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Biochar as an amendment material for improvement of expansive soil properties in Central Asia

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ABSTRACT

Soil salinity in Central Asia negatively impacts soil structure, leading to degradation and reduced water infiltration. This not only hampers agricultural productivity but also makes the land less suitable for construction due to its high susceptibility to deformation. Environmentally friendly materials like biochar, a carbon-rich substance, show promise in reducing the deformation of saline soils. However, the mechanisms behind its effectiveness are not yet fully understood. This study aims to analyse saline clays' dispersion and sedimentation behaviour under varying pore water salinity levels (0 % to 10%). A biochar content of 5 % was selected as it is found to be optimum for plant growth and erosion resistance. It was found from the study that the biochar increases the aggregation of soil particles and enhances flocculation, improving soil dispersion characteristics. Biochar facilitates soil particle aggregation by increasing the cation exchange capacity. At higher pore water salinity levels (5% and 10%), the sedimentation behaviour of biochar-treated soil particles deviates from expectations, showing slower sedimentation rates and lower sedimentation heights. This is because the sodium ions are adsorbed by biochar, reducing salt's effect on dispersion and sedimentation. The results demonstrate that biochar effectively enhances the stability of saline soils and, hence, has a potential use for ground improvement in the Central Asian region.

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1. Introduction

Soil salinization is a critical environmental challenge in Central Asia, particularly in the arid and semi-arid regions of Kazakhstan, Kyrgyzstan, and Uzbekistan. Approximately 50-60% of irrigated lands in these areas are affected by salinity. Some regions such as the Aral Sea basin experiences near-total topsoil salinization due to excessive irrigation and relatively poor drainage practices (Qadir et al., 2009; Rengasamy, 2010). This widespread salinization accelerates soil degradation and can lead to differential settlement in foundations, subgrades, and drainage systems, posing significant risks to infrastructure. Excessive salinity disrupts soil ecosystems (Leogrande & Vitti, 2019) and alters clay behavior: high sodium ion concentrations in porewater promote particle dispersion and swelling, exacerbating structural deterioration (Amini et al., 2016). These changes reduce permeability, impair water infiltration, and create hydraulic imbalances, further compounding agricultural and geotechnical challenges. Addressing saline soil management is therefore essential for both ecological sustainability and engineering resilience in Central Asia.

In recent years, biochar, a carbon sink material, has been widely used as a soil conditioner to enhance soil's physical and chemical properties (Sansalvador et al., 2014). The application of biochar can be considered an essential material in promoting soil quality and maintaining crop productivity, especially in drought and semi-drought areas in Central Asia (Abdullaeva et al., 2014; Garg et al., 2023; Jabborova et al., 2023). Biochar is generally produced by pyrolysis of biomass. Biochar possesses a porous structure, large surface area and wealthy functional groups (Wani et al., 2020). The porous structure of biochar is known to enhance the water retention capacity of saline and alkaline soils (Artiola et al., 2012). In addition, the wealthy functional groups (hydroxyl and carboxyl groups) of biochar tend to react with the salts in the soil to reduce salinity. In addition, several surface functional groups of biochar (depending on biochar type) can help in the sorption of contaminant ions, thereby suppressing their impact on the environment (Mandal et al., 2021).

Similarly, biochar is also found to reduce the sodium adsorption ratio, the saturated extract's electrical conductivity, the salt ion concentration, and the exchangeable sodium percentage (dos Santos et al., 2021). The ion and cation exchange capabilities, and hence, adsorption capacity, are known to be enhanced by biochar (Ghezzehei et al., 2014). Further, biochar can influence hydration and swelling in clay particles. Crystallisation expansion is a physical and chemical process dominated by water molecules' adsorption. On the other hand, expansion through the osmotic process is driven by the formation and expansion of the diffusion double layer (Liu et al., 2022). Clay and sediment particles generally undergo flocculation and aggregation (Yan et al., 2024). Flocculation is regulated by the diffusion process and the inter-particle force (Goodarzi et al., 2016). Moreover, granularity can also cause variation in rheological behaviours (Au et al., 2013), which can further impact the sedimentation and the dispersion of the clay.

Wang et al. (2019) studied the effects of biochar on the physical properties of silt loam while, Reddy et al. (2018) explored the influence of biopolymers on the dispersion characteristics of red mud. Findings suggested that particle aggregation is enhanced with the use of biopolymer. Rattan et al. (2023) further examined the impact of biopolymers on water retention and plant growth in soils correspond to Central Asian region. However, there is limited research with regard to use of biochar for mitigating dispersion and sedimentation in expansive soils (with presence of salt). It can be hypothesized that biochar can be useful to form ionic bonds with clay particles for reducing dispersion. Further, it can also enhance microbial activity for stabilizing microstructure of soils. This study explores biochar's influence on the dispersion and sedimentation of expansive soils (kaolin and bentonite) under presence of varying porewater salinities (0%, 1%, 5%, 10% NaCl). Experiments were conducted in a temperature- and humidity-controlled chamber. Dispersion and sedimentation tests were performed on biochar-amended soils (0%, 5%, 10% biochar) as compared to an unamended control.

2. Materials and Methods

The testing methodology described by Yan et al. (2024) was adopted. The study employed two clayey soils (kaolin and bentonite) amended with biochar at 0%, 5%, and 10% ratios by weight. NaCl was selected as the additive since, it is the dominant salt species in Central Asian saline soils, constituting 60-80% of soluble salts in affected regions like the Aral Sea basin (Gorbunov et al., 2020). Further, it is also the most common electrolyte in arid soil porewater, that provides representative conditions for dispersion behavior studies. The well-established properties of NaCl enables relatively easy comparison with existing literature (Zhou et al., 2017). Four salinity levels were examined to cover the typical range found in Central Asian soil corresponding to 0% (control/non-saline), 1% (moderately saline, common in marginal agricultural lands), 5% (highly saline, threshold for most crop failures) and 10% (extreme salinity, found in drainage zones and abandoned fields).

The selected concentrations reflect both current conditions and projected intensification of salinization due to climate change and irrigation practices in the region (Qadir et al., 2021). All experiments were conducted in temperature- and humidity-controlled chambers (25±1°C, 60±5% RH) to simulate typical Central Asian growing season conditions.The liquid and plastic limits of kaolin are 48 % and 24 %, while those of bentonite soil are 147 % and 41 %, respectively. pH for kaolin and bentonite are 7.8 and 7.4, respectively. The particle size range of bentonite is broader and more broadly distributed than kaolin's. Notably, kaolin contains no clay fraction (< 0.002 mm), whereas bentonite has a significant clay fraction, making up 67 % of its composition. The specific gravity (Gs) of kaolin was measured at 2.5, while that of bentonite was found to be 2.8.

On the other hand, biochar material was obtained using pyrolysis of the peach pit (Yan et al., 2024). The biochar produced from the peach pit is abundant in functional groups, such as C=O, OH, and CHO, which play a crucial role in the adsorption of sodium ions in literature (Ma et al., 2022). Peach (Prunus persica) was selected because it is abundant, has a larger specific surface area, and has higher carbon content than biochar produced from poultry litter (Yan et al., 2024).

Crumb testing has been previously adapted as an indicator to examine the dispersion characterization of the waste (ASTM D6572-21; 2020). Cubes of 20 mm size were compacted using each soil at their corresponding liquid limits (i.e., 48 % for Kaolin and 147 % for bentonite). The dispersion level was evaluated at 2-minute and 6-hour intervals to assess the turbidity of dense clouds that had developed due to debris. The detailed testing procedure is mentioned in Yan et al. (2024). It can be understood that Grades 1, 2, 3, and 4 refer to different states of soil particles, such as non-dispersive, intermediate, dispersive, and highly dispersive. Procedures specified in Palomino and Santamarina (2005) were adapted for sedimentation testing.

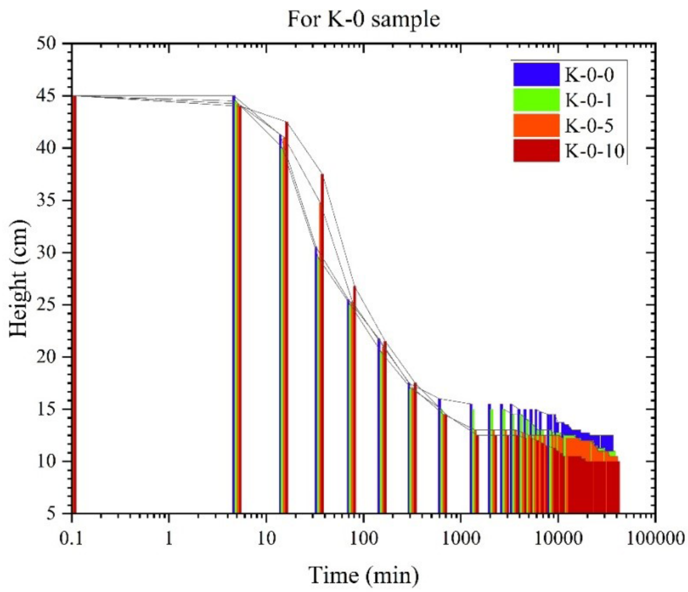
3. Results and Discussion

3.1. Dispersion Characteristics of Biochar Amended Saline Clay

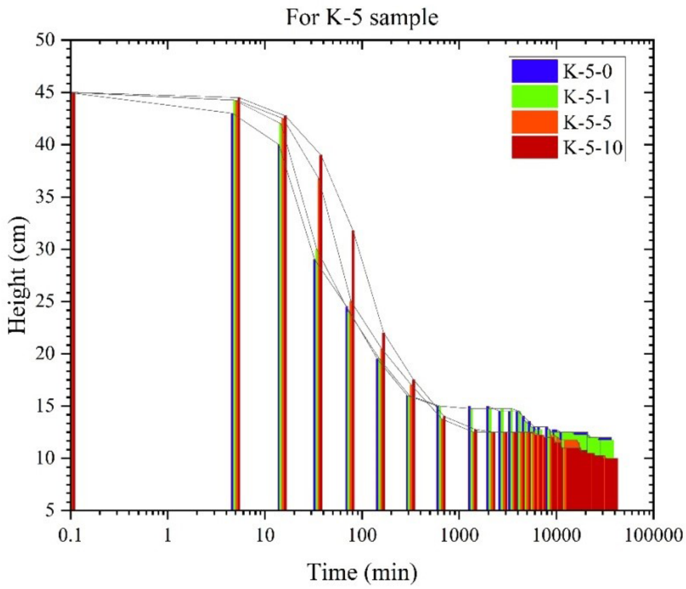
The changes in soil structure enhanced by biochar under varying pore water salinity levels have been well illustrated and described by Yan et al. (2024). It was stated in their study that the presence of multivalent cations in biochar counteracts the adverse effects of sodium ion (Na^+) accumulation, which typically weakens soil aggregates and instead promotes their formation. Biochar acts as a binder, creating larger soil aggregates and thus reducing the average soil void ratio. The oxidised surface of biochar contains functional groups (hydroxyl and carboxyl groups) (Kim et al., 2023). Microscopic analysis reveals that soil micro-aggregates coalesce after the addition of biochar. This improvement is likely due to reduced repulsive forces and increased attractive forces as biochar content rises, leading to less soil dispersion. Microbial activity due to the presence of biochar produces mucus, and mycelium forms connections between soil particles and biochar, contributing to the binding of soil particles into micro-aggregates. These micro-aggregates then combine to form larger structures (Jien & Wang, 2013)—higher biochar content results in more pronounced particle aggregation. Due to the presence of biochar, there can likely be an enhancement in the average mass-weighted diameter of aggregates. This is expected due to aggregation caused by biochar mineralisation (Cheng et al., 2006). Gunarathne et al. (2020) observed that biochar's cation exchange capacity (CEC) outperforms other organic amendments like compost and sludge. Biochar can decrease soil salinity stress, while other organic materials may induce more salinity. The reduction in soil pores become more evident with an increase in biochar content (Yan et al., 2024). Untreated clay samples showed better dispersion, as shown from the turbidity of the water in the beaker, and therefore showed significant dispersion behavior (Reddy et al., 2018). The observation can be attributed to the expansion of the particles and the enhancement of the spacing between them, which reduces the inter-particle force and leads to the loss of true cohesion. The high dispersion in saline-alkaline land is mainly due to the high level of exchangeable sodium ions. These research results provide valuable insights into the role of biochar in decreasing dispersion, and provide solutions for environmentally friendly soil management under challenging saline-alkaline conditions common in Central Asia.

3.2. Sedimentation Behavior

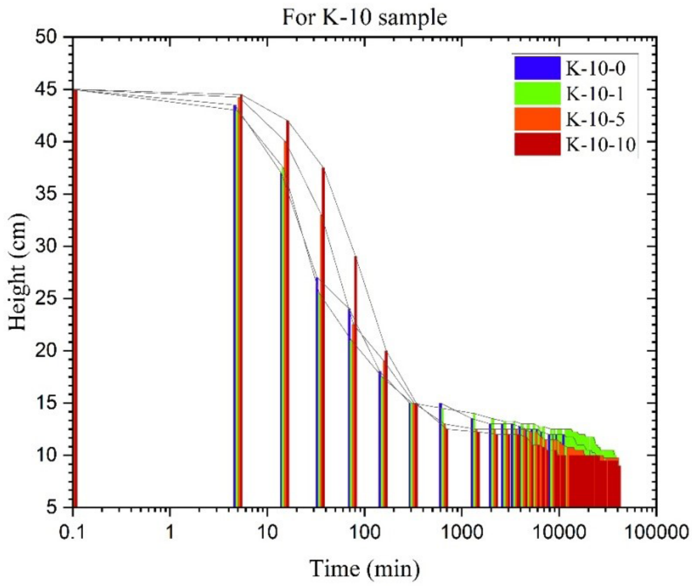
Figures 1 and 2 respectively show the changes in soil height of biochar-modified kaolin and bentonite soils with sedimentation time at different pore water salinity levels. As can be seen from the figure, when bare kaolin is mixed with deionized water, the sedimentation rate of the second 5000-minute interval (t=5001-10,000 min) is reduced ten times compared with the first 5000 minutes. On the other hand, the sedimentation rate in bare bentonite soil remains relatively stable over time. The sedimentation height of kaolin and bentonite decreases, and the salinity of pore water increases. In the brine environment, clay particles form a flocculation structure and enhance sedimentation. Once the sedimentation reaches the limit, the influence of pore water salinity on the height of kaolin soil is negligible. This phenomenon has also been observed in previous studies (Zhang et al., 2019). A study by Sides and Barden (1971) found that kaolin tends to form large colloidal inert particles, making flocculation more difficult. As the NaCl concentration increases, the thickness of the sediment decreases, which can be attributed to the degree of flocculation in the suspension (Mitchell, 1956). Lina et al. (2023) It was observed that the aggregation of kaolin becomes more significant with the increase of salt content, because the dissolved salt changes the inter-particle force through osmotic suction, affecting the soil structure and reducing sedimentation and dispersion. Yan et al. (2024) Found that clay can form unique face-to-face and edge-to-edge aggregations at high salinity levels, thereby changing the soil height during sedimentation experiments. This structural change is due to enhanced soil aggregation and reduced dispersion of clay particles in NaCl solution. However, Qadir et al. (2009) Found that the presence of excessive salt can also cause soil to disintegrate, expand and disperse. This is an important consideration in Central Asia, where secondary salinization is a major problem. Figures 3 and 4 show the sedimentation heights of biochar-modified soils (kaolin and bentonite, respectively) under different pore water salinity conditions. With the increase of salt content, adding 5% and 10% biochar reduces the height of kaolin soil by about 1.5-3% and 4.5-13.5%, respectively. The effect of biochar on bentonite is not as obvious as that on kaolin. At higher pore water salinity, 5% and 10% biochar reduce the height of kaolin soil by 1.5-2.8% and 2.5-8.5%, respectively. For 5% biochar modified bentonite at 0% pore water salinity, the soil height remains the same, while 10% biochar increases the soil height by 1%. Głodowska et al. (2017) Revealed that the porous structure of biochar adsorbs sodium ions from the soil solution and converts them into large colloidal inert particles. This adsorption capacity reduces sodium-induced clay flocculation through the porous structure, surface area and functional groups of biochar. Therefore, biochar reduces salinity-driven flocculation and improves soil stability-a promising mechanism for improving salt-affected soils in regions such as Central Asia. In summary, the results can be divided into three key salinity response categories: (1) low salinity (0-1% NaCl), in which biochar effectively improves dispersion and structure; (2) medium salinity (1-5% NaCl), in which the benefits persist but decrease; and (3) high salinity (5-10% NaCl).



(a)

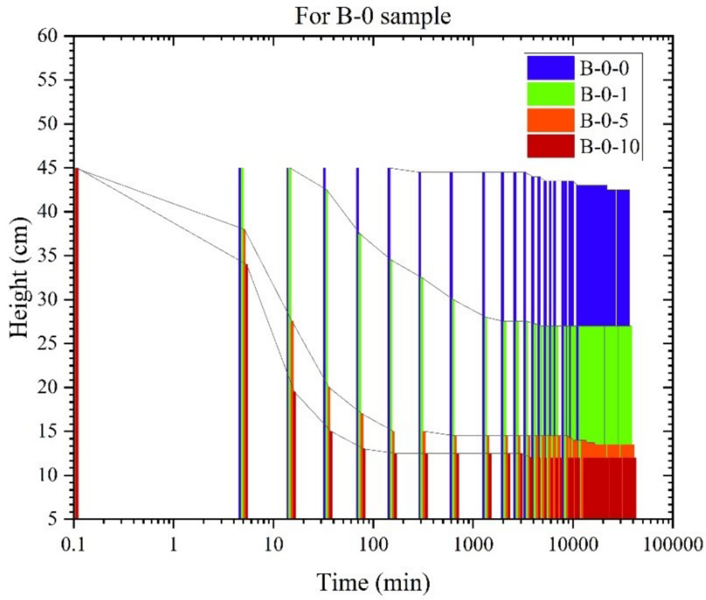


(b)



(c)

Figure 1. Illustration of the sedimentation height of kaolin soils amended with biochar at (a) 0 %, (b) 5 %, and (c) 10 % content


For B-0 sample
B-0-0
B-0-1
B-0-5
B-0-10
Height (cm)
Time (min)
60
55
50
45
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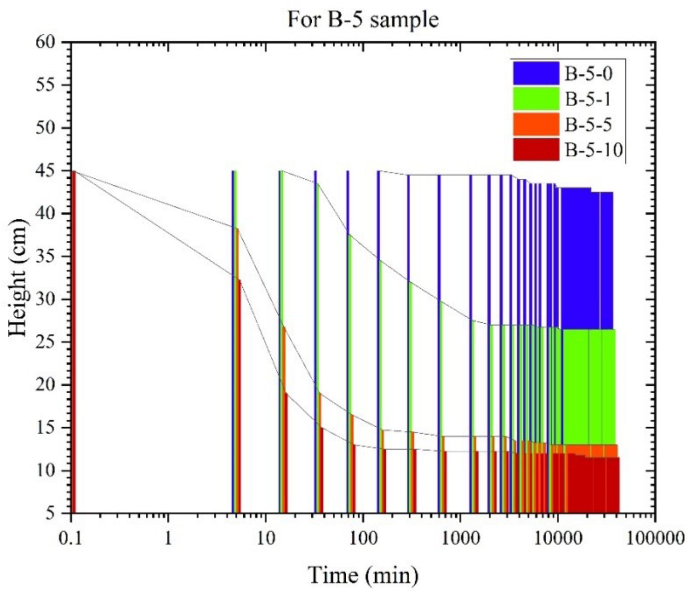
35
30
25
20
15
10
5
0.1
1
10
100
1000
10000
100000

(a)


For B-5 sample
B-5-0
B-5-1
B-5-5
B-5-10
Height (cm)
Time (min)
60
55
50
45
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35
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25
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15
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5
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1
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100
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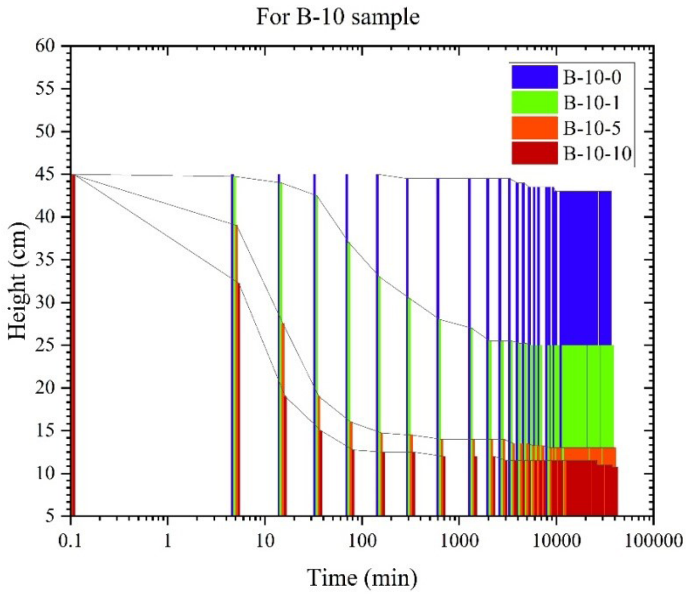
(b)



(c)

Figure 2. Illustration of the sedimentation height of bentonite soils amended with biochar at (a) 0 %, (b) 5 %, and (c) 10 % content

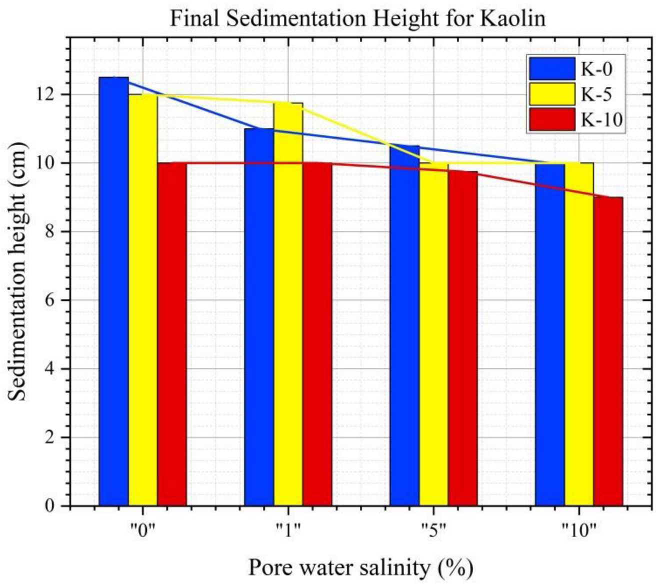


Figure 3. Illustration of the sedimentation height of biochar-amended kaolin under different pore water salinity conditions

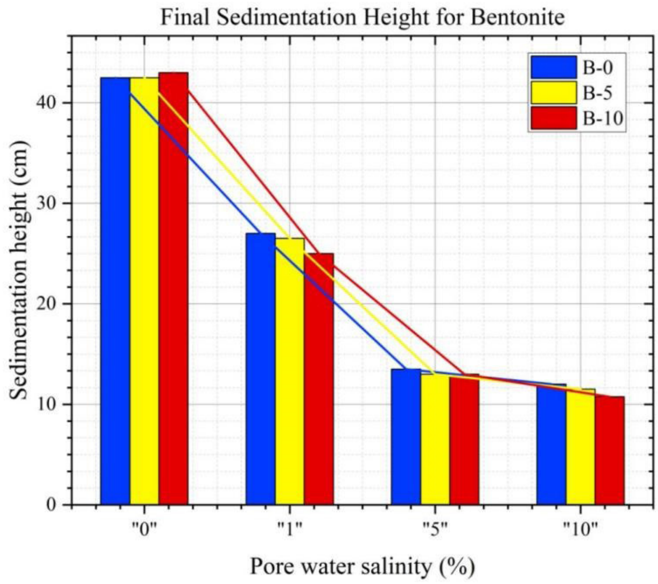


Figure 4. Illustration of the sedimentation height of biochar-amended kaolin under different pore water salinity conditions

4. Conclusions

This study investigates the influence of biochar on the dispersion and sedimentation behavior of clayey soils under varying salinity conditions. Experiments were conducted using biochar at different amendment ratios (0%, 5%, 10%) and NaCl concentrations (0%, 1%, 5%, 10%), selected to reflect salinity ranges typical of Central Asian soils. Results indicate that biochar enhances clay dispersion through ionic bonding with clay particles while promoting microbial activity, thereby improving soil structure. However, these beneficial effects diminish with increasing porewater salinity, underscoring the need for context-specific biochar application in soil management. Peach pit biochar exhibited a more pronounced impact on kaolin's sedimentation behavior compared to bentonite, with clay response depending on flocculation degrees. The findings demonstrate biochar's efficacy in regulating clay dispersion and enhancing soil fabric structure, particularly under low-salinity conditions. While its effectiveness declines with higher salinity, biochar amendment shows potential to mitigate some adverse effects of elevated salinity, offering practical relevance for degraded soils in regions like Central Asia. Although the discussion focuses on laboratory data, the study bridges mechanistic insights with field-scale implications. A systematic classification of the results could further clarify their applicability across diverse soil types and salinity regimes.

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