

Effects of Bentonite on the Physicochemical Properties of Aeolian Sandy Soil and Growth of Sudan Grass: Postprint

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Abstract

Drought and desertification have become worldwide resource and environmental issues, severely limiting agricultural and forestry production and crop growth in desertified regions. Therefore, developing a material that can both retain water and improve soil physicochemical properties is crucial for the development of these areas. Bentonite, as a natural mineral, possesses a unique crystal structure that endows it with excellent water absorption, storage, retention, and adsorption capacities. Investigating the effects of adding bentonite materials at different mass fractions and combinations on the water retention capacity, physical property improvement, and plant growth of aeolian sandy soil holds significant practical importance. The results showed that: (1) The addition of 0.5% bentonite (B1), 2.0% bentonite (B4), and 2.0% bentonite + 1.0% organic fertilizer (BF4) significantly increased the water content of aeolian sandy soil by 19.4%~21.9%. (2) All bentonite treatments significantly improved the physical properties of aeolian sandy soil. Specifically, when the bentonite addition rate increased from 1.5% to 2.0%, the bulk density of potted soil decreased significantly by 9.9%~11.1% ($P < 0.05$), total porosity increased significantly by 11.7%~13.1% ($P < 0.05$), permeability coefficient decreased significantly by 56.7%~73.3% ($P < 0.05$), and field water capacity increased significantly by 15.4%~16.1% ($P < 0.05$). (3) The addition of bentonite ($B > 0.5\%$) significantly increased the pH of aeolian sandy soil ($P < 0.05$), while other treatments had no significant effect on pH ($P > 0.05$). The addition of bentonite and humic acid (BA) and bentonite + organic fertilizer + humic acid (BFA) significantly increased the electrical conductivity of aeolian sandy soil ($P < 0.05$). (4) Regarding plant growth, the study found that the addition of bentonite and organic fertilizer increased the germination rate and biomass of *Sorghum sudanense*. (5) Correlation analysis and redundancy analysis results indicated that bentonite and organic fertilizer play important roles in plant growth by improving soil physicochemical properties. (6) Scanning electron microscopy

(SEM) results revealed that bentonite rapidly absorbs water and expands upon contact with water, binding sand particles together and fully exerting its adsorption and binding functions. In summary, the addition of bentonite and organic fertilizer to aeolian sandy soil can improve its physical properties, enhance its water retention capacity, and is beneficial for the improvement of aeolian sandy soil and vegetation restoration in desertified regions.

Full Text

Preamble

Effects of Bentonite on the Physical and Chemical Properties of Aeolian Sandy Soil and Growth of *Sorghum sudanense*

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Abstract: Drought and desertification have become worldwide resource and environmental problems that severely limit agricultural and forestry production and crop growth in desertification areas. Developing materials that can both retain water and improve soil physicochemical properties is therefore crucial for sustainable development in these regions. Bentonite, a natural mineral with a unique crystal structure, exhibits excellent water absorption, storage, and retention capabilities, along with strong adsorption capacity. This study investigated the effects of adding bentonite at different mass fractions and in various combinations with organic fertilizer and humic acid on the water retention capacity, physical property improvement, and plant growth in aeolian sandy soil. The results demonstrated: (1) The addition of bentonite at 0.5% (B₁), 2.0% (B₄), and the combination of 2.0% bentonite with 1.0% organic fertilizer (BF₄) significantly increased soil moisture content by 19.4%–21.9% (P<0.05). (2) All bentonite treatments significantly improved the physical properties of aeolian sandy soil, with bentonite additions exceeding 0.5% significantly reducing bulk density by 9.9%–11.1% (P<0.05), increasing total porosity by 11.7%–13.1% (P<0.05), decreasing permeability coefficient by 56.7%–73.3% (P<0.05), and increasing field water-holding capacity by 15.4%–16.1% (P<0.05). (3) Bentonite

addition exceeding 0.5% significantly increased soil pH ($P < 0.05$), while other treatments showed no significant effect on pH ($P > 0.05$). The combination of bentonite with humic acid (BA) and the combination of bentonite, humic acid, and organic fertilizer (BFA) significantly increased soil electrical conductivity ($P < 0.05$). (4) Plant growth studies revealed that bentonite (B) and bentonite-organic fertilizer (BF) treatments improved both germination rate and biomass of *Sorghum sudanense*. (5) Correlation and redundancy analyses indicated that bentonite and organic fertilizer significantly influenced plant growth by improving soil physicochemical properties. (6) Scanning electron microscopy revealed that bentonite rapidly absorbs water and expands when hydrated, binding sand particles together and demonstrating its adsorption and cementation functions. In conclusion, adding bentonite and organic fertilizer to aeolian sandy soil can improve its physical properties and water retention capacity, which is beneficial for soil improvement and vegetation restoration in desertification areas.

Keywords: bentonite; soil amelioration; physicochemical properties; growth status

1.1 Materials Selection

This study utilized the annual herbaceous plant *Sorghum sudanense* (Sudan grass) as the experimental subject for pot experiments. Sudan grass was selected for its high yield, drought tolerance, high nutritional value, rapid growth, and strong regeneration capacity [16]. The aeolian sandy soil used in the pot experiments was collected from the southwestern side of the Mosuowan Desert Research Station of the Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, located in the Gurbantunggut Desert (45°07' 11" N, 86°00' 56" E). The sampling depth was 0–20 cm, with the soil consisting primarily of fine sand, of which particles with diameters of 0.05–0.25 mm accounted for 61.4%. The organic matter content of the aeolian sandy soil was $1.5 \text{ g} \cdot \text{kg}^{-1}$, total nitrogen content was $0.1 \text{ g} \cdot \text{kg}^{-1}$, total phosphorus content was $0.3 \text{ g} \cdot \text{kg}^{-1}$, and available nitrogen content was $6.0 \text{ mg} \cdot \text{kg}^{-1}$. The particle size distribution is shown in .

The bentonite used in this experiment was a natural sodium-based bentonite with specific physical properties detailed in . Organic fertilizer was a high-quality universal organic fertilizer for plants, flowers, and fruits. Humic acid was purchased from Angel Yeast Co., Ltd.

1.2 Experimental Design

This study established 17 treatment groups: pure aeolian sandy soil (CK), bentonite-only treatments (B_1 – B_4), bentonite combined with organic fertilizer (BF_1 – BF_4), bentonite combined with humic acid (BA_1 – BA_4), and bentonite

combined with both organic fertilizer and humic acid (BFA₁–BFA₄). Except for the CK and pure bentonite treatments, all other treatments included four gradients (see for specific ratios). In the BF and BFA combinations, organic fertilizer was added at 1.0% of sand mass. In the BA and BFA combinations, humic acid was added at 0.5% of sand mass. Bentonite was added at 0.5%, 1.0%, 1.5%, and 2.0% of sand mass across the gradient treatments. Each treatment had five replicates.

The pot experiment was conducted under controlled indoor conditions. Pots measured 20.0 cm in height and 15.0 cm in diameter at the opening. On May 15, 2021, five seeds were sown per pot and covered with 0.5–1.0 cm of soil. Initial watering brought soil moisture to 70% of saturated water content. After seedling emergence, plants were thinned to three uniform, robust seedlings per pot when the average plant height reached 5 cm. Plants were subsequently watered every three days to maintain soil moisture at 70% of saturated water content. The average room temperature during the 90-day growth period was 25°C, with average humidity set at 40%. Plants were harvested after 90 days for biomass determination, and soil samples were collected from each pot for physicochemical property analysis.

1.3 Soil Analysis

Soil physicochemical properties were analyzed using standard methods from *Methods for Agrochemical Analysis of Soil* [17] and *Determination of Soil Physical Properties* [18]. Soil pH and electrical conductivity were measured using the potentiometric method (soil-water ratio of 1:5) with a PHSJ-5 pH meter and DDS-307 conductivity meter. Soil bulk density, total porosity, and permeability coefficient were determined using the ring knife method. Field water-holding capacity (maximum water-holding capacity) was measured using the Wilcox method. Soil water content (mass water content) was determined gravimetrically. Plant biomass was measured by washing harvested plants with deionized water, drying surface moisture, and weighing fresh weight.

1.4 Scanning Electron Microscopy Analysis

Aeolian sandy soil mixed with 2.0% bentonite by mass was hydrated with 20% water by mass and air-dried indoors. After drying at 105°C and cooling, samples were observed using a Zeiss Supra55 VP scanning electron microscope to examine the physical structure of bentonite-treated aeolian sandy soil.

1.5 Statistical Methods

Data organization and analysis were performed using Microsoft Excel 2019 and SPSS 26.0 software. One-way ANOVA was used to analyze soil water content, pH, electrical conductivity, bulk density, total porosity, permeability coefficient, field water-holding capacity, Sudan grass germination rate, and biomass, with least significant difference (LSD) tests for pairwise comparisons. Origin 2022b software was used for figure preparation.

2.1.1 Soil Water Retention Capacity

The comparison of soil water content across different treatments is shown in [Figure 1: see original paper]. On day 1 after watering, no significant differences existed among treatments ($P > 0.05$). By day 7, the B_1 , B_4 , and BF_4 treatments showed significantly higher soil water content compared to CK ($P < 0.05$), while other treatments did not differ significantly from CK ($P > 0.05$). By day 14, water content in CK, BF_2 , BA_1 , BA_2 , and BFA_1 treatments decreased significantly by 10.0%–11.9% compared to day 7 ($P < 0.05$), whereas B_4 , BF_4 , BA_4 , and BFA_4 treatments showed significant increases of 19.4%–21.9% ($P < 0.05$). By day 21, water content in CK, BF_1 , BF_2 , BA_1 , BA_2 , BFA_1 , and BFA_2 treatments decreased significantly by 18.2%–36.6% ($P < 0.05$), while B_4 , BF_4 , BA_4 , and BFA_4 treatments remained significantly elevated by 20.2%–21.9% ($P < 0.05$).

2.1.2 Soil Physicochemical Properties

The addition of bentonite ($B > 0.5\%$) significantly increased soil pH ($P < 0.05$), while other treatments showed no significant effect on pH ($P > 0.05$). The BA and BFA treatments significantly increased soil electrical conductivity ($P < 0.05$), whereas other treatments had no significant effect ($P > 0.05$). As shown in , when bentonite addition exceeded 0.5%, potting soil bulk density decreased significantly by 9.9%–11.1% ($P < 0.05$), total porosity increased significantly by 11.7%–13.1% ($P < 0.05$), and field water-holding capacity increased significantly by 15.4%–16.1% ($P < 0.05$). In other treatments, as bentonite addition increased from 0.5% to 2.0%, bulk density decreased significantly by 4.6%–14.5% ($P < 0.05$), permeability coefficient decreased significantly by 6.8%–19.4% ($P < 0.05$), total porosity increased significantly by 18.2%–36.6% ($P < 0.05$), and field water-holding capacity increased significantly by 60.0%–80.0% ($P < 0.05$).

2.2 Effects of Different Bentonite Additions on Sudan Grass Germination and Growth

Different bentonite treatments produced varying effects on Sudan grass germination and growth. As shown in [Figure 3: see original paper], B and BF treatments increased germination rates by 6.7%–26.7% compared to CK. When bentonite addition was low (B=0.5%), germination rates increased by 13.3%–33.3%. However, germination rates decreased as bentonite addition increased from 1.0% to 2.0%, particularly in BA treatments where rates declined by 26.7%–40.0%. Biomass increased by 13.5%–16.5% with B addition and by 20.0%–40.0% with BF addition. When B=0.5%, biomass increased by 41.1%–61.8%. However, BA addition significantly reduced biomass by 1.5%–8.6% ($P<0.05$).

2.3 Correlation and Redundancy Analysis

Correlation analysis revealed that bentonite was significantly positively correlated with soil pH, electrical conductivity, and field water-holding capacity ($P<0.01$), significantly positively correlated with total porosity ($P<0.05$), and significantly negatively correlated with soil bulk density and permeability coefficient ($P<0.01$). Organic fertilizer was significantly negatively correlated with soil pH ($P<0.05$) and permeability coefficient ($P<0.01$), and significantly positively correlated with other soil properties ($P<0.01$). Humic acid was significantly positively correlated with electrical conductivity and field water-holding capacity ($P<0.01$). Redundancy analysis showed that soil physicochemical properties under bentonite addition explained 53.165% of the variation in Sudan grass growth status. Germination rate was positively correlated with soil bulk density and permeability coefficient, and negatively correlated with electrical conductivity and total porosity. Biomass was positively correlated with permeability coefficient and pH, and negatively correlated with electrical conductivity and bulk density. Different treatments indirectly affected plant growth by influencing soil physicochemical properties.

2.4 Scanning Electron Microscopy Observations

[Figure 5: see original paper] presents SEM images of aeolian sandy soil and soil treated with 2.0% bentonite at 300 \times magnification. Natural aeolian sandy soil exhibited relatively smooth surfaces with large voids between sand particles that were not adsorbed or cemented together. In contrast, bentonite addition formed coatings on sand particle surfaces upon hydration, with bentonite binding, adsorbing, and aggregating with aeolian sand particles to create rough-surfaced aggregates.

3.1 Bentonite's Role in Improving Aeolian Sandy Soil Physical Structure

Soil bulk density, total porosity, and permeability coefficient are key indicators characterizing soil physical properties that influence water, nutrient, air, and heat conditions and affect crop health [19]. Clay minerals, with their large specific surface area and adsorption/cementation capabilities, play important roles in improving soil physical structure [8]. In B treatments, increasing bentonite content significantly reduced bulk density and increased porosity, confirming that bentonite addition benefits aeolian sandy soil physical properties. This aligns with Zhou Lei's findings [21] that a single application of 2.0% bentonite significantly improved sandy soil structure, reducing bulk density by 2.0%–9.0% and increasing total porosity. These effects relate to bentonite's colloidal value, swelling capacity, methylene blue adsorption, water absorption/expansion properties, cementation, and large specific surface area [34]. As observed via SEM, these characteristics enable bentonite to effectively adsorb and cement fine particles, promote macro-aggregate formation, and improve soil bulk density and porosity. Additionally, bentonite addition significantly reduced permeability coefficient, consistent with Zhao Xu et al.'s [35] indoor simulation results showing reduced saturated hydraulic conductivity, air conductivity, and relative gas diffusivity. This occurs because bentonite's water absorption and expansion properties allow it to retain water, swell, and block soil pores, obstructing water percolation pathways. Bentonite also exhibits rheological properties when hydrated and maintains its expanded state upon drying, demonstrating the rheological and solidification characteristics of soil amendments described in previous research [20].

Field water-holding capacity is a crucial indicator of soil water retention, particularly important for irrigation and water management in arid regions [27]. This study demonstrated that bentonite and organic fertilizer addition improved aeolian sandy soil water retention and increased field water-holding capacity, consistent with findings by Ma Bin et al. [28] and Li Jijin et al. [29]. This improvement occurs because bentonite's high clay content and hygroscopicity enable it to adsorb water volumes 8–20 times its own weight [30], while bentonite and organic matter increase clay content, promote aggregate formation, and alter the loose structure of aeolian sand, thereby enhancing water retention capacity [31].

3.2 Potential Salinization Risk from Bentonite Addition

Soil pH and electrical conductivity are indicators that rapidly reflect general soil chemical conditions [32]. This study found that bentonite addition exceeding 0.5% significantly increased soil pH ($P < 0.05$), while other treatments did not significantly affect pH. This may occur because bentonite contains exchangeable base cations (Na^+ , K^+ , Ca^{2+} , Mg^{2+}) and carbonates that increase soil alkalinity, while humic acid and organic fertilizer contain acidic organic colloids that neu-

tralize soil alkalinity. Electrical conductivity reflects soluble salt content, with excessive salinity negatively impacting plant growth. This study showed that bentonite and humic acid addition was significantly positively correlated with electrical conductivity, with BA and BFA treatments significantly increasing aeolian sandy soil conductivity. This may result from the sodium-based bentonite containing Na^+ and carbonates, and humic acid containing basic groups, leading to increased soil conductivity. Therefore, practical bentonite application must consider addition rates to avoid soil salinization and may require selection of salt-tolerant plant species. Bentonite should be avoided in saline-alkali soils to prevent exacerbating salinization problems.

3.3 Effects of Bentonite Addition on Sudan Grass Growth

This study demonstrated that bentonite addition to aeolian sandy soil improved Sudan grass germination rates and biomass, consistent with most previous research. Harbi et al. [33] reported that bentonite addition significantly increased marigold yield in greenhouse pot experiments. Song Jiping et al. [36] found that bentonite had significant positive effects on cucumber growth. These benefits likely occur because bentonite improves soil physical structure and water retention while introducing essential macro- and micronutrients, creating favorable water, nutrient, air, and heat conditions that enhance photosynthetic characteristics [37] and promote plant growth.

This study's combined application of bentonite and organic fertilizer increased both germination rate and biomass compared to the control, likely due to synergistic effects that improved water and nutrient retention in aeolian sandy soil. Similar results were reported by Wang Ying et al. [38] and Zhou Lei et al. [31], particularly showing that adding humic acid or mushroom residue to bentonite-based amendments promoted aggregate formation and improved water/fertilizer retention in sandy soils, significantly enhancing corn germination, daily height increment, and seedling dry matter accumulation rate.

However, this study found that humic acid addition negatively affected Sudan grass growth, with both germination rate and biomass decreasing compared to the control. This correlates with the rapid water content decline in humic acid treatments over time and may result from increased soil salinity (electrical conductivity) inhibiting germination and growth [39]. Another possibility is that bentonite and humic acid form a consolidated surface crust after water absorption and drying, impeding seedling emergence [40]. These findings suggest that humic acid should be used cautiously with bentonite, as it may limit plant growth despite humic acid's generally recognized benefits, possibly due to interaction effects that warrant further investigation.

3.4 Application Prospects of Bentonite in Aeolian Sandy Soil Improvement

China possesses the world's largest bentonite reserves, with diverse types that are easily mined and inexpensive [41]. Most wind-sand disaster areas and their neighboring regions have abundant bentonite resources. Utilizing bentonite's natural properties combined with local agricultural and forestry waste (crop straw, dead branches, leaves, rice husks, wood chips) to prepare soil amendments enables resource-efficient, site-specific solutions that reduce costs for sandy soil improvement and vegetation restoration in wind-sand disaster areas. However, considering salinization issues in arid desert regions and bentonite's potential to cause secondary salinization, ecological restoration efforts should select not only water-saving and drought-resistant species but also halophytes or salt-alkali tolerant species.

4 Conclusion

Aeolian sandy soils in desert regions are dominated by sand particles with minimal clay content, resulting in loose structure and poor water-holding capacity that urgently require improvement. Bentonite's water absorption, expansion, and cementation properties enable it to effectively adsorb and bind sand particles, promoting aggregate formation. This study confirmed that adding bentonite and organic fertilizer to aeolian sandy soil not only improved water retention but also enhanced physical properties, thereby increasing Sudan grass germination rate and biomass. These effects positively influence plant growth and survival in arid regions. Therefore, rational development and utilization of bentonite combined with other organic materials to leverage its beneficial properties is significant for improving aeolian sandy soil quality, ecological restoration, and vegetation reconstruction in arid desertification areas.

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