Effects of Bentonite Amendment on Physicochemical Properties and Vegetation Growth of Wind-eroded Desertified Soil: Postprint

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Abstract

Abstract: Desertification is a critical ecological and environmental challenge facing the world today, seriously constraining the sustainable development of regional economies and ecological environments. In recent years, clay minerals have been widely used in the improvement of aeolian sandy soils, and bentonite, with its unique 2:1 layered structure, demonstrates promising application prospects in the amelioration of aeolian sandy soils. This study investigates the effects of different bentonite application rates (no bentonite addition (B0), 2% bentonite addition (B2), 4% bentonite addition (B4)) on the physicochemical properties of wind-eroded desertified soils and vegetation growth. The results indicate: (1) Bentonite addition increased soil silt and clay content, and enhanced the water retention and water holding capacity of aeolian sandy soils by 12%~88%. (2) The shear strength of aeolian sandy soils with B2 and B4 bentonite addition increased by 150% and 205%, respectively, compared to the B0 treatment. (3) Bentonite addition can induce crust formation on the sand surface, which is beneficial for stabilizing shifting sand. (4) The aeolian sandy soil with B4 bentonite addition significantly increased plant coverage, biomass, and plant height by 32%~33%, 56%~85%, and 71%~107%, respectively. In summary, bentonite addition not only improved the water holding capacity of sandy land, ameliorated soil physical properties and stabilized shifting sand surfaces, but also promoted plant growth.

Full Text

Effects of Bentonite Addition on Physicochemical Properties and Vegetation Growth of Wind-Eroded Sandy Soil

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Abstract

Desertification represents a severe ecological and environmental challenge worldwide, significantly constraining sustainable regional economic and environmental development. In recent years, clay minerals have been widely applied for wind-eroded sandy soil improvement, with bentonite showing particularly promising prospects due to its unique layered structure. This study investigated the effects of different bentonite application rates [no bentonite addition (B0), 2% bentonite addition (B2), and 4% bentonite addition (B4)] on the physicochemical properties of wind-eroded sandy soil and vegetation growth. The results demonstrated that: (1) Bentonite addition increased soil silt and clay content, enhancing water retention and water-holding capacity by 12%-88%. (2) The shear strength of wind-eroded sandy soil with B2 and B4 treatments increased by 150% and 205%, respectively, compared with the B0 treatment. (3) Bentonite application facilitated crust formation on sandy surfaces, beneficial for sand fixation. (4) Bentonite addition significantly improved plant coverage, biomass, and height by 32%-33%, 56%-85%, and 71%-107%, respectively. In summary, bentonite amendment not only enhanced water-holding capacity and improved soil physical properties and surface stabilization but also promoted plant growth in sandy environments.

Keywords: sandy soil amelioration; soil water conservation; soil shear strength; sand fixation mechanisms

1 Introduction

Desertification constitutes one of the most pressing ecological and environmental issues globally. As one of the countries severely affected by land desertification, China faces desertified land covering a substantial portion of its total territory, causing soil and vegetation degradation and triggering wind-sand hazards. Current biological and engineering sand control methods exhibit various limitations regarding water resource requirements, engineering investment, effectiveness, and maintenance. Natural, non-toxic sandy soil amendments with wide availability, low cost, and environmental safety are considered important materials for the "green material world" of the 21st century.

Bentonite, as a natural inorganic amendment, holds significant potential for desertification control and ecological restoration due to its extensive distribution, large reserves, and adsorptive properties. Previous research has demonstrated that bentonite fills voids between sand particles, binding them into aggregates and facilitating soil physical crust formation. Studies have shown that bentonite application improves soil hydrothermal conditions and enhances water and nutrient retention capacity. Other investigations have found that adding woody peat and bentonite can increase organic carbon content and promote carbon accumulation. Research in sandy soils has identified bentonite as an effective material for soil ecological restoration.

However, most existing studies have focused on bentonite's effects on soil physicochemical properties or remained confined to laboratory-controlled experiments, with little investigation into field-based sand surface stabilization and ecological restoration. This gap has limited the full exploitation of bentonite' s potential in desertification prevention and ecological recovery.

Chaiwopu Lake, an important water supply source in the southern intermountain basin of Urumqi, was once the largest natural freshwater lake near Urumqi, recognized as one of the "New Ten Scenic Spots" of the city and serving as the "kidney" and "lung" of Xinjiang' s capital. As a representative temperate arid zone lake wetland in China, it plays a crucial role in climate regulation, water conservation, and flood prevention for Urumqi. However, due to excessive groundwater extraction, the lake has experienced continuous area shrinkage, regional environmental deterioration, and ecosystem imbalance. Since 2015, Urumqi has implemented emergency ecological restoration measures including "fallowing to replenish the lake." Although these efforts have substantially restored the lake area from a minimum of 0.18 km^2, dramatic fluctuations in lake and groundwater levels have triggered ecological problems, particularly severe wind erosion and desertification in the western lake area. Therefore, ecological restoration of the wind-eroded and desertified zone is essential for ensuring Urumqi' s ecological security.

1.1 Study Area Overview

The study area is located in the western part of Chaiwopu Lake, Xinjiang Uygur Autonomous Region (43°49 85 N, 87°90 95 E). The region has an annual average temperature of 5.0°C, with abundant wind resources and prevailing westerly winds. Annual precipitation is 64 mm, while annual evaporation reaches 2716 mm. The area experiences more than 200 windy days annually, with maximum wind speeds exceeding 26 $m \cdot s^{-1}$ on over 120 days. The soil texture is sandy soil formed by wind erosion and desertification, with basic physicochemical properties shown in Table 1.

[**Figure 1: see original paper**] Summary map of the study area

**** Physical and chemical properties of bentonite

**** Mineral composition and physical properties of bentonite

1.2 Experimental Materials

The bentonite used in this experiment was sodium-based bentonite provided by Qitai County Guoping Bentonite Mine in Xinjiang. The physicochemical properties of the bentonite are presented in Table 1. The planted grass species were *Agropyron cristatum* and *Artemisia desertorum*, sourced from Changji Boyun Grass Industry Co., Ltd. Irrigation water was drawn from a reservoir in the study area, with drip irrigation applied at a flow rate of 3 $L \cdot h^{-1}$, irrigating once every 120 days for a duration of 14.10 hours each time.

**** Bentonite material ratio and management method

1.3 Experimental Design

The experiment consisted of field experiments (sand surface fixation and vegetation planting) and laboratory experiments (bentonite water retention) to analyze the effects of bentonite on soil water-holding capacity, sand surface stabilization, soil physicochemical properties, and vegetation growth status.

1.3.1 Field Experimental Design To investigate the fixation effect of bentonite on wind-eroded sandy soil, crust formation experiments were conducted on May 15, 2023. Bentonite was added at two gradients (2% and 4%) to surface wind-sand soil (0–10 cm), mixed evenly, and moistened to form crusts upon surface drying. The crust experiment plots measured 2 m × 3 m. On May 25, seeds were sown with *A. cristatum* at 15 $kg \cdot hm^{-2}$ and *A. desertorum* at 7.5 $kg \cdot hm^{-2}$. Seeds were mixed and sown manually in rows along both sides of drip irrigation lines with 25 cm spacing and 2–3 cm depth. An additional plot without bentonite addition (B0) was established as a control for seeding. To more intuitively understand bentonite' s effects on vegetation growth while minimizing irrigation impacts, plants from the undisturbed native environment (CK) were measured as a control when determining plant indicators.

When plant biomass reached its maximum, plant and soil samples were collected to study the effects of different bentonite ratios on vegetation growth and soil physicochemical properties. Vegetation was harvested from 0.5 m × 0.5 m quadrats using a five-point sampling method in each plot. Plant height was measured with a ruler, coverage estimated visually, and plants cut at ground level. After harvesting, shear strength was measured and 0–10 cm soil samples were collected using a quartering method to retain 0.5 kg per plot. Vegetation samples were oven-dried at 105°C to record dry matter weight, and soil samples were labeled and returned to the laboratory for natural state analysis.

To assess the fixation effect of bentonite on wind-sand soil, surface shear strength of different bentonite crusts was measured 120 days after crust formation. Shear strength of the undisturbed native sandy environment (CK) was also measured for comparison to minimize irrigation effects.

1.3.2 Laboratory Experimental Design To investigate water retention capacity after bentonite application, wind-sand soil from the study area was brought to the laboratory. Bentonite was added at 2% and 4% ratios, mixed evenly, and 100 g of dried soil samples were placed in rings (volume 79.8 mm × 20 mm). Samples were saturated to maximum water-holding capacity, then placed in a constant temperature incubator at 25°C to measure daily weight changes. Each treatment was replicated three times.

1.4 Sample Collection and Measurement

Soil total nitrogen (TN) and total phosphorus (TP) contents were measured using perchloric acid digestion (SEA1 Auto Analyzer3, Germany). Soil ammonium nitrogen (NH_4^+-N) and nitrate nitrogen (NO_3^--N) contents were extracted with calcium chloride and measured using a continuous flow analyzer (SEA1 Auto Analyzer3). Soil pH and electrical conductivity (EC) were measured at a soil-water ratio of 1:5. Soil organic carbon (SOC) was determined using the potassium dichromate heating method. Field water-holding capacity was measured using the ring method. Soil bulk density and total porosity were calculated using standard formulas. Particle size distribution was measured using a laser particle size analyzer (Bettersize, Dandong). Sand surface shear strength was measured using a POCKET VANE ESTER-type three-head shear apparatus with a large spiral head. According to the instrument manual, shear strength was calculated using the formula: y = 0.2x, where x is the dial reading and y is the shear strength value ($kg \cdot cm^{-2}$).

Soil particle size was classified according to the USDA system: sand (50–2000 m), silt (2–50 m), and clay (<2 m). Fractal dimension was calculated following Wang Guoliang et al. The formula is: D = 3 - [log(V(r<RI)/VT)] / log(RI/rmax), where D is the fractal dimension of soil particle size, r is soil particle size, RI is the particle size of class i, rmax is the maximum soil particle size (0.25 mm), V(r<RI) is the soil volume with particle size smaller than RI, and VT is the sum of volume fractions of all particle size classes. Soil total porosity was calculated using bulk density with the formula: Total porosity (%) = (1 - bulk density/2.65) × 100%, assuming a soil particle density of 2.65 $g \cdot cm^{-3}$.

1.5 Data Processing

Soil physicochemical properties, vegetation growth, and shear strength indicators were organized using Excel 2016. Differences among treatments were analyzed using one-way ANOVA with Duncan's multiple comparison test. Relationships between soil physicochemical indicators, shear strength, and vegetation growth were analyzed using the "linkET" package in R software.

2 Results and Analysis

2.1 Effects of Bentonite Addition on Soil Water Retention Capacity Changes in water content of wind-sand soil under different bentonite treatments are shown in Figure 2. On day 1 after watering, no significant differences existed among treatments ($P > 0.05$). However, from day 3 to day 15, water content in bentonite-treated soils was significantly higher than in the B0 treatment ($P < 0.05$), with B4 showing significantly higher water content than B2 ($P < 0.05$). By day 30, the B4 treatment still exhibited significantly higher water content than B0 ($P < 0.05$), while the difference between B2 and B0 was not significant ($P > 0.05$). Overall, water content showed a positive correlation with bentonite application rate.

[**Figure 2: see original paper**] Change of indoor soil moisture content

2.2 Effects of Bentonite Addition on Soil Shear Strength Soil shear strength represents the soil' s resistance to shear failure. As shown in Figure 3, shear strength increased with bentonite application gradient. The shear strength of B2 and B4 treatments increased by 150% and 205%, respectively, compared with B0 ($P < 0.05$). The native environment (CK) showed the lowest shear strength. Compared with the B0 treatment that received only water, B2 and B4 treatments increased shear strength by 13%-34% and 35%-47%, respectively ($P < 0.05$), demonstrating a positive correlation between shear strength and bentonite addition.

Visual observation revealed that loose wind-sand soil (Figure 4a) developed a fixed physical crust after bentonite application (Figure 4b). Bentonite demonstrated effective physical crust formation on sandy surfaces, with the crust remaining intact and persistent even after 120 days (Figure 4c, d).

[**Figure 3: see original paper**] Shear strength of bentonite treated with different proportions
[**Figure 4: see original paper**] Contrast between bentonite crust and primary sandy soil

2.3 Effects of Bentonite Addition on Soil Physical Properties Although bentonite improved soil physical properties to some extent, differences among treatments were not significant. As shown in Figure 5, bentonite addition increased soil water content, total porosity, and field water-holding capacity while decreasing soil bulk density. Compared with B0, bentonite treatments increased soil water content, total porosity, and field water-holding capacity by 3%-4%, 1%-3%, and 3%-5%, respectively. Soil water content showed a positive correlation with bentonite application rate, while soil bulk density decreased by 0.7%-5% across bentonite treatments.

As shown in Table 4, wind-sand soil in the Chaiwopu area is dominated by silt, followed by sand, with clay being the least abundant. Bentonite treatments increased clay content, and fractal dimension increased with bentonite application rate.

[**Figure 5: see original paper**] Effects of bentonite on the physical properties of some soils

**** Soil particle composition and fractal dimension under different bentonite treatments

2.4 Effects of Bentonite Addition on Soil Chemical Properties Bentonite had varying effects on soil chemical properties (Figure 6). Soil pH showed a decreasing trend with increasing bentonite application, while EC exhibited an initial decrease followed by an increase. Compared with B0, pH in B2 and B4 treatments decreased by 1.5%-5% and 0.7%-2.6%, respectively. Total nitrogen, total phosphorus, and organic carbon showed no significant differences among treatments ($P > 0.05$), though nitrate nitrogen content in B4 treatment was significantly lower than in B0 ($P < 0.05$).

[**Figure 6: see original paper**] Effects of bentonite on chemical properties of some soils

2.5 Effects of Bentonite Addition on Vegetation Growth Bentonite addition promoted vegetation growth (Figure 7). Compared with CK, watering and bentonite addition significantly increased plant coverage ($P < 0.05$), with increases of 18%-162% for B2 and 31%-442% for B4. Plant biomass and height also increased by 32%-33% and 56%-85%, respectively, with B4 treatment showing significant improvement over B0 ($P < 0.05$). Plant height and biomass were also positively affected, increasing by 71%-107%.

[**Figure 7: see original paper**] The impact of bentonite on plant height, coverage and biomass

[**Figure 8: see original paper**] Photos of plant growth in different treatment plots of bentonite

Correlation analysis revealed significant relationships between plant growth and environmental factors (Figure 9). Soil fractal dimension and shear strength were the main factors affecting plant growth ($P < 0.001$). Plant growth was positively correlated with soil water content, total porosity, and shear strength, and negatively correlated with bulk density ($P < 0.05$). Shear strength was negatively correlated with fractal dimension ($P < 0.01$), while total porosity was significantly negatively correlated with bulk density ($P < 0.001$).

[**Figure 9: see original paper**] Analysis of correlation between bentonite planting vegetation and soil physicochemical properties and shear strength

3 Discussion

3.1 Role of Bentonite in Soil Water Retention Water is a key limiting factor for desert plant growth. Wind-sand soils have weak interparticle forces, large porosity, and poor water-holding capacity. Using clay minerals as soil amendments to improve wind-sand soil has been widely adopted. Numerous studies have shown that clay content can significantly improve soil moisture, enzyme activity, and fertility. Research indicates that clay microstructure characteristics are closely related to soil water retention curves. Clay application has been found to not only conserve water but also increase crop yields by 4–5 times. Therefore, using clay to improve wind-sand soil structure and water retention is considered an effective approach.

As a clay mineral, bentonite exhibits excellent water absorption and retention properties, which are particularly important in wind-sand soils. Laboratory water retention experiments showed that B4 treatment had significantly higher soil water content than B0, indicating that bentonite addition enhances water retention capacity. However, in field conditions, bentonite application showed only modest improvements in soil water content, likely due to complex environmental factors. Bentonite can expand 10–30 times when absorbing water, filling soil pores and increasing aggregate formation when applied to sandy land. This creates a network-like structure that effectively fixes surface soil particles, making sandy soil structure more compact and stable while reducing erosion by water and wind forces.

3.2 Role of Bentonite in Desertified Soil Remediation Sandy soils have loose particles, strong mobility, and weak interparticle interactions. As shown in Figure 4, bentonite application clearly induced crust formation on sandy surfaces (Figure 4b) compared with original sandy soil (Figure 4a). Shear strength increased by 150%-205% ($P < 0.05$). Abulimiti et al. demonstrated that bentonite-formed crusts had significantly higher strength than biological crusts under the same conditions, consistent with our results. While biological crust development requires several years in nature, bentonite mixed with sand particles forms crusts upon wetting and drying, greatly reducing crust formation time. The crust maintained relatively complete coverage after four months. Studies have shown that in arid regions with sparse vegetation, 1%–2% bentonite crust can effectively fix sand sources. However, unlike biological crusts, bentonite crusts cannot self-repair once damaged, reducing wind erosion resistance. Therefore, bentonite should be applied in areas with limited or no human disturbance to minimize maintenance requirements.

3.3 Cost-Effectiveness of Bentonite in Desertification Control As a readily available natural material, bentonite offers not only feasibility and durability but also superior economic benefits. For windbreak and sand fixation applications (e.g., in mining areas), bentonite can be mixed with 0.5 cm thick soil at a moderate ratio of 1%-2%, with raw material costs of 17,000–20,000 yuan per hectare. For slope protection and topsoil reinforcement, raw material costs are 34,000–40,000 yuan per hectare. Bentonite costs are lower than biological sand fixation, chemical sand fixation, and special material barriers. Although straw checkerboards and shelterbelts have lower raw material costs, their construction and maintenance costs exceed those of bentonite, as straw checkerboards require regular replacement and shelterbelts need long cultivation periods. For example, shelterbelts along the Tarim Desert Highway require over 10 years to mature.

3.4 Soil Physicochemical Response to Bentonite In this study, most soil physicochemical properties showed no significant differences between bentonite treatments and the control (B0), unlike results from Gao et al. and Mi et al. who reported significant improvements. This discrepancy may be attributed to the relatively short experimental duration (120 days), preventing full expression of bentonite properties. Research indicates bentonite effects can persist for 3–5 years, and complex field conditions may also influence results. The wind-sand soil in Chaiwopu is dominated by silt particles (Table 4), likely due to the lacustrine environment where gravel-grade sediments are ground into smaller, more stable sand fractions (0.001–2 mm) by water and wave action.

Fractal dimension reflects soil physical properties and structural complexity, serving as a quantitative indicator for soil fertility evaluation—higher fractal dimensions indicate greater fine particle content and better soil structure. In this study, B4 treatment showed the highest fractal dimension, increasing with bentonite addition, demonstrating that bentonite improved sandy soil structure.

3.5 Effects of Bentonite on Plant Growth Compared with CK and B0 treatments, B4 significantly increased plant height, coverage, and biomass, confirming that bentonite addition benefits vegetation growth. Previous studies have shown bentonite promotes growth of oats and alfalfa, consistent with our results. Bentonite increased plant biomass (Figure 7), likely due to its water retention properties facilitating water cycling in arid regions and creating favorable growth conditions. Bentonite also improved soil structure ($P > 0.05$), allowing plant roots to penetrate and expand more easily in the loosened, well-aerated soil. Good water permeability prevented root hypoxia and rot from waterlogging, providing a solid foundation for aboveground growth.

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4 Conclusion

Bentonite addition increased soil silt and clay content, improving water retention and water-holding capacity of wind-sand soil. The crust formed between bentonite and sandy soil significantly enhanced shear strength, which is important for sand fixation in desert and desertified areas. However, most soil physicochemical properties showed no significant differences from the control, possibly due to experimental duration and complex field conditions. For vegetation growth, B4 treatment significantly increased coverage, biomass, and plant height. Correlation analysis revealed significant relationships between soil fractal dimension, shear strength, and vegetation growth. In summary, bentonite amendment improved water-holding capacity, facilitated sand particle fixation, and promoted ecological restoration and plant growth in wind-eroded and desertified areas.

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