfrozen water content not only governs water migration and energy exchange processes during soil freezing, but also serves as an essential factor in maintaining ecosystem functions in cold regions. As an important limiting factor for ecosystem productivity in cold regions, soil unfrozen water provides necessary water availability for overwintering microbial activities, root survival of shrubs and herbaceous plants, and vegetation recovery in early spring (He et al. 2023; Nikrad et al. 2016). Furthermore, water migration and ice–water phase transitions during freezing processes can redistribute soil nutrients and particle arrangements, triggering a series of eco-environmental issues, including frost heave, thaw settlement, and soil structural degradation (Zhang et al. 2024; He et al. 2023). Therefore, elucidating the variations in soil freezing temperature and unfrozen water content, as well as their controlling mechanisms, is of great significance for understanding land degradation processes in cold regions and improving soil ecological stability.

Different soil types exhibit distinct variations in freezing temperature and unfrozen water content due to differences in soil structure, particle characteristics, organic matter content, and water conditions (Wan et al. 2015; Cao, Liu, et al. 2024; Meng et al. 2024). As soil temperature continuously decreases, the freezing process of soil water is jointly governed by pore structure, water distribution characteristics, and soil thermal properties (Cui et al. 2024; Wan et al. 2023). Consequently, regulating soil structure and hydrothermal properties has become a key strategy for improving the functions of degraded soils in cold regions. In recent years, biochar, a stable carbon-rich material derived from biomass under oxygen-limited pyrolysis conditions, has attracted increasing attention in soil remediation and degraded land restoration due to its well-developed pore structure, large specific surface area, abundant surface functional groups, and excellent chemical stability (Wu et al. 2025; Liu et al. 2018). Biochar exhibits a strong immobilization capacity for contaminants and can stabilize heavy metal ions in soil through adsorption, complexation, ion exchange, and precipitation, thereby reducing their mobility and bioavailability (Qiu et al. 2021). Meanwhile, biochar can improve soil aggregate structure, optimize pore-size distribution, enhance soil water-holding capacity, and modify soil heat transfer processes, thereby potentially affecting soil freezing processes and water phase transition behavior (Fu et al. 2019, 2023; Bikbulatova et al. 2018). Therefore, biochar is not only an effective material for heavy metal contamination remediation but also a promising strategy for regulating ecological restoration processes in degraded lands in cold regions.

With the expansion of industrial and agricultural activities in cold regions, increasing quantities of heavy metal contaminants have been introduced into soil environments. Among these, lead pollution has attracted considerable attention due to its high toxicity, persistence, and long-term ecological risks (Fang et al. 2025). Once present in soils, Pb can not only alter soil physicochemical properties and microbial ecological functions (Yan, Dong, Wijayawardena, et al. 2019), but also influence contaminant migration behavior under freeze–thaw conditions by modifying soil water distribution patterns and interfacial chemical processes (Wu, Rui, et al. 2022; Zeng et al. 2023). Therefore, investigating the regulatory effects of biochar on soil freezing processes in Pb-contaminated soils is crucial for the remediation of contaminated soils and ecological restoration in cold regions. However, the effects of biochar on soil freezing temperature and unfrozen water content in seasonally frozen soils remain poorly understood. In particular, under heavy metal contamination conditions, the combined effects of biochar, soil water states, and soil structural characteristics on freeze–thaw hydrothermal processes have yet to be systematically elucidated (Li et al. 2022, 2020; Gao et al. 2020).

Previous studies have demonstrated that biochar can effectively regulate soil hydrothermal properties in frozen soils by stabilizing soil temperature variations during freeze–thaw cycles, optimizing pore structures, mitigating freeze–thaw-induced structural damage, and enhancing soil water retention capacity (Fu et al. 2019, 2023). Additionally, several studies have reported that biochar application increases the unfrozen water content in seasonally frozen soils, suggesting that it may delay the freezing process by altering soil water distribution states (Bikbulatova et al. 2018; Ma et al. 2019). However, the effects of biochar on soil freezing behavior are not always consistent, as its performance is jointly influenced by multiple factors, including soil density, initial water content, biochar application rate, and environmental temperature. These interactions may contribute to discrepancies among reported findings (Fu et al. 2019, 2023; Bikbulatova et al. 2018; Ma et al. 2019). Currently, the mechanisms by which biochar regulates freezing temperature and unfrozen water content in seasonally frozen soils under multifactor interactions remain poorly understood. In particular, under Pb-contaminated soil conditions, the effects of biochar on freeze–thaw processes and water phase transition behavior in contaminated soils have not yet been fully elucidated.

In our previous study, we examined the variation patterns of soil freezing temperature under the combined effects of biochar, lead contamination, and initial water content, and conducted statistical analyses to identify their relationships. The results indicated that biochar content was negatively correlated with soil

TABLE 1 | Soil susceptible salt ion content.

Ion type	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	NO_3^-
Ionic mass share (%)	0.007	0.005	0.008	0.004	0.005	0.008	0.002

TABLE 2 | Basic physical and chemical indicators of soil.

ω (%)	ρ_d (g/cm^3)	pH	CEC (mol/kg)	OMC (%)
6.7	1.74	7.85	17.50	16.08

freezing temperature, suggesting that biochar may inhibit the transformation of soil water into ice crystals during the remediation of Pb-contaminated soils by altering soil water distribution and pore structure (Han et al. 2024). However, prior research has primarily focused on the effects of individual factors and has not fully considered the role of soil structural conditions in regulating freezing processes via biochar. Therefore, the present study incorporates soil dry density as an additional influencing factor and systematically investigates variations in soil freezing temperature and unfrozen water content under different conditions of dry density, biochar content, Pb content, and initial water content. The objective of this study is to elucidate the regulatory mechanisms of biochar on freezing behavior and water phase transition processes in seasonally frozen soils under multifactor interactions. The findings offer theoretical insights and technical references for the remediation of Pb-contaminated soils, restoration of degraded lands, and soil and water conservation in cold regions.

2 | Materials and Methods

2.1 | Experimental Materials

2.1.1 | Soil

Loess from a construction site in Qilihe District, Lanzhou City, Gansu Province, China, was selected as the experimental soil. The soil was yellowish-brown and exhibited no distinct stratification. After natural air-drying, it was sieved through a 2 mm standard mesh. Test results of basic physicochemical properties of soils showed: initial water content: 6.7%; maximum dry density: 1.74 g/cm^3, pH: 7.85, cation exchange capacity (CEC): 17.50 mol/kg, and organic matter content (OMC): 16.08%. Among soluble salt ions, the mass fractions of Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, $SO_4{}^{2-}$, and $NO_3{}^-$ were 0.007%, 0.005%, 0.008%, 0.004%, 0.005%, 0.008%, and 0.002%, respectively (Tables 1 and 2).

2.1.2 | Biochar

Corn straw biochar used in the experiment was supplied by an environmental protection technology company in Henan province, China. The production process involved cleaning and air-drying the feedstock, followed by pyrolysis at 500°C under limited oxygen for 2–3 h, and subsequent cooling to room temperature. The biochar contained 42.21% organic carbon (OC), 8.34% nitrogen (N), 2.31% phosphorus (P), and 16.12% potassium (K). Its pH was 9.46, ash content was 7.23%, and the production yield was approximately 3:1 (Table 3). The particle size distribution curves of the loess and biochar are presented in Figure 1.

2.1.3 | Heavy Metal

Lead(II) chloride ($PbCl_2$, purity ≥ 99.5%, batch number Q/12HB 3899-019, Tianjin Kemiou Chemical Reagent Co. Ltd., China) was used as the source of soil Pb contamination.

2.2 | Experiment Design

To discuss the effects of biochar on soil temperature and water under freezing and freeze–thaw conditions, the following test schemes were designed in this experiment (Table 4). First, three dry densities of 1.50, 1.55, and 1.60 g/cm^3 and three biochar contents of 0%, 3%, and 5% were set under the fixed condition of 15% initial water content, aiming to reveal the changes in biochar soil temperature and water under different compaction degrees during soil freezing. Second, under the background of maintaining the same dry density (1.55 g/cm^3) and initial water content (15%), biochar dosing of 0%, 3%, and 5% were set, and Pb contents of 0%, 1%, and 2% were introduced, aiming to preliminarily reveal the influence laws of biochar on the temperature and water of Pb-contaminated soil. Finally, in order to deeply analyze the effect of biochar on the content of unfrozen water in soil with different Pb concentrations, the addition of biochar in the experiment was set at 0%, 1%, 3%, 5%, and 7%, the initial water content was set at 10%, 15%, 20%, 25%, and 30% and the Pb content was set at 0%, 0.5%, 1%, 1.5%, and 2%. In each experiment, the addition amounts of biochar and $PbCl_2$ were accurately calculated and prepared based on their weight percentages relative to the dry mass of the soil.

2.3 | Experimental Procedures

2.3.1 | Soil Preparation

During the soil preparation, the naturally air-dried soil was oven-dried at 105°C until a constant weight was achieved. Subsequently, predetermined masses of the dried soil, corn stalk biochar, and $PbCl_2$ reagent were accurately weighed using an electronic balance. A specific mass of distilled water was used to dissolve the $PbCl_2$. Then the solution was thoroughly and uniformly mixed with the corresponding mass of dry soil. The above mixture was transferred into a sealed bag and stored statically at room temperature for 24 h to obtain soil samples contaminated with a specific Pb concentration. A designated mass of biochar was thoroughly mixed into the Pb-contaminated soil samples. After being sealed and left to stand at room temperature for another 24 h. The soil samples, containing specified amounts of both biochar and Pb, were obtained.

2.3.2 | Compaction and Freezing of Soil Sample

During the soil compaction, the amount of soil to be filled in each layer was accurately calculated to ensure that the height of a single layer is 40 mm after compaction, and the final total height of the soil is 80 mm. During the soil sample compaction process, after the first layer of soil samples was compacted, the temperature sensor and frequency-domain reflection (FDR) sensor were buried at the center of the soil mass. Later, the second layer of soil samples was input and compacted. The top of the column was sealed with plasticine to prevent water evaporation and minimize external thermal disturbance during the experiment. During the freezing process, a series of temperature gradients (2°C, 0°C, −2°C, −5°C, −10°C, and −15°C) were set, and the temperature was kept for 4 h at each target temperature point to ensure the full balance state between phase changes of water and heat transmission in the soil mass. For the thawing phase, the cooling system was switched off, and the samples thawed naturally at laboratory room temperature to simulate a natural thawing process.

2.3.3 | Data Collection and Analysis

Figure 2 is the soil sample freezing process schematic. Temperature and moisture sensors were connected to a multichannel data logger. The logger was programmed to automatically record readings from all sensors at 30-s intervals. Basic data collation and graphical visualization were performed using SPSS 21.0 and Origin 2019 software to clarify the dynamic variation characteristics of soil freezing temperature and unfrozen water content under different biochar dosages, lead contamination levels, initial water contents, and soil dry densities. One-way analysis of variance (ANOVA) was adopted to quantitatively distinguish the significant differences in soil hydrothermal indicators under multifactor coupling conditions. Pearson correlation analysis was further conducted to reveal the correlation strength between each influencing factor (biochar dosage, lead concentration, initial water content) and soil unfrozen water content; interactive effects among multiple variables were also quantified.

3 | Results

3.1 | Effects of Dry Density on Biochar Soil Freezing Temperature and Unfrozen Water Content

From Figure 3a–c, it can be seen that the temperature of the biochar soil changes differently with the increase of soil dry density. When the dry density was 1.50 g/cm^3 (Figure 3a), the temperature in 0% biochar soil decreased the fastest, followed by 5% biochar soil, and 3% biochar soil temperature decreased the slowest. From Figure 3a, it can also be seen that the effects of the three biochar contents used on soil freezing temperature are not obvious. In addition, the differences in the soil temperature drop curves on 0% and 5% biochar during the soil temperature drop were small and almost overlapped. When the dry density was 1.55 g/cm^3 (Figure 3b), the 5% biochar soil temperature decreased the fastest, followed by 3% biochar soil, and the 0% biochar soil temperature decreased the slowest. From Figure 3b, it can be seen that the biochar-free soil has the highest freezing temperature, while the addition of biochar reduces the soil

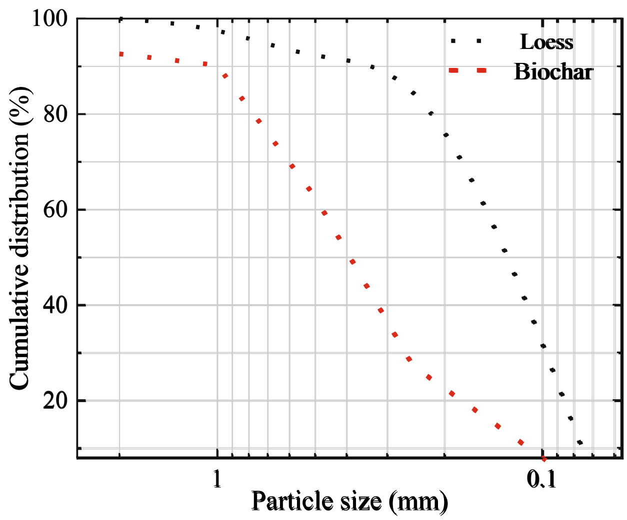

FIGURE 1 | The particle size distribution curve of loess and biochar. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 | Physical–chemical parameters of biochar.

Parameters	Temperature (°C)	OC (%)	N (%)	P (%)	K (%)	pH	Ash (%)	Rate
Numerical value	500	42.21	8.34	2.31	16.12	9.46	7.23	3:1

TABLE 4 | The experimental design for soil freezing temperature and unfrozen water content.

		Variable level			
Soil conditions	Research content	Dry density (g/cm^3)	Biochar (%)	Lead (%)	Initial water content (%)
Dry density and biochar	Freezing temperature and unfrozen water	1.50, 1.55, 1.60	0, 3, 5	—	15
Lead and biochar	Freezing temperature and unfrozen water	1.55	0, 3, 5	0, 1, 2	15
Biochar, lead and initial water content	Unfrozen water	1.55	0, 1, 3, 5, 7	0, 0.5, 1, 1.5, 2	10, 15, 20, 25, 30

freezing temperature. In addition, the soil temperature curves of different biochar contents overlapped during the freezing stabilization stage, and the soil temperature changes were not obvious. At dry density of 1.60 g/cm^3 (Figure 3c), the 5% biochar soil temperature decreased the fastest, followed by 3% biochar soil, and 0% biochar soil decreased the slowest. From Figure 3c, it can be seen that the soil freezing temperature without biochar application is the highest, followed by the 3% biochar soil, and the 5% biochar freezing temperature is the lowest. In addition, there was no significant change in soil temperature with overlapping soil temperature curves with different biochar contents during the freezing stabilization stage, which was similar to the behavior observed in soil with a dry density of 1.55 g/cm^3.

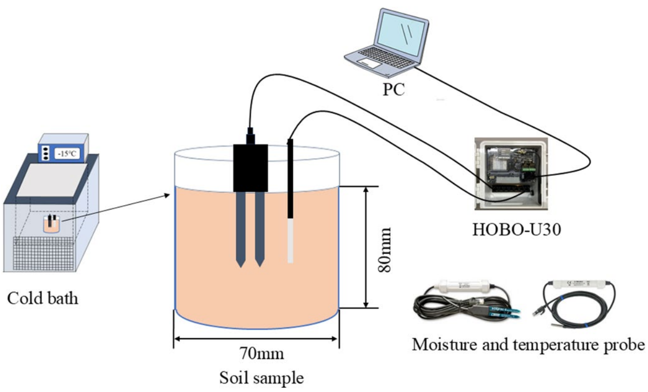

FIGURE 2 | The soil sample freezing process schematic. [Colour figure can be viewed at wileyonlinelibrary.com]

Under different biochar content levels, variations in dry density influenced the soil unfrozen water content (Figure 3d–f). In soils with a dry density of 1.50 g/cm^3, 0% biochar soil unfrozen water content decreases the most quickly, followed by that in soil with 5% biochar; the unfrozen water content in soil with 3% biochar decreases the most slowly. However, the variation difference of unfrozen water content in soil with 0%, 3%, and 5% biochar increases gradually as the freezing process continues, finally reaching the maximum in the freezing stable stage. In soils with a dry density of 1.55 g/cm^3, unfrozen water content in soil with 5% biochar decreases the most quickly, followed by those in soil with 3% and 0% biochar successively. As soil freezing continues, the unfrozen water content in soil with 5% biochar presents the sharpest reduction during the freezing transition, followed by those in soil with 0% and 3% biochar successively. In the freezing stable stage, the unfrozen water content in soil with 5% biochar is the highest, followed by those in soil with 0% and 3% biochar successively. When the dry density of the soil was 1.60 g/cm^3, at the initial freezing stage, the 5% biochar soil unfrozen water content decreased the fastest, followed by that in 3% biochar soil, and the 0% biochar soil unfrozen water content decreased the slowest. When the soil continues to freeze, the soil with different biochar contents differences in unfrozen water content gradually narrow. Finally, in the freezing stable stage, the differences in unfrozen water content among the three biochar contents in the soil reach the minimum; this is contrary to the variation law of unfrozen water in soil with a dry density of 1.50 g/cm^3.

The above experimental data show that with the increase of soil dry density, biochar changes from inhibiting the decline of

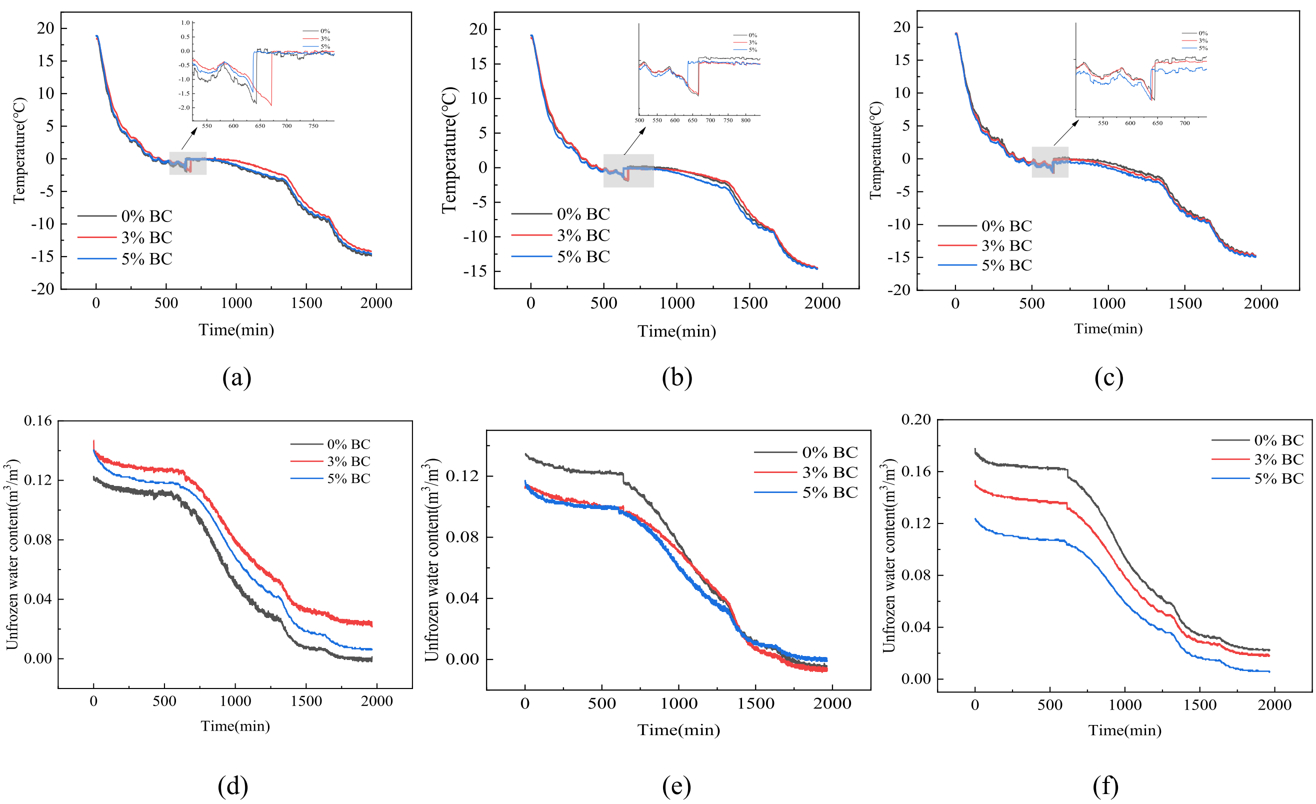

FIGURE 3 | Temperature and water variation patterns in soils with different dry densities and biochar contents. (a) $\rho_d = 1.50$ g/cm^3 temperature curve. (b) $\rho_d = 1.55$ g/cm^3 temperature curve. (c) $\rho_d = 1.60$ g/cm^3 temperature curve. (d) $\rho_d = 1.5$ g/cm^3 water curve. (e) $\rho_d = 1.55$ g/cm^3 water curve. (f) $\rho_d = 1.60$ g/cm^3 water curve. [Colour figure can be viewed at wileyonlinelibrary.com]

soil temperature to promoting its decline. Moreover, with the increase of soil dry density, the higher the biochar content, the lower the soil freezing temperature. The effect of dry density on soil unfrozen water content was mainly manifested in the rapid freezing, freezing transition, and stable freezing stages, and biochar promoted soil freezing with the increase of soil dry density.

3.2 | Effects of Lead Content on Biochar Soil Freezing Temperature and Unfrozen Water Content

With the increase of soil lead content, the effects of different biochar content on soil temperature and unfrozen water content were different (Figure 4). From Figure 4a–c, it can be seen that the effects of biochar content on soil temperature are different with the increase of soil lead content. When the soil lead content was 0%, the 3% biochar soil freezing temperature was the lowest, and the freezing temperatures of 0% and 5% biochar soil were similar. As the soil continued to freeze, the 5% biochar soil temperature changed rapidly, followed by 0% biochar soil, and the 3% biochar soil temperature changed the slowest. When the soil lead content was 1%, compared with the control group, both 3% and 5% biochar reduced the soil freezing temperature. As the soil continued to freeze, the 5% biochar soil temperature changed rapidly, followed by 0% biochar soil, and the 3% biochar soil temperature changed the slowest. When the soil lead content was 2%, compared with the control group, 3% biochar had little effect on soil freezing temperature, and 5% biochar reduced freezing temperature. As the soil continued to freeze, the 5% biochar soil temperature changed rapidly, followed by 3% biochar soil, and the 0% biochar soil temperature changed the slowest.

In terms of unfrozen water content (Figure 4d–f), the variation characteristics of unfrozen water across different freezing stages (rapid freezing, stable freezing, and rapid thawing) were jointly influenced by lead concentration and biochar dosage. Under lead-free conditions, 5% biochar accelerated the decline in unfrozen water content during the rapid freezing stage, but its unfrozen water content was relatively higher after the stable freezing stage. When the lead content was 1%, the unfrozen water content of soil with different biochar content varied similarly in the rapid freezing stage and the stable freezing stage, with the largest unfrozen water content in 3% biochar soil, followed by 5% biochar soil, and 0% biochar soil with the lowest unfrozen water content. When the lead concentration increased to 2%, the unfrozen water content in the 0% biochar treatment decreased most rapidly during the rapid freezing stage, while 5% biochar accelerated its decline during the stable freezing stage. Additionally, the unfrozen water change curves of some treatments intersected, such as the 0% and 3% biochar treatments under lead-free conditions, and the 3% and 5% biochar treatments under higher lead conditions.

In summary, lead contamination not only intensified the regulatory effect of biochar on soil temperature but also altered the direction and stage-specific characteristics of biochar's influence on unfrozen water dynamics, reflecting complex interactions among heavy metals, biochar, and soil.

3.3 | Effects of Temperature on Soil Unfrozen Water Content With Different Biochar Contents and Lead Contents

As the soil freezing temperature decreases, the unfrozen water content in the soil shows a gradual decreasing trend. However, the specific variation characteristics of the unfrozen water

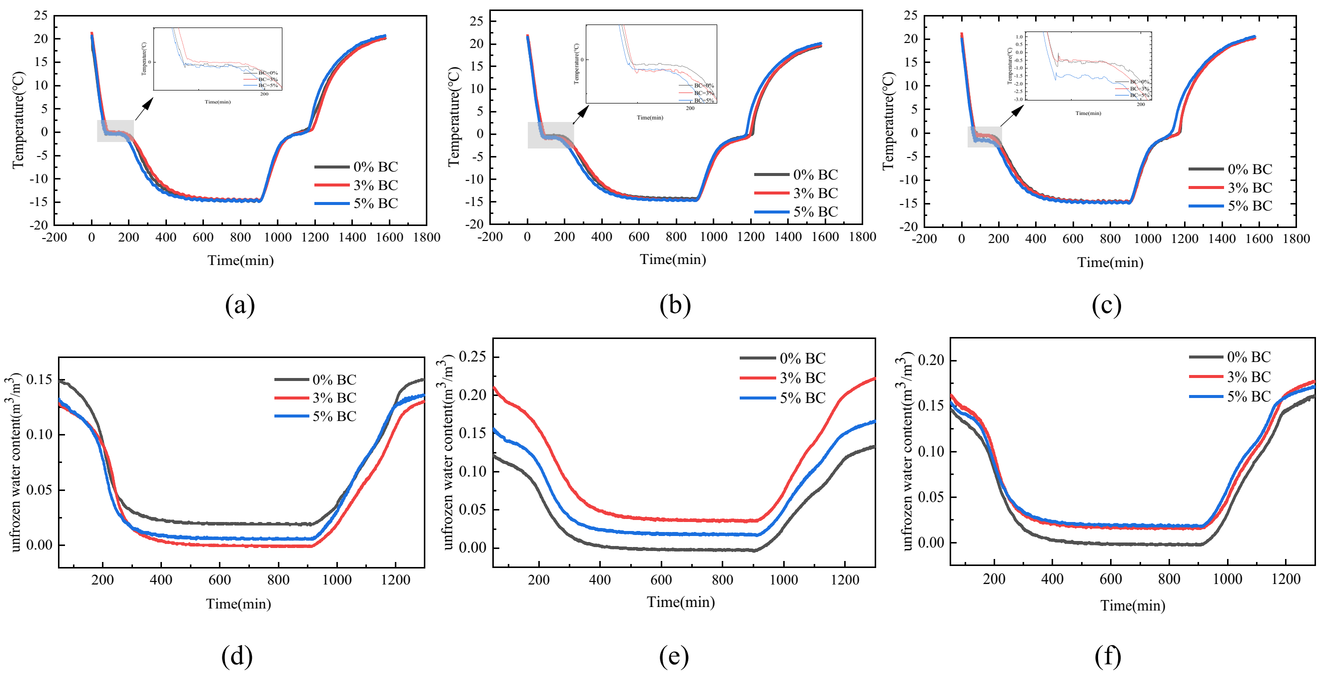

FIGURE 4 | Temperature and water variation patterns in soils with different lead contents and biochar contents. (a) 0% Pb temperature curve. (b) 1% Pb temperature curve. (c) 2% Pb temperature curve. (d) 0% Pb water curve. (e) 1% Pb water curve. (f) 2% Pb water curve. [Colour figure can be viewed at wileyonlinelibrary.com]

content differ among soils with different biochar contents and Pb contents (Figure 5).

In uncontaminated soil, the unfrozen water content of soils with different biochar contents exhibits phased characteristics as the temperature changes. In the temperature range of 0°C to −2°C, the unfrozen water content decreases rapidly. After entering the range of −2°C to −5°C, the rate of decrease in the unfrozen water content significantly slows down. When the temperature drops to the range of −5°C to −15°C, the soil enters the stable freezing stage, and the downward trend of the unfrozen water content becomes indistinct. Compared with the control group (0% biochar), unfrozen water contents in soil samples with 1%, 3%, and 7% biochar are higher than that of the control group, while the unfrozen water content in soil samples with 5% BC is lower. In the soils contaminated with 1% Pb, the unfrozen water content of soils with different biochar contents shows an obvious decreasing trend in both temperature ranges of 0°C to −2°C and −2°C to −5°C. When the temperature drops to the range of −5°C to −10°C, the unfrozen water content enters a stage of stable decrease, and when the temperature is in the range of −10°C to −15°C, the decrease in unfrozen water content is not significant. Compared with the control soil, only the 1% biochar treatment increased the soil's unfrozen water content, while the other biochar contents (3%, 5%, and 7%) all decreased the unfrozen water content, with the 5% and 7% biochar treatments showing the most prominent reduction effect. In the soils contaminated with 2% Pb, the unfrozen water content of soils with different biochar contents shows an obvious decreasing trend in the three temperature ranges of 0°C to −2°C, −2°C to −5°C, and −5°C to −10°C. However, as the temperature gradually decreases, the decreasing amplitude of the unfrozen water content decreases step by step. When the temperature is in the range of −10°C to −15°C, the decreasing rate of the unfrozen water content is the slowest and basically tends to be stable. Compared with the control soil, the 1% biochar treatment reduces the soil unfrozen water content, while the other biochar contents (3%, 5%, and 7%) all increase the soil unfrozen water content. In summary, soil unfrozen water content decreased in distinct phases as temperature dropped, a pattern jointly regulated by biochar application rate and lead Pb contamination level.

3.4 | Effects of Biochar Content on Soil Unfrozen Water Content With Different Lead Contents and Initial Water Content

As shown in Figure 6, under conditions of lower initial water content (10%–15%), the addition of 1%–3% biochar can increase the unfrozen water content of the soil. In contrast, the higher application rates of 5% and 7% biochar show limited enhancing effects, with the 7% treatment yielding the smallest increase. When the initial water content increases to 20%–25%, the effect of biochar on soil unfrozen water content changes. With the increase of biochar content, the unfrozen water content of lead-free soil and lead-containing soil changed differently. For example, under the condition of 20% water content, for lead-free soil, the 1% biochar treatment has a minor impact, while the 3%–7% biochar treatments all increase the unfrozen water content, with the 3% treatment showing relatively better effectiveness. For lead-contaminated soil, the 1% and 3% biochar treatments instead reduce the unfrozen water content, while the effects of the 5% and 7% biochar treatments vary with the lead concentration;

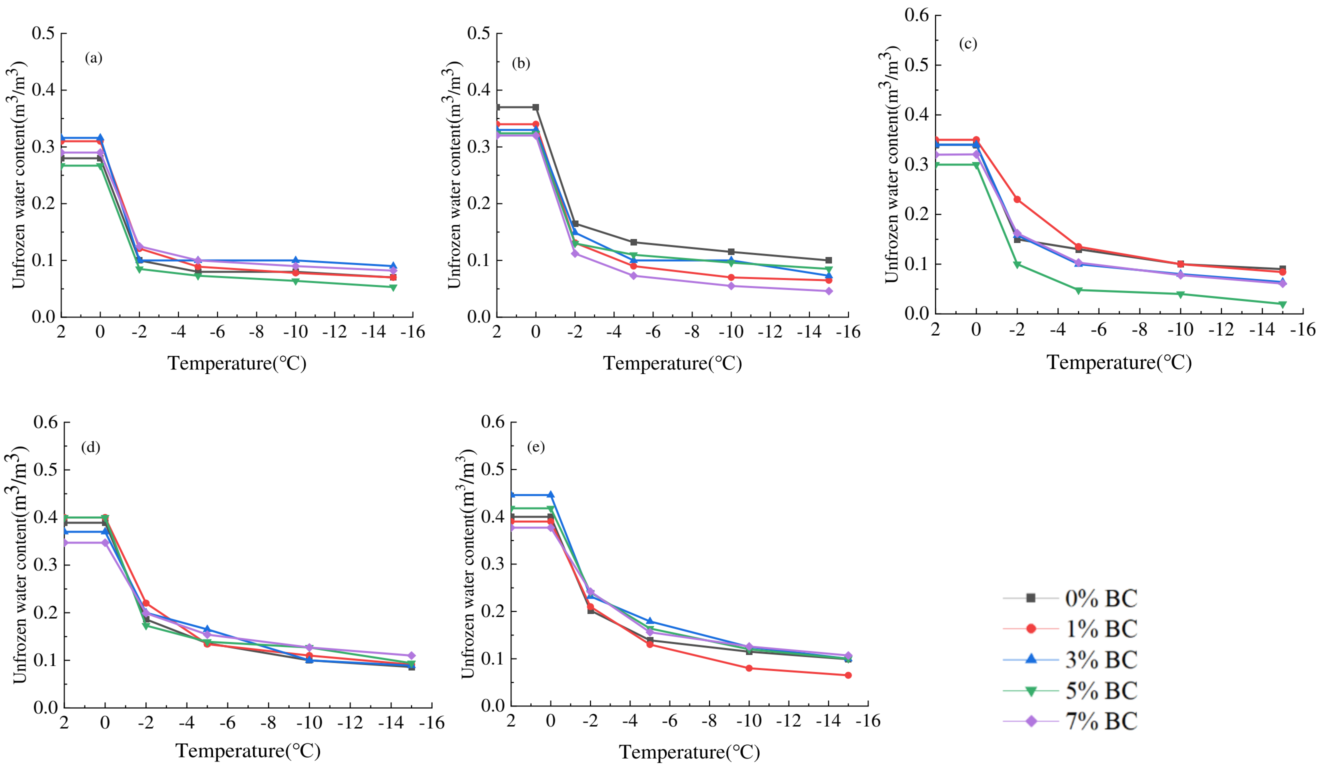

FIGURE 5 | Effects of temperature on unfrozen water content in soils with different biochar contents and lead contents. (a) 0% Pb. (b) 0.5% Pb. (c) 1% Pb. (d) 1.5% Pb. (e) 2% Pb. [Colour figure can be viewed at wileyonlinelibrary.com]

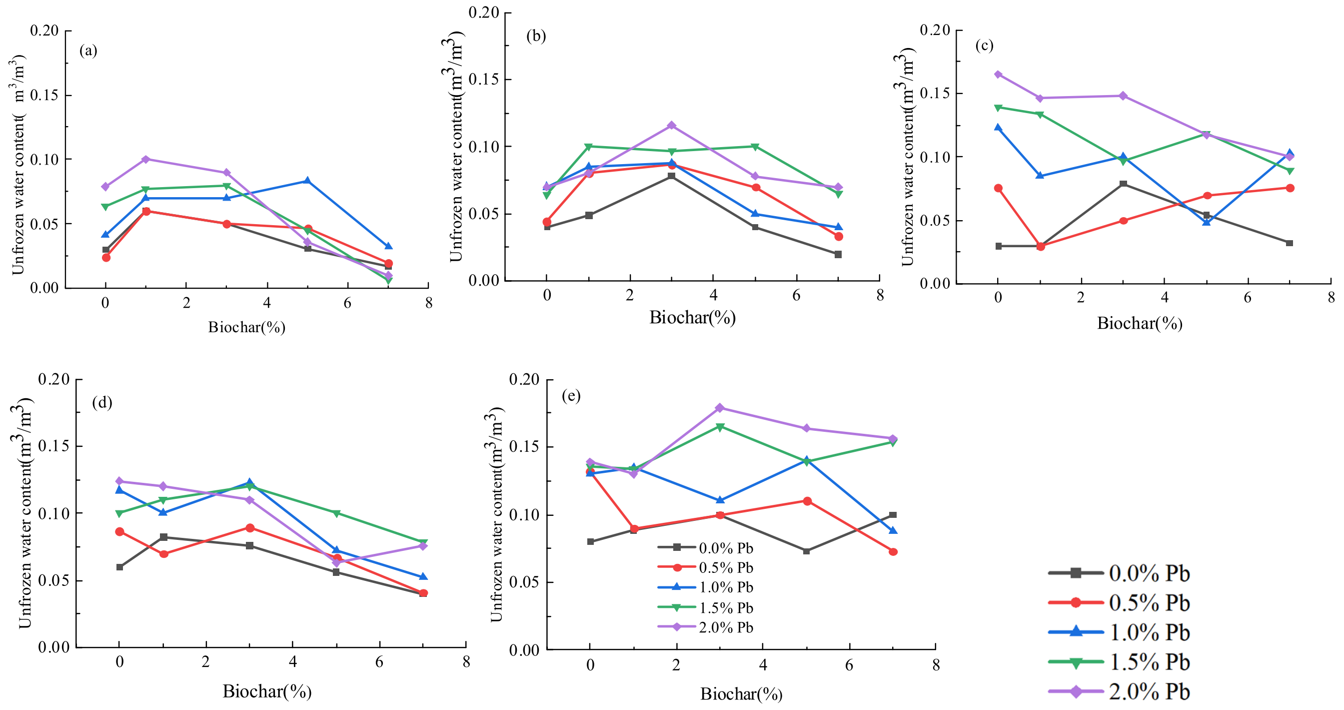

FIGURE 6 | Effects of biochar content on soil unfrozen water content with different lead contents and initial water contents. (a) 10% initial water content. (b) 15% initial water content. (c) 20% initial water content. (d) 25% initial water content. (e) 30% initial water content. [Colour figure can be viewed at wileyonlinelibrary.com]

they show a slight increase at lead concentrations of 0.5% and 1%, but shift to a decrease at lead concentrations of 1.5% and 2%. When the initial water content is 30%, with the increase of biochar content, the change in soil unfrozen water content is different from the previous. For lead-free soil, the addition of 1%, 3%, and 7% biochar all increases the unfrozen water content, while only the 5% biochar treatment reduces it. For lead-contaminated soil, the 1% biochar treatment mainly acts to reduce the unfrozen water content. The effects of the 3%, 5%, and 7% biochar treatments depend on the level of lead contamination. They show an insignificant effect on unfrozen water content at lead concentrations of 0.5% and 1%, but exhibit an increasing trend at lead concentrations of 1.5% and 2%. Therefore, biochar mainly showed an enhancing effect on soil unfrozen water content in soil with lower initial water content and lower pollution, and 3% biochar content was the optimal usage. However, in soils with high initial water content and heavy pollution, the enhancement effect of biochar on unfrozen water content will be weakened.

3.5 | Effects of Initial Water Content on Soil Unfrozen Water Content With Different Lead Contents and Biochar Contents

It can be seen from Figure 7a that with the increase of initial water content, the unfrozen water content of 0%, 3%, 5% and 7% biochar soil gradually increased, and the unfrozen water content of 1% biochar soil decreased first and then increased, which was different from the change mode of unfrozen water content in other soils. As shown in Figure 7b, the response of unfrozen water content to the initial water content in soil with different biochar content varied. With the increase of initial water content, the content of unfrozen water in 0% biochar soil gradually increased, and the content of unfrozen water in 1%, 3%, 5% and 7% biochar soil increased first, then decreased, and then increased. In Figure 7c, with the increase of initial water content, the unfrozen water content of 0%, 3%, and 7% biochar soil increased first. Then it decreased; the content of unfrozen water in 1% biochar soil gradually increased, and the content of unfrozen water in 5% biochar soil decreased first and then increased. In Figure 7d, the unfrozen water content of 0%, 1%, 3%, and 5% biochar soil increased gradually with the increase of initial water content, while the unfrozen water content of 7% biochar decreased first and then increased. In Figure 7e, the unfrozen water content of 0%, 1%, and 3% biochar soil showed a gradual upward trend with the increase of initial water content. The unfrozen water content of 5% and 7% biochar soil gradually increased in the range of 10%–20% initial water content, and when the initial moisture content reached 25%, the content of unfrozen water in 5% and 7% biochar soil decreased, and then increased again with the increase of initial moisture content. In addition, it can be seen from Figure 7 that the 20% moisture content at the increase of the initial moisture content is the turning point of most soil unfrozen water changes. For example, 1% biochar soil in Figure 7a, 1%, 3%, and 5% biochar soil in Figure 7b, 7% biochar soil in Figure 7c, 5% biochar soil in Figure 7d, and 5% and 7% biochar soil in Figure 7e. Therefore, the change pattern of soil unfrozen water content was closely related to soil biochar content, heavy metal content, and soil initial water content.

3.6 | Statistical Analysis

Correlation analysis (Figure 8) showed that the Pb content, initial water content, and unfrozen water content were

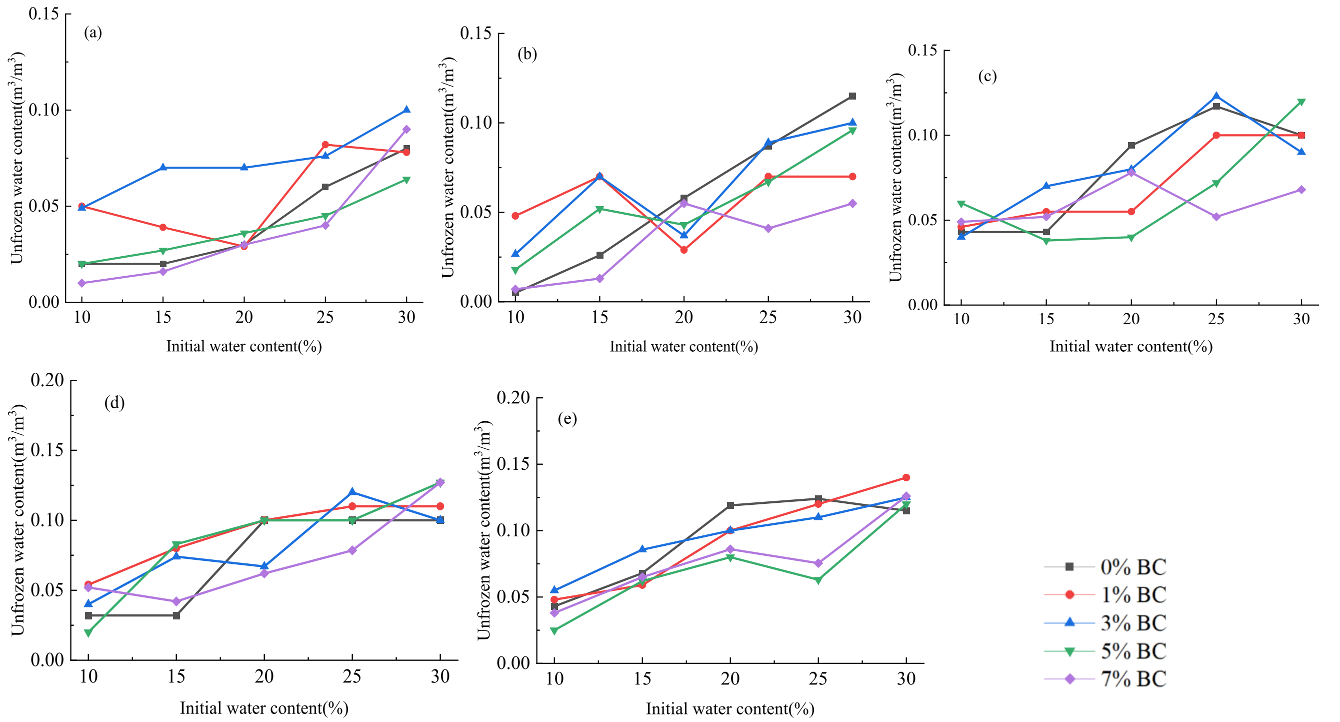

FIGURE 7 | Effect of initial water content on unfrozen water content in soils with different biochar contents and lead contents. (a) 0% Pb. (b) 0.5% Pb. (c) 1% Pb. (d) 1.5% Pb. (e) 2% Pb. [Colour figure can be viewed at wileyonlinelibrary.com]

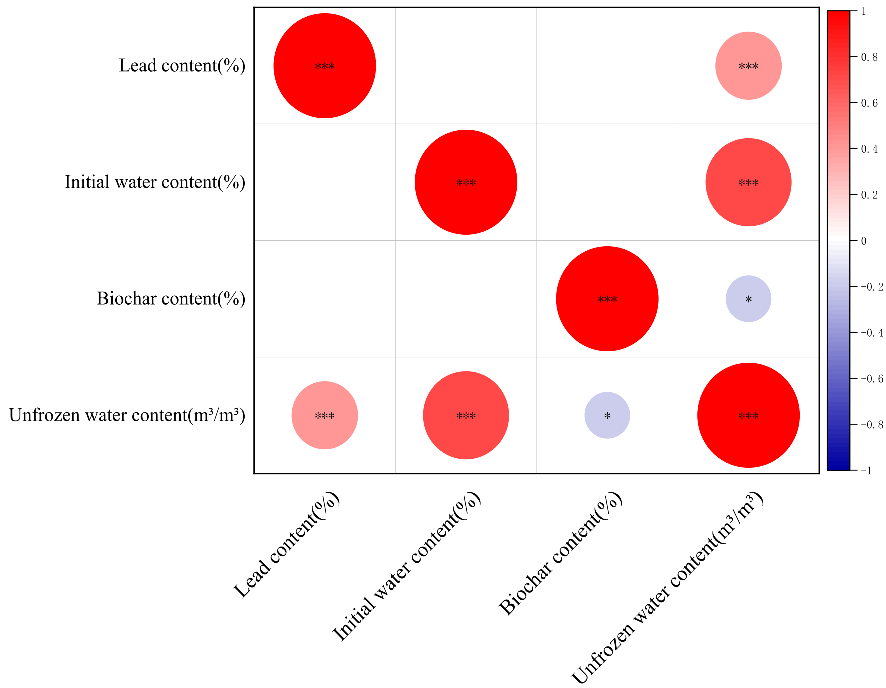

FIGURE 8 | Correlation analysis of soil unfrozen water content. *$p \leq 0.05$, **$p \leq 0.01$, and ***$p \leq 0.001$. [Colour figure can be viewed at wileyonlinelibrary.com]

significantly positively correlated ($p < 0.001$), while the biochar content was weakly negatively correlated with the unfrozen water content ($p < 0.05$), indicating that the initial water content and Pb content were the key positive factors affecting the unfrozen water content. The results of the three-way analysis of variance (Table 5) further validate this trend. The main effects of biochar content, initial water content, and heavy metal content on unfrozen water content were extremely significant ($p < 0.001$), and the influence intensity of initial water content was the highest ($F = 75.160$). In terms of interaction effects, the interaction between the initial water content and the heavy metal content ($F = 1.827$, $p = 0.046$) and the biochar content and the initial water content ($F = 2.483$, $p = 0.005$) had significant interactions, indicating that these factors did not independently

TABLE 5 | Results of three-way analysis of variance on the influence of different factors on the soil unfrozen water content.

Item	Sum of squares	Degree of freedom	Average squared value	F	Significance
Modified model	0.114[a]	60	0.002	9.007	0.000
Intercept	0.591	1	0.591	2792.980	0.000
Biochar content	0.008	4	0.002	9.441	Significant
Initial water content	0.064	4	0.016	75.160	Significant
Lead content	0.024	4	0.00	27.947	Significant
Initial water content × Lead content	0.006	16	0.000	1.827	Significant
Biochar content × Lead content	0.004	16	0.000	1.328	Not Significant
Biochar content × Initial water content	0.008	16	0.001	2.483	Significant
Error	0.014	64	0.000		
Total	0.719	125			
Corrected total	0.128	124			

Note: [a]$R^2 = 0.894$ (Adjusted $R^2 = 0.79$).

affect the unfrozen water content, but had a synergistic regulatory effect. The interaction between biochar content and heavy metal content was not significant ($p = 0.209$). The overall fit of the model was good ($R^2 = 0.894$, adjusted $R^2 = 0.795$), which could explain 89.4% of the variation in unfrozen water content, and the results were reliable.

4 | Discussion

4.1 | Effect of Dry Density on Biochar Soil Freezing Temperature and Unfrozen Water Content

Biochar can influence soil hydrothermal dynamics by improving soil pore structure, promoting aggregate formation, and altering the arrangement of soil particles (Li et al. 2023; Yang et al. 2024). However, after biochar is incorporated into the soil, its effects are not solely determined by its own pore structure but are also modulated by the degree of soil compaction.

Under low dry density conditions ($\rho_d = 1.50\,g/cm^3$), the differences in soil freezing temperature among treatments with varying biochar addition amounts are minimal. This suggests that under high porosity conditions, the freezing behavior of soil water is primarily governed by the original pore structure, while the contributions of newly formed pores and biochar surface adsorption to the water phase change process are relatively limited. Consequently, the differences in soil freezing temperature among treatments with different biochar addition amounts remain small. As dry density further increases ($\rho_d = 1.55$–$1.60\,g/cm^3$), soil particles become more densely packed, pore space is reduced, and the contact area between soil particles increases. The soil heat transfer mode gradually shifts from being primarily influenced by solid particles and pore air under low-density conditions to being mainly governed by solid particle heat transfer. Under such conditions, the regulatory effect of biochar on the soil freezing process changes accordingly. The results indicate that as dry density and biochar addition amount increase, the soil freezing temperature gradually decreases. This may be due to the fact that, under high compaction conditions, biochar alters the arrangement of soil particles and the pore structure, leading to a differentiated water environment in soils with varying biochar addition amounts. Additionally, the rich microporous structure and surface functional groups of biochar enhance the adsorption of water molecules, increase the proportion of bound water, and reduce the content of freezable free water (Bikbulatova et al. 2018), thereby lowering the soil freezing temperature.

Due to differences in temperature variations during the freezing process of soils amended with various biochar types, the unfrozen water content within the same freezing duration exhibits distinct characteristics. Overall, as dry density increases, soils treated with 0%, 3%, and 5% biochar all show a rising rate of temperature drop, corresponding to a decline in unfrozen water content. This suggests that temperature changes during freezing are key factors influencing the dynamics of unfrozen water in soil (Meng et al. 2024; Wan et al. 2023). Furthermore, existing studies have indicated that biochar can reduce soil thermal conductivity, enhance water retention capacity, and increase unfrozen water content, with its regulatory effect typically strengthening as the biochar application rate increases (Fu et al. 2019; Li et al. 2022), which is different from the results of this study. Most existing studies have focused on surface mixing or low-density soil conditions (He et al. 2023; Fu et al. 2019; Li et al. 2022). In contrast, this study further considers the impact of compaction on pore structure and hydrothermal transfer processes by controlling the dry density of the biochar-soil mixture. Consequently, the findings of previous studies are relatively consistent with the patterns observed under low dry density conditions ($\rho_d = 1.50\,g/cm^3$) in this study, but differ from those under high dry density conditions ($\rho_d = 1.55$–$1.60\,g/cm^3$). Additionally, Yan, Dong, Li, et al. (2019) reported that biochar application increased soil water content in winter wheat fields during the growing season, with the optimal effect observed at an application rate of 40 tons per hectare. However, further increases in application rate did not lead to continued rises in soil water content. Other scholars have indicated that biochar does not necessarily improve soil water-holding capacity; this effect depends on factors such as soil type, biochar type, and application method (Jeffery et al. 2015; Hardie et al. 2014). Therefore, the influence of biochar on soil temperature and unfrozen water content is closely related to both biochar type and soil type. An appropriate amount of biochar may reduce the soil freezing temperature and increase the unfrozen water content, thereby alleviating the damage caused by freeze–thaw cycles to soil structure.

4.2 | Effect of Lead Content on Biochar Soil Freezing Temperature and Unfrozen Water Content

In the biochar-amended frozen soil system, lead (Pb) pollution, as a critical environmental stressor, can regulate the soil freezing process and the dynamic changes in unfrozen water content by altering soil solution properties, water occurrence states, and soil particle–water interface characteristics (Cao, Liu, et al. 2024; Cao, Chou, et al. 2024). Consequently, it influences the regulatory effect of biochar on soil hydrothermal conditions during freeze–thaw cycles (Figures 4 and 9). Biochar possesses a rich pore structure and abundant surface functional groups, which can increase the proportion of effective soil pores, enhance water retention capacity, and alter the occurrence state of water (Fu et al. 2019, 2023). Therefore, under low Pb pollution levels (1%), biochar addition improves soil water-holding capacity, lowers the soil freezing temperature, and increases the unfrozen water content after freezing (Figure 4b,e). However, as Pb content increases, the solute effect of Pb ions becomes more pronounced, further reducing the freezing temperature and raising the unfrozen water content (Cao, Liu, et al. 2024; Han et al. 2024). Meanwhile, Pb ions compete with soil particles and active sites on the biochar surface for adsorption, modifying the binding mode between water molecules and the solid surface. This may affect the water storage state within the biochar pores, thereby weakening the water retention effect of biochar (Qiu et al. 2021; Li et al. 2017). Under conditions of low biochar addition (3% biochar), the influence of Pb ions on the freezing behavior of soil water is relatively strong, and the limited pore structure and adsorption sites of biochar are insufficient to offset the changes in water state induced by Pb ions through adsorption. As a result, the regulatory effect of 3% biochar on the freezing temperature is relatively weak (Figure 4c,f). Nevertheless, because 3% biochar provides a certain number of micropores and surface functional groups, the final unfrozen water content of the treated soil remains higher than that of soil without biochar. In contrast, high-addition biochar (5% biochar) possesses a rich microporous structure and more active adsorption sites, enabling it to affect the occurrence state of more water under high Pb concentration (2%) conditions. Thus, the 5% biochar treatment exhibits a pronounced effect in lowering the soil freezing temperature and increasing the unfrozen water content. Overall, when Pb enters the soil, its solute effect reduces the chemical potential of the soil aqueous solution, thereby lowering the soil freezing temperature (Cao, Liu, et al. 2024; Han et al. 2024). Meanwhile, the interaction between Pb ions and the active sites on the surfaces of soil particles and biochar may alter the water adsorption state (Zhang et al. 2026; Cao, Chou, et al. 2024), causing the regulation of the water freezing process by biochar to exhibit a clear Pb concentration dependence.

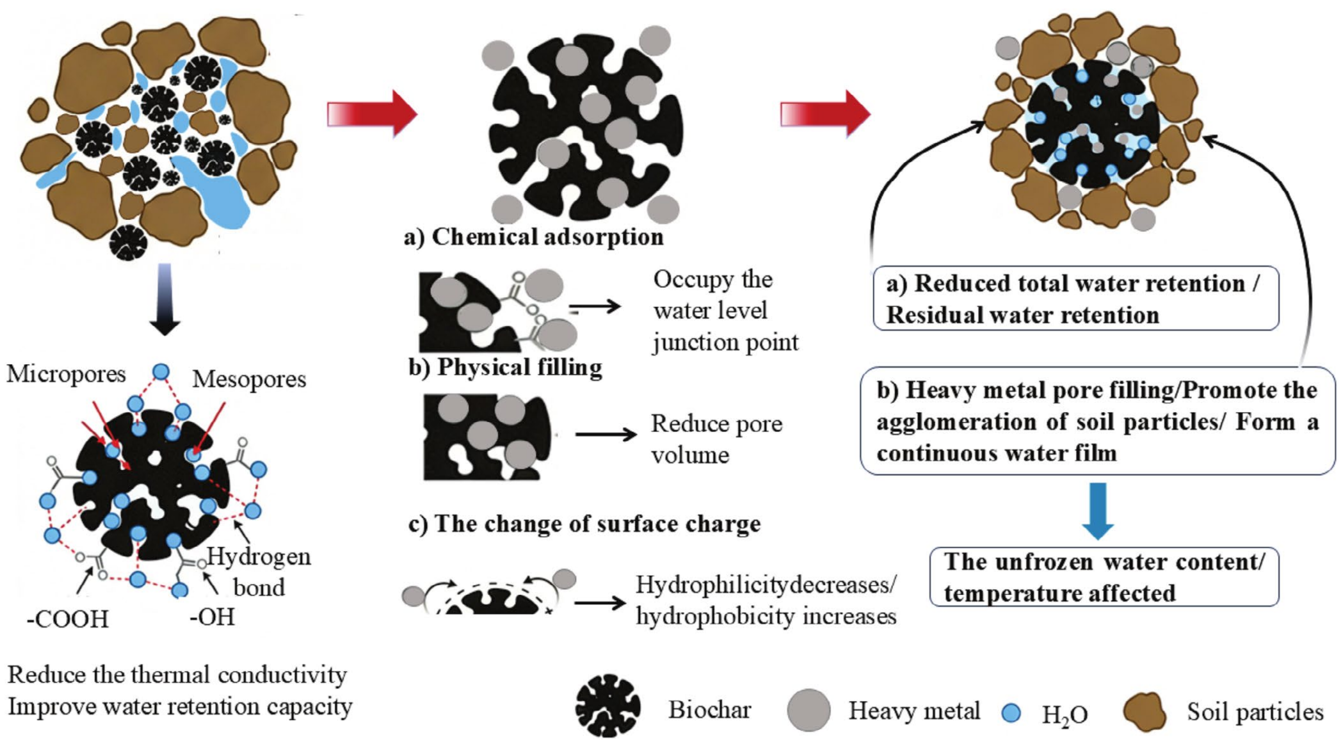

FIGURE 9 | Schematic of biochar effects on freezing temperature and unfrozen water content in heavy metal-contaminated soil. [Colour figure can be viewed at wileyonlinelibrary.com]

4.3 | Effects of Initial Water Content on Soil Unfrozen Water Content With Different Biochar Content and Lead Content

Initial water content is a key factor influencing the soil freezing process (Cao, Chou, et al. 2024; Gao et al. 2026). It not only determines the degree of saturation of pore water in the soil, but also affects the migration behavior of Pb ions and the interfacial interaction between biochar and soil water (Wu, Rui, et al. 2022; Han et al. 2024), thereby regulating the effect of biochar on the unfrozen water content in Pb-contaminated soil (Figures 6 and 7).

Under low initial water content conditions (10% and 15%), the overall soil water content remains low, and water is primarily stored in soil and biochar pores as capillary-adsorbed water and bound water on particle surfaces. Under these conditions, the unfrozen water content in the soil is mainly governed by the water adsorption capacity and interfacial binding strength (Bikbulatova et al. 2018; Han et al. 2024). As illustrated in Figure 6a,b, the addition of a low amount of biochar (1% and 3%) significantly increases the unfrozen water content of Pb-contaminated soil after freezing, whereas the effect of higher biochar additions (5% and 7%) is relatively weak. This finding is consistent with the conclusions reported by Rabbi et al. (2021). The analysis indicates that, under low water conditions, an appropriate amount of biochar enhances the soil's ability to retain limited water by optimizing the pore structure, increasing effective adsorption sites, and strengthening hydrogen bonding (Bikbulatova et al. 2018; Han et al. 2024). Consequently, more water is retained as bound water, thereby increasing the unfrozen water content of the soil. In this study, as biochar addition increased further, the soil water content became insufficient to fully saturate the newly introduced pore structure. Consequently, the additional pores generated by excessive biochar could not be effectively transformed into water-holding pores. Therefore, high-dose biochar application did not continue to increase the soil unfrozen water content. When the initial water content rose to 20%–30%, the effect of biochar on unfrozen water content in Pb-free soil followed a pattern similar to that observed under low water content conditions, indicating that the biochar pore structure and surface functional groups could still regulate water freezing behavior. However, in Pb-contaminated soil, the variation pattern of unfrozen water content exhibited clear differences, suggesting that Pb pollution altered the interaction between biochar and water under high water content conditions. Under such conditions, a large amount of water entered the soil and biochar pores, enhancing the mobility of Pb^{2+} in the soil solution and enabling interactions with the oxygen-containing functional groups of biochar through competitive adsorption and surface complexation (Zhang et al. 2026; Wang et al. 2021). On the one hand, Pb^{2+} may occupy certain active sites on the biochar surface, thereby weakening the binding affinity between water molecules and biochar (Wu, Wang, et al. 2022). On the other hand, the interaction between Pb ions and soil colloids or mineral particles may alter the pore structure and interfacial water state, consequently affecting the stable occurrence of unfrozen water (Nartowska and Sihag 2024). Furthermore, under high water content conditions, soil mineral expansion and particle migration may further modify pore connectivity and reduce the water retention capacity of some biochar pores (El-Naggar et al. 2018; Bandara et al. 2020). Thus, under the combined influence of high initial water content and Pb contamination, the regulatory effect of biochar on unfrozen water is jointly constrained by Pb concentration and water state. Statistical analysis results further indicate that initial water content not only directly affects the soil unfrozen water content but also exhibits a significant interaction with biochar content and Pb content, suggesting that initial water content is a critical regulatory factor determining the effect of biochar on the freezing behavior of water in Pb-contaminated soil. Therefore, the effect of biochar on the unfrozen water content of seasonal frozen soil is not a simple promoting effect but is jointly governed by initial water content, Pb pollution level, and biochar dosage.

4.4 | Limitations and Prospects

Existing studies have primarily focused on the effects of material properties such as biochar type, pyrolysis temperature, and particle size on the hydrothermal characteristics of different soils. However, a systematic understanding of the regulatory mechanisms by which biochar influences soil hydrothermal processes under the combined influence of soil intrinsic conditions (e.g., dry density and initial water content) and pollution stress factors (e.g., Pb content) remains lacking (Fu et al. 2019; Bikbulatova et al. 2018; Yan, Dong, Li, et al. 2019; Wu, Wang, et al. 2022). This gap is particularly pronounced in seasonal frozen soil regions. Current research on the effects of biochar on freezing temperature and unfrozen water content is still limited. Most existing studies focus on temperature and water dynamics during the freeze–thaw process in agricultural soils, and it is generally believed that biochar can delay soil temperature changes during freeze–thaw and increase unfrozen water content. The primary explanatory mechanisms are attributed to biochar's porous structure, thermal insulation properties, water absorption capacity, and its role in optimizing soil pore structure (Qiu et al. 2021; Fu et al. 2019, 2023; Yan, Dong, Li, et al. 2019). However, these conclusions are often drawn under specific soil structure conditions and cannot fully account for the regulatory mechanisms of biochar on the freeze–thaw process under complex environmental conditions.

For instance, in previous column experiments, the soil dry density was maintained at approximately $1.35\,g/cm^3$, resulting in a relatively loose soil structure, and it was found that biochar addition reduced soil thermal conductivity (He et al. 2023). However, by regulating soil dry density, this study reveals that with increasing soil compaction, biochar addition leads to a decrease in soil freezing temperature and an increase in the rate of temperature decline. This suggests that the state of soil structure may be an important factor influencing the regulatory effect of biochar on soil heat transfer processes. At low soil dry density, biochar may primarily enhance thermal insulation by increasing porosity and reducing heat conduction; at high soil dry density, the impact of biochar on water occurrence state and freezing processes may become dominant. Therefore, the discrepancies between existing research findings and those of this study may be attributed to differing soil structural conditions. Furthermore, this study also demonstrates that the effect of biochar on soil freezing temperature and unfrozen water content is not simply a single promotional effect, but is jointly regulated by dry density, Pb content, initial water content, and the amount of biochar added, indicating that the regulation of freeze–thaw processes by biochar exhibits significant environmental dependence.

Although this study identifies the influence patterns of biochar on the freezing temperature and unfrozen water content of seasonal frozen soil under both single-factor and multifactor coupling effects, certain limitations remain. Future research should further incorporate additional influencing factors such as soil type, mineral composition, solute type and concentration, biochar type, pyrolysis conditions, particle size distribution, and the number of long-term freeze–thaw cycles to establish a more comprehensive mechanistic understanding of how biochar regulates the hydrothermal processes in frozen soil. Moreover, future studies should integrate microstructural characterization, water migration analysis, and model simulation to further elucidate the internal linkages among biochar's effects on ice-water phase change, heat transfer, and pollutant migration. Such research will help improve the application efficiency of biochar in remediating polluted and degraded soils in cold regions and provide theoretical support for mitigating the risks of soil structure degradation, water imbalance, nutrient loss, and vegetation degradation caused by freeze–thaw cycles and heavy metal contamination.

5 | Conclusions

Through laboratory freezing and freeze–thaw experiments combined with statistical analysis, the effects of dry density, Pb pollution level, initial moisture content, and biochar addition on seasonal frozen soil freezing temperature and unfrozen water content were systematically studied. The results show that soil dry density, pollution levels, and moisture status together regulate the impact of biochar on soil freeze–thaw hydrothermal processes.

1. Soil dry density and biochar application rate are important factors influencing soil freezing behavior. As soil dry density increases, biochar addition generally lowers the soil freezing temperature and alters the soil freezing process. However, its effect on soil unfrozen water content is strongly dependent on the specific soil conditions.
2. Pb contamination alters the regulatory effect of biochar on soil freezing behavior. Across different Pb contamination levels, the addition of 5% biochar effectively decreases the soil freezing temperature and increases the final unfrozen water content after freezing. These results suggest that an appropriate biochar application rate can enhance water retention during the freezing process of Pb-contaminated soils.
3. Initial water content is an important factor in regulating biochar's impact on soil unfrozen water content. Under low initial moisture content, biochar addition has a significant effect on the unfrozen water content, and as initial moisture content increases, Pb pollution levels further regulate the action patterns of biochar.
4. Statistical analysis showed that initial moisture content and Pb content were significantly positively correlated with unfrozen water content, while biochar content was weakly negatively correlated with unfrozen water content. Additionally, there was a significant interaction between biochar content and initial moisture content, indicating a synergistic regulatory effect, whereas the interaction between biochar and Pb content was not statistically significant.

Overall, this study reveals the variation patterns of biochar's regulation of seasonal frozen soil freezing temperature and unfrozen water content under multifactor coupling. It indicates that soil dry density, moisture status, and pollution conditions are key factors determining the freeze–thaw regulatory effects of biochar. This research deepens the understanding of how biochar improves hydrothermal processes in cold-region polluted and degraded soils and provides a theoretical basis for heavy metal-polluted soil restoration and ecological stability enhancement in seasonally frozen regions.

Author Contributions

Shanbo Han: investigation, resources, data curation, writing – original draft. **Yaling Chou:** conceptualization, methodology, writing – review and editing, funding acquisition. **Wei Cao:** conceptualization, methodology, funding acquisition. **Yu Wang:** visualization. **Fupeng Yang:** validation. **Xunkun Guo:** validation.

Acknowledgments

This research was supported by the Joint Fund of Natural Science Foundation of Zhejiang Province (Grant No. LQZSZ26B060002), the Scientific Research Foundation of Hangzhou City University (2024010), and the National Natural Science Foundation of China (Grant No. 52168052).

Funding

This work was supported by the Natural Science Foundation of Zhejiang Province (LQZSZ26B060002), the Scientific Research Foundation of Hangzhou City University (2024010), and the National Natural Science Foundation of China (52168052).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Bandara, T., A. Franks, J. Xu, N. Bolan, H. Wang, and C. Tang. 2020. "Chemical and Biological Immobilization Mechanisms of Potentially Toxic Elements in Biochar-Amended Soils." *Critical Reviews in Environmental Science and Technology* 50: 903–978. https://doi.org/10.1080/10643389.2019.1642832.

Bikbulatova, S., A. Tahmasebi, Z. Zhang, S. K. Rish, and J. Yu. 2018. "Understanding Water Retention Behavior and Mechanism in Biochar." *Fuel Processing Technology* 169: 101–111. https://doi.org/10.1016/j.fuproc.2017.09.025.

Bing, H., and W. Ma. 2011. "Laboratory Investigation of the Freezing Point of Saline Soil." *Cold Regions Science and Technology* 67: 79–88. https://doi.org/10.1016/j.coldregions.2011.02.008.

Cao, W., Y. Chou, C. Liu, et al. 2024. "Experimental Study on Unfrozen Water Content of Loess Polluted by Heavy Metals." *Cold Regions Science and Technology* 225: 104274. https://doi.org/10.1016/j.coldregions.2024.104274.

Cao, W., C. Liu, Y. Chou, and E. Peng. 2024. "Experimental Study on Freezing Temperature and Its Influencing Factors of Loess Contaminated by Heavy Metals." *Case Studies in Thermal Engineering* 61: 105034. https://doi.org/10.1016/j.csite.2024.105034.

Cui, L., J. Chen, Z. Xiao, Q. Yuan, X. Zhao, and J. Xue. 2024. "A Simple Model of the Soil Freezing Characteristic Curve for Saline Soils With Two Freezing Stages." *Journal of Hydrology* 637: 131378. https://doi.org/10.1016/j.jhydrol.2024.131378.

El-Naggar, A., S. M. Shaheen, Y. S. Ok, et al. 2018. "Biochar Affects the Dissolved and Colloidal Concentrations of Cd, Cu, Ni, and Zn and Their Phytoavailability and Potential Mobility in a Mining Soil Under Dynamic Redox Conditions." *Science of the Total Environment* 624: 1059–1071. https://doi.org/10.1016/j.scitotenv.2017.12.190.

Fang, K., G. Xu, Y. Wang, et al. 2025. "Spatial Distribution, Source Identification, and Risk Assessment of Heavy Metals in Sediments of the Yellow River Basin, China." *Applied Sciences* 15: 5188. https://doi.org/10.3390/app15095188.

Fu, Q., J. Shi, T. Li, et al. 2023. "Improvement of Soil Physical Structure and Hydraulic Characteristics in Cold Regions by Different Regulation Modes." *Transactions of the Chinese Society for Agricultural Machinery* 54: 374–385. https://doi.org/10.6041/j.issn.1000-1298.2023.09.037.

Fu, Q., H. Zhao, T. X. Li, et al. 2019. "Effects of Biochar Addition on Soil Hydraulic Properties Before and After Freezing–Thawing." *Catena* 176: 112–124. https://doi.org/10.1016/j.catena.2019.01.008.

Gao, F., S. Zhang, J. Fang, A. Xu, and X. He. 2026. "Numerical Investigation on Moisture Migration in Freezing Silty Subgrade Soils: Effects of Initial Moisture Content and Thermal Gradient." *Cold Regions Science and Technology* 248: 104954. https://doi.org/10.1016/j.coldregions.2026.104954.

Gao, Y., T. Li, Q. Fu, et al. 2020. "Biochar Application for the Improvement of Water–Soil Environments and Carbon Emissions Under Freeze–Thaw Conditions: An In Situ Field Trial." *Science of the Total Environment* 723: 138007. https://doi.org/10.1016/j.scitotenv.2020.138007.

Han, S., W. Cao, Y. Chou, and E. Peng. 2024. "Experimental Study on the Change in Freezing Temperature During the Remediation of Pb-Contaminated Soils With Biochar." *Atmosphere* 15: 1483. https://doi.org/10.3390/atmos15121483.

Hardie, M., B. Clothier, S. Bound, G. Oliver, and D. Close. 2014. "Does Biochar Influence Soil Physical Properties and Soil Water Availability?" *Plant and Soil* 376: 347–361. https://doi.org/10.1007/s11104-013-1980-x.

He, Z., R. Hou, Q. Fu, T. Li, S. Zhang, and A. Su. 2023. "Evolution Mechanism of Soil Hydrothermal Parameters Under Freeze–Thaw Cycles: Regulatory Significance of Straw and Biochar." *Journal of Cleaner Production* 385: 135787. https://doi.org/10.1016/j.jclepro.2022.135787.

Jeffery, S., M. B. J. Meinders, C. R. Stoof, et al. 2015. "Biochar Application Does Not Improve the Soil Hydrological Function of a Sandy Soil." *Geoderma* 251: 47–54. https://doi.org/10.1016/j.geoderma.2015.03.022.

Li, H., X. Dong, E. B. da Silva, L. M. de Oliveira, Y. Chen, and L. Q. Ma. 2017. "Mechanisms of Metal Sorption by Biochars: Biochar Characteristics and Modifications." *Chemosphere* 178: 466–478. https://doi.org/10.1016/j.chemosphere.2017.03.072.

Li, M., J. Guo, and Y. Zhang. 2023. "Water and Gas Permeability Characteristics and Functional Relationships of Biochar-Amended Clay." *Transactions of the Chinese Society of Agricultural Engineering* 39: 54–61. https://doi.org/10.11975/j.issn.1002-6819.202305098.

Li, Q., T. Li, D. Liu, Q. Fu, R. Hou, and S. Cui. 2022. "The Effect of Biochar on the Water–Soil Environmental System in Freezing–Thawing Farmland Soil: The Perspective of Complexity." *Science of the Total Environment* 807: 150746. https://doi.org/10.1016/j.scitotenv.2021.150746.

Li, Q., M. Wang, Q. Fu, et al. 2020. "Short-Term Influence of Biochar on Soil Temperature, Liquid Moisture Content and Soybean Growth in a Seasonal Frozen Soil Area." *Journal of Environmental Management* 266: 110609. https://doi.org/10.1016/j.jenvman.2020.110609.

Liu, J., K. Zhang, W. Shi, and J. Yan. 2024. "Effects of Freeze–Thaw on the Detachment Capacity of Soils With Different Textures on the Loess Plateau, China." *Journal of Hydrology* 644: 132082. https://doi.org/10.1016/j.jhydrol.2024.132082.

Liu, X., J. Li, L. Yu, et al. 2018. "Simultaneous Measurement of Bacterial Abundance and Composition in Response to Biochar in Soybean Field Soil Using 16S rRNA Gene Sequencing." *Land Degradation & Development* 29: 2172–2182. https://doi.org/10.1002/ldr.2838.

Ma, X., Q. Fu, S. Xu, et al. 2019. "Influence of Biochar on Soil Thermal Properties in Northern Cold Regions." *Transactions of the Chinese Society for Agricultural Machinery* 50: 298–305. https://doi.org/10.6041/j.issn.1000-1298.2019.10.034.

Meng, F., Q. Chen, J. Du, et al. 2024. "Evaluating Soil Freezing Characteristic Curve Models for Predicting Unfrozen Water Content in Freezing Soils." *Physics and Chemistry of the Earth, Parts A/B/C* 135: 103697. https://doi.org/10.1016/j.pce.2024.103697.

Nartowska, E., and P. Sihag. 2024. "Exploring Machine Learning Models to Predict the Unfrozen Water Content in Copper-Contaminated Clays." *Cold Regions Science and Technology* 227: 104296. https://doi.org/10.1016/j.coldregions.2024.104296.

Nikrad, M. P., L. J. Kerkhof, and M. M. Häggblom. 2016. "The Subzero Microbiome: Microbial Activity in Frozen and Thawing Soils." *FEMS Microbiology Ecology* 92: fiw081. https://doi.org/10.1093/femsec/fiw081.

Qiu, B., X. Tao, H. Wang, W. Li, X. Ding, and H. Chu. 2021. "Biochar as a Low-Cost Adsorbent for Aqueous Heavy Metal Removal: A Review." *Journal of Analytical and Applied Pyrolysis* 155: 105081. https://doi.org/10.1016/j.jaap.2021.105081.

Rabbi, S. M. F., B. Minasny, S. T. Salami, A. B. McBratney, and I. M. Young. 2021. "Greater, but Not Necessarily Better: The Influence of Biochar on Soil Hydraulic Properties." *European Journal of Soil Science* 72: 2033–2048. https://doi.org/10.1111/ejss.13105.

Wan, X., Y. Lai, and C. Wang. 2015. "Experimental Study on the Freezing Temperatures of Saline Silty Soils." *Permafrost and Periglacial Processes* 26: 175–187. https://doi.org/10.1002/ppp.1837.

Wan, X., J. Zhu, W. Pei, et al. 2023. "A Theoretical Model on Unfrozen Water Content in Soils and Verification." *Journal of Hydrology* 622: 129675. https://doi.org/10.1016/j.jhydrol.2023.129675.

Wang, Z., T. Li, D. Liu, et al. 2021. "Research on the Adsorption Mechanism of Cu and Zn by Biochar Under Freeze–Thaw Conditions." *Science of the Total Environment* 774: 145194. https://doi.org/10.1016/j.scitotenv.2021.145194.

Wu, D., W. Zhang, W. Sun, et al. 2025. "Biochar as a Long-Term Strategy for Rehabilitating Degraded Soils: Multi-Omics Analysis of Soil–Metabolite–Microbe Interactions in Continuous Soybean Cultivation." *Land Degradation & Development* 36: 4718–4731. https://doi.org/10.1002/ldr.5664.

Wu, J., T. Wang, N. Shi, and W. P. Pan. 2022. "Insight Into Mass Transfer Mechanism and Equilibrium Modeling of Heavy Metals Adsorption on Hierarchically Porous Biochar." *Separation and Purification Technology* 287: 120558. https://doi.org/10.1016/j.seppur.2022.120558.

Wu, T., D. Rui, J. Zhang, G. Li, S. Wang, and Y. Ito. 2022. "Removal of Heavy Metal Pollutant From Clayey Soil Based on Repeated Ice

Segregation: A Laboratory Evaluation." *Cold Regions Science and Technology* 201: 103626. https://doi.org/10.1016/j.coldregions.2022.103626.

Yan, K., Z. Dong, M. A. A. Wijayawardena, Y. Liu, Y. Li, and R. Naidu. 2019. "The Source of Lead Determines the Relationship Between Soil Properties and Lead Bioaccessibility." *Environmental Pollution* 246: 53–59. https://doi.org/10.1016/j.envpol.2018.11.104.

Yan, Q., F. Dong, J. Li, et al. 2019. "Effects of Maize Straw-Derived Biochar Application on Soil Temperature, Water Conditions and Growth of Winter Wheat." *European Journal of Soil Science* 70: 1280–1289. https://doi.org/10.1111/ejss.12863.

Yang, B., Y. Chen, and S. Yuan. 2024. "Investigation on Structure, Evaporation, and Desiccation Cracking of Soil With Straw Biochar." *Land Degradation & Development* 35: 3126–3135. https://doi.org/10.1002/ldr.5122.

Zeng, J., C. B. Tabelin, W. Gao, et al. 2023. "Heterogeneous Distributions of Heavy Metals in the Soil–Groundwater System Empowers the Knowledge of Pollution Migration at a Smelting Site." *Chemical Engineering Journal* 454: 140307. https://doi.org/10.1016/j.cej.2022.140307.

Zhang, J., Z. Zhang, J. Li, D. Rui, L. Xu, and G. Li. 2026. "Effect of Freeze–Thaw Cycle on Biochar-Stabilized Heavy Metal-Contaminated Soils: A Comparative Analysis in Seasonally Frozen Regions With and Without Groundwater Recharge." *Cold Regions Science and Technology* 241: 104712. https://doi.org/10.1016/j.coldregions.2025.104712.

Zhang, Z., W. Bao, L. Tian, Z. Huang, and R. Chen. 2024. "Study on the Effect of Pore Structure Changes Induced by Freeze–Thaw–Wetting–Drying Cycles on Water Retention Characteristics of Compacted Loess." *Construction and Building Materials* 455: 139213. https://doi.org/10.1016/j.conbuildmat.2024.139213.