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Mechanisms of clay mulch in soil stabilization and dust control

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ABSTRACT

Wind erosion is among the most important land degradation processes especially in the arid and semi-arid regions. The use of clay mulches has gained attention as a novel and environmentally friendly method for soil stabilization and reduction of dust emissions. However, it is not yet fully clear how these mulches influence the development and reinforcement of soil surface seals (crusts), nor how the resulting changes affect soil shear strength (SS) and penetration resistance (PR).. This study aimed to experimentally evaluate the effects of bentonite clay mulch, applied at rates of 20 to 60 g m^{-2}, on the SS, PR, and saturated hydraulic conductivity (Ks) of the surface seal of a salt affected soil sample from the Segzi region (Isfahan Province). The results showed that both rainfall application and hand spraying, when applied alone, formed a surface seal with higher SS and PR and lower Ks compared to the untreated soil. Application of clay mulch, at 30 g m^{-2} rate, significantly increased shear strength (up to 36%) and reduced Ks (28-33%) compared to the control. However, with increasing mulch application rate from 30 to 50 g m^{-2}, the relative effect of mulch on increased shear strength diminished (from 36% to 7%), indicating the dominant role of sprayed water on initial seal formation. Microscopic examination revealed that the soil had very high salinity, which led to the formation of a mixed clay-salt type surface seal. The morphology of salt crystals in the presence of clay mulch differed markedly from that in the control sample. Considering both the seal SS and its Ks, the application of 20 g m^{-2} bentonite clay is proposed as the optimal rate for soil stabilization and dust suppression. However, due to the high soil salinity, generalization of the results to non-saline or low-salinity soils requires further investigation.

Keywords: Bentonite, salt crust, rainfall simulator, shear strength, penetration resistance.

1. Introduction

Wind erosion in the arid and semiarid areas is one of the most important land degradation processes in arid and semi-arid regions of the world, recognized as a serious challenge to sustainable production, food security, and the management of agricultural and natural ecosystems (Rafahi, 2012; Webb et al., 2014; Brahney et al., 2024). The environmental consequences of wind erosion extend beyond reduced soil fertility and land degradation and include emission of fine particles (dust) into the atmosphere, intensification of dust storms, air pollution, and increased respiratory diseases in the urban and rural areas (Nield et al., 2016a; Brahney et al., 2024; Papatheodorou and Achilleos, 2025). Furthermore, wind erosion acts as a key agent in the transport of microplastics from contaminated soils to remote areas and even oceans (Yu et al., 2025), and in the emission and transport of heavy metals into the atmosphere, thereby not only reducing air quality but also affecting the human and animal food chain through deposition on water and soil resources (Zhang et al., 2025). Wind erosion intensity is influenced by several factors including wind speed, soil moisture, surface roughness, particle size distribution, and the presence of surface crusts (Dong et al., 2002; Webb et al., 2014; Zamani and Mahmoodabadi, 2013).

In recent decades, the intensity, frequency, and extent of dust events in Iran have increased to such an extent that they have become a national and regional crisis. Isfahan province, due to its geographical location, arid and semi-arid climate, and presence of multiple wind erosion hotspots, is one of the critical areas for dust production in central Iran. Based on studies conducted to date, 16 wind erosion hotspots have been identified in this province, the most important of which is the Segzi region, covering an area of over 43,000 ha and located 25 km east of Isfahan (Jalalian, 2017a). In this region, the average wind speed at a height of 10 m is 3.04 m s^{-1}, the maximum recorded wind speed is 22 m s^{-1}, and east-west and northeast winds in summer play the greatest role in transporting dust toward Isfahan (Jalalian, 2017a).

In recent years, various methods have been tested for stabilizing sand dunes, susceptible soils and reducing dust emissions. Petroleum mulches, despite their suitable initial efficiency in stabilizing sand dunes, are no longer recommended as a long-term and sustainable solution because of their adverse environmental effects (including emissions of carcinogenic aromatic hydrocarbons and water and soil pollution) and high implementation costs (International Agency for Research on Cancer, 2013). In contrast, non-petroleum mulches, including biological, polymeric, and mineral mulches, have received considerable attention.

Clay mulch (including bentonite clay) is one of the recently introduced non-petroleum mulches. While most studies have focused on its effectiveness in stabilizing sands and controlling wind erosion on laboratory (Majidi et al., 2006; Hazirei et al., 2013; Naghizade Asl et al., 2017, 2019, 2021; Emami et al., 2021), limited studies (Seyedhoseini et al., 2023) have addressed its application for dust control from medium- to fine-textured soils. In this case, bentonite clay is suspended in water and sprayed onto the soil surface. For controling dust, two pilot projects were implemented in the Segzi region in 2016 and 2017 (Jalalian, 2017a, 2017b). Based on preliminary evaluations, the use of clay mulch (at 160 kg ha^{-1}, equivalent to 16 g m^{-2}) was reported to be successful. Furthermore, the application of this clay, while effectively reducing or even controlling wind erosion, increased or maintained soil moisture, thereby facilitating the restoration of native vegetation and the success of more seedling planting, and improved soil structure to a depth of approximately 5 cm (Jalalian, 2017a).

The mechanism of wind erosion control using clay mulch relies on the formation of a surface seal. This surface sealing phenomenon is common in many arid and semi-arid regions, particularly in soils with low organic matter content, resulting in a lack of stable aggregates. It typically occurs in soils with a medium to fine texture that contain some dispersible clay or fine silt. In soils with very low aggregate stability, rainfall can cause slaking, disrupting the soil structure and creating fine pores that limit water infiltration. As rain continues, a water layer forms and becomes saturated with dispersed clay and silt particles, which then block the fine pores and creates a surface seal that is 1 to 3 mm thick (Avizehgan et al., 2021). This layer enhances the shear strength of the soil and serves as a barrier against wind-driven sand and dust.

Given that the application rate of clay is quite low at 16 g m^{-2}, equivalent to only a 0.2-0.35% increase in the clay content of the 3-5 mm thick surface layer of a medium-textured soil, the following question arises: can such a negligible amount of clay significantly influence the thickness and mechanical strength of the resulting surface seal? Additionally, if the surface seal becomes more resistant, will this result in a significant reduction in soil infiltration, thereby leading to increased runoff and water erosion during the rainy season? Addressing these questions necessitates thorough laboratory tests, including rainfall simulation, shear and penetration resistance measurements, and the assessment of saturated hydraulic conductivity, as well as microscopic analysis of the formed crusts.

There is limited information on the effect of purely clay mulches (without polymeric materials) at very low concentrations on the mechanical and hydraulic properties of surface seals in saline soils. The present study aims to fill this knowledge gap and provide quantitative answers to the proposed questions, with the following specific objectives: (1) to investigate the effect of clay mulch on the formation or increased resistance of the surface seal at different application rates; (2) to determine the effect of clay mulch on saturated hydraulic conductivity; and (3) to characterize the morphology and microstructure of the formed surface seal using optical microscopy.

2. Materials and Methods

2.1. Study area, soil sampling, and preparation

The Segzi region, recognized as the most significant wind erosion hotspot in Isfahan province, is located 25 km east of Isfahan. This area features highly diverse soil properties and a fragile ecosystem. Surface soil samples (top 10 cm) were collected from the coordinates 32° 42' 04" N, 52° 00' 10" E around the pilot project implementation site. Once transferred to the laboratory, the samples were thoroughly mixed and passed through a 4 mm sieve to remove coarse particles (≥4 mm) and plant residues. A portion of the samples was then passed through a 2 mm sieve for the analysis of physical and chemical properties, including texture, organic carbon, salinity (EC), pH, carbonate, gypsum, and soluble ions, using standard methods (Klute, 1986; Page et al., 1982). Soil texture was loam, with 16.2 % clay, 44.6 % silt and 39.2 % sand. The results of the chemical analysis indicated that the soil exhibited very high salinity (EC = 98.8 dS m^{-1}) and sodicity (SAR = 95.3 (meq/l)$^{0.5}$) along with considerable concentrations of sodium (1390 meq L^{-1}) and chloride (1570 meq L^{-1}) ions. The contents of organic carbon and calcium carbonate equivalent of the sample were about 0.4 and 21.3 %, respectively.

2.2. Preparation of clay suspension and application rates

The properties of the bentonite clay utilized in this project are detailed in the report by Jalalian (2017a). To identify the optimal suspension concentration, defined as the concentration at which the clay remains suspended and can be sprayed uniformly, preliminary tests with various concentrations were conducted. Ultimately, a concentration of 6 g L^{-1} was determined to be suitable. The suspension was prepared by adding bentonite clay to distilled water and mixing it thoroughly. During the spraying process, the spray container was continuously shaken to maintain the uniformity of the suspension. Different application rates of clay (20, 30, 40, 50, and 60 g m^{-2}) were implemented by spraying the corresponding volumes of the 6 g L^{-1} suspension on the surfaces of soil samples. For each clay mulch treatment, a control treatment was included, which involved spraying an equivalent volume of pure water without clay.

2.3. Sample preparation and pre-treatment (simulation of natural conditions)

To account for soil sample disturbance and better replicate laboratory conditions in relation to natural conditions,

Figure 1. Photographs of equipments and experiment setup

three types of pre-treatments were applied to the samples: (a) Dry Soil: This was the dry control group, which did not undergo any pre-treatment. (b) Saturated and Dried: This treatment simulated the consolidation effect after disturbance. (c) Simulated Rainfall Application: This method involves applying rainfall with a specified intensity and duration to more accurately mimic field conditions. For this treatment, the samples were exposed to rainfall at an intensity of 50-75 mm h^{-1} for 10-15 min, and in some instances, for 30 min. After the rainfall simulation, the samples were allowed to dry before applying clay mulch and control treatments. All experiments were conducted using plastic containers of various dimensions (7, 10, and 16.5 cm in diameter) alongside a metal tray with a specified number of replicates (Figure 1). A set 12 metal trays, made of galvanized iron and measuring 20 cm in width, 40 cm in length, and 5 cm in depth were constructed with permeable bottoms for the experiments.

2.4. Measurement of shear strength and penetration resistance

The shear strength (SS) was measured using a shear vane apparatus specifically designed to evaluate the undrained shear strength of fine-grained soils and surface crusts (ASTM International, 2018). Penetration resistance (PR) was assessed using a pocket soil penetrometer (Bradford, 1980). SS and PR measurements were taken at specified time intervals (2, 4, 6, 8, 10, 12, 14, and 16 days after treatment application), and at various soil moisture contents. Pre-tests indicated that a moisture range of 10-30% by weight yielded the best repeatability. At each measurement time, after determining both SS and PR, the moisture content of the soil surface layer (SM) was measured gravimetrically.

The effects of clay mulch on the SS and PR of the soil surface layer were tested in three experimental series to investigate and compare various factors.

In the first series, four treatments were evaluated: (1) Sample saturation followed by drying (saturation-drying) and then tap water spraying. (2) Sample saturation-drying and then clay spraying at a rate of 20 g m^{-2}. (3) Rainfall application for 15 minutes at an intensity of 75 mm h^{-1} (rainfall-drying), followed by drying and then tap water spraying. (4) Rainfall-drying, then clay spraying at a rate of 20 g m^{-2}. Simultaneous measurements of SS, PR, and SM were conducted at 2, 4, 6, and 7 days after spraying. Each treatment at each time was prepared in duplicate using 10-cm-diameter cups. SS was measured with two replicates per container, and penetration resistance included more than 10 replicates per container.

In the second series of experiments, two treatments were evaluated: (1) tap water spraying, (2) clay was sprayed at a rate of 40 g m^{-2}. Simultaneous measurements of SS, PR, and SM were taken on dayes 2, 4, 6, 8, 10, 12, 14, and 16 after spraying. Treatments were prepared in duplicate at each time point using 7 cm cups. In addition, a separate series using 16.5 cm containers was conducted at three times to assess the effect of container size.

Third series of experiments: Three sub-series, including: (3-1) Comparison of 30 g m^{-2} clay mulch treatment with control (only distilled water spraying) in 7 cm cups with 30-min rainfall pre-treatment (75 mm h^{-1}) followed by drying; (3-2) Comparison of 30 g m^{-2} treatment with control (only distilled water spraying) in 16.5 cm diameter containers with 30-min rainfall pre-treatment; and (3-3) Comparison of 30 and 50 g m^{-2} clay mulch treatments with

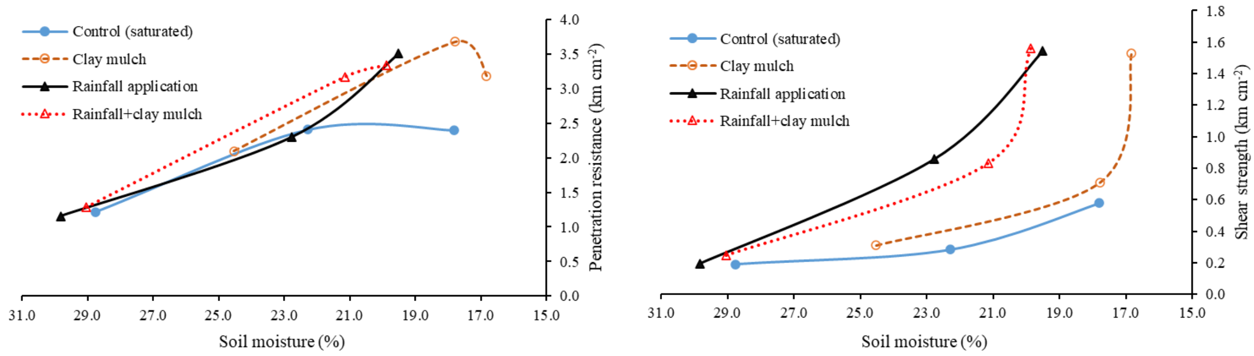

Figure 2. Shear strength and penetration resistance of soil under different treatments at different moisture (time) levels in the first series of experiments

their respective controls (only water at the same volume as the clay suspension) on dry soil (without pretreatment) in 16.5 cm diameter containers.

2.5. Measurement of saturated hydraulic conductivity

To investigate the effect of clay mulch on soil infiltration and its potential impact on runoff generation, we measured the saturated hydraulic conductivity (Ks) using the constant-head method. Soil samples were placed in cylinders with a diameter of 5 cm and a height of 7 cm, with four replicates for each treatment. Three series of experiments were conducted at two-month intervals.

First series: Five treatments including the following: 1) control (24-hour saturation); 2) control + pure water spraying (7.95 mm, equivalent to the suspension volume for the 30 g m^{-2} treatment); 3) control + clay spraying (30 g m^{-2}, 7.95 mL suspension); 4) rainfall application for 10 minutes at 75 mm h^{-1}; and 5) treatment 4 + drying + clay spraying. The water used in this series was a 0.01 M calcium chloride solution.

Second series: Four treatments on dry soil, including: Control 1 (spraying 3.5 mL water – equivalent to 20 g m^{-2} treatment); Treatment 1 (spraying 3.5 mL suspension, 20 g m^{-2} clay); Control 2 (spraying 10.6 mL water); and Treatment 2 (spraying 10.6 mL suspension, 40 g m^{-2} clay). Tap water was used.

Third series: Six treatments on dry soil, including three control levels (spraying 3.5, 10.6, and 15.9 mL of water) and three treatment levels (spraying suspension equivalent to 20, 40, and 60 g m^{-2} of clay). Tap water was used.

2.6. Moisture retention and water vapor absorption test

Moisture retention test: This study aimed to investigate the effect of clay mulch on evaporation reduction. Samples were prepared in cups measuring 7 cm in diameters and depth of 4 cm, with four replicates. The treatments were as follow: Control 1: Spraying 12.8 mL of water. Treatment 1: Spraying 12.8 mL of a suspension equivalent to 20 g of clay per square meter. Control 2: Spraying 25.6 mL of water. Treatment 2: Spraying 25.6 mL of a suspension equivalent to 40 g of clay per square meter.

Water vapor absorption test: Similar samples that had been air-dried for 10 days, were placed in a vapor chamber for 20 minutes, and the amount of absorbed moisture was determined gravimetrically.

2.7. Microscopic examination of crusts

To investigate the microstructure and morphology of the surface seals, we collected samples with a thickness of several millimeters from the surfaces of both control and mulched samples after they were fully dried (Slattery & Bryan, 1992). Due to the high salinity and the inability to harden the saturated samples with resin (which is necessary for thin section preparation), we employed a direct method. This involved placing thin samples under an optical microscope and capturing photographs at suitable magnifications.

3. Results

3.1. Shear strength and penetration resistance

In the first series of experiments (Figure 2), the application of 20 g m^{-2} clay mulch and rainfall application increased the shear strength. Shear strength was clearly a function of moisture content and increased progressively as the moisture decreased below approximately 20 wt %. Notable observations include the following: (1) no difference between treatments at high moisture content, (2) a greater effect of rainfall than clay spraying alone, and (3) a sudden exponential increase in shear strength for mulched treatments at lower moisture contents (less than about 21%). In terms of penetration resistance (Figure 2), the behavior of the treatment was more complex. While there were notable differences between treatments with rainfall application at intermediate moisture contents (between about 22-26%), and without rainfall application at lower moisture contents, contrasting behavior was

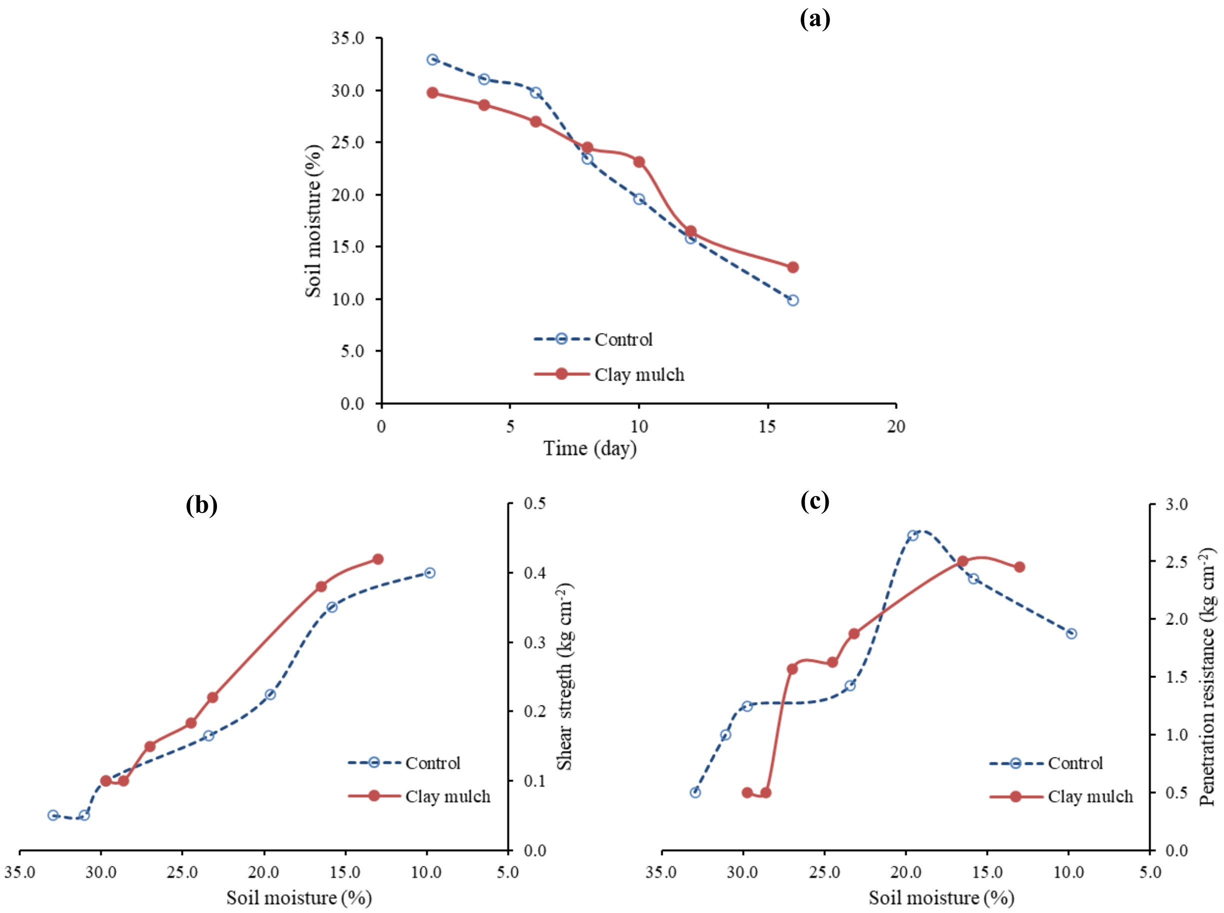

Figure 3. Changes in soil moisture (SM) with time (a), shear strength at different SM (b), and penetration resistance at different SM (c) in the second series of experiments

observed as the moisture decreased due to the brittleness and fragility of the crust layer.

The results of the experiments with a 40 g m^{-2} clay application (Figure 3) showed that the rate of moisture decrease in the clay-mulched sample was slower than in the control sample, indicating reduced evaporation intensity due to surface seal formation. The shear strength in the treated sample was consistently higher than that of the control, and the difference was more pronounced at moisture contents less than 25%. The penetration resistance exhibited a more complex behavior; in the control sample, it initially increased and then decreased with decreasing soil moisture content, which is attributed to the brittleness of the surface crust under near-dry conditions.

In the third series of experiments, two clay mulch application levels (30 and 50 g m^{-2}) along with their corresponding controls, were tested on dry soil. The results of the shear strength and penetration resistance measurements are presented in Table 1. A 66% increase in the amount of sprayed water and clay suspension resulted in a 79% and 39% increase in the SS of the surface seal layer, respectively. In contrast, spraying 107 mL of clay suspension (equivalent to 30 g m^{-2}) compared to spraying 107 mL of water (control) caused a 38.5% increase in the SS. However, with increasing application rate, the difference from the control decreased to 7.5%, which is not statistically significant. These results indicate that the role of clay in strengthening weak surface seals is more pronounced, and as the surface seal resistance increases due to increased rainfall intensity or duration, the effect of the clay mulch becomes statistically negligible compared to the water-only control. The PR test results support the findings related to the SS measurements. A 66% increase in sprayed water and clay suspension resulted in a 60% and 17% increase in the PR of the surface seal layer, respectively. Additionally, when comparing the application of 107 mL of clay suspension (equivalent to 30 g m^{-2}) to the control of 107 mL of water, there was a 43% increase in PR. However, as the application rate increased, the difference in PR compared to the control decreased to 5%, a not significant value.

3.2. Saturated hydraulic conductivity

The results of the first series (Table 2) showed that water

Table 1. Shear strength and penetration resistance of the control and clay mulch application levels

Control; water volume (mL)#	Mulch application level ($g\ m^{-2} \approx mL$)&	Soil moisture ($g\ g^{-1}$)		Shear strength ($kg\ cm^{-2}$)		Penetration resistance ($kg\ cm^{-2}$)	
		Control	Mulched	Control	Mulched	Control	Mulched
107	30 - 107	0.115	0.119	0.052[c]	0.072[b]	0.777[c]	1.111[b]
178	50 - 178	0.179	0.177	0.093[a]	0.100[a]	1.244[a]	1.303[a]

In control, just spraying water equal to the suspension volume of the corresponding mulch level.
& Mulch application implemented by spraying clay suspension (at concentration of 6 g L).
*Comparison using Duncan's test was conducted among four treatments (two control and two mulched samples); different letters indicate a significant difference at the 5% level.

Table 2. Results of saturated hydraulic conductivity (Ks, $cm\ h^{-1}$) measurements in the first series of experiments

Treatment description	Ks	Treatment description	Ks
Control (saturated)	7.26[a]	Spraying 3.5 mL of water	3.52[a]
Control + pure water spraying	5.01[b]	Spraying 3.5 mL suspension (20 $g\ m^{-2}$ clay)	2.27[c]
Control + clay spraying	1.22[d]	Spraying 10.6 mL of water	2.52[b]
Rainfall application	3.67[c]	Spraying 10.6 mL suspension (40 $g\ m^{-2}$ clay)	1.94[d]
Rainfall application + clay spraying	1.44[d]		

* Different letters indicate a significant difference at the 5% level using Duncan's test.

Table 3. Results of moisture retention (weight %) and water vapor absorption (weight % moisture)

Treatment	Treatment description	Moisture retention (%)	Water vapor absorption (%)
Control 1	Spraying 12.8 mL of tap water on dry soil	4.26[c]	9.84[a]
Treatment 1	Spraying 12.8 mL clay suspension (20 g clay m^{-2})	4.36[c]	9.32[b]
Control 2	Spraying 25.6 mL of tap water on dry soil	7.33[b]	8.97[c]
Treatment 2	Spraying 25.6 mL clay suspension (40 g clay m^{-2})	11.05[a]	8.40[d]

* Different letters indicate a significant difference at the 5% level using Duncan's test.

spraying, rainfall application, and clay spraying (30 $g\ m^{-2}$) all caused a significant reduction in saturated hydraulic conductivity (Ks). Water spraying and rainfall led to reduction in Ks by 31 and 49%, respectively. On the other hand, spraying clay suspension (clay mulch) reduced Ks by 83% (1.22 vs. 7.26 $cm\ h^{-1}$). Water spraying and rainfall led to surface seal formation, and clay spraying strengthened the surface seal, thereby reducing water infiltration. This finding, as an indicator of surface seal formation that will resist wind erosion after drying, is certainly useful and consistent with the hypotheses. However, from the perspective of runoff generation potential during the rainy season, it may be problematic. Based on the results of the second series of saturated hydraulic conductivity tests (Table 2), the effects of water spraying (surface seal formation) and clay mulch (surface seal strengthening) on reducing hydraulic conductivity were evident. Increasing the amount of water and suspension both significantly reduced saturated hydraulic conductivity.

3.3. Effect of clay mulch on moisture retention and water vapor absorption

Moisture content was measured five days after the treatments were implemented (Table 3). At the 20 $g\ m^{-2}$ application rate, there was no significant difference between the mulched and control samples. However, at the 40 $g\ m^{-2}$ rate, the mulched samples retained approximately 50% more moisture after five days than the control samples. This demonstrates the effectiveness of clay mulch in reducing evaporation. The results from the water vapor absorption test (Table 3) indicate that as the surface seal strengthens—achieved by increasing the water and/or clay application levels—water vapor diffuses into the soil more slowly. Consequently, the corresponding samples had lower moisture contents.

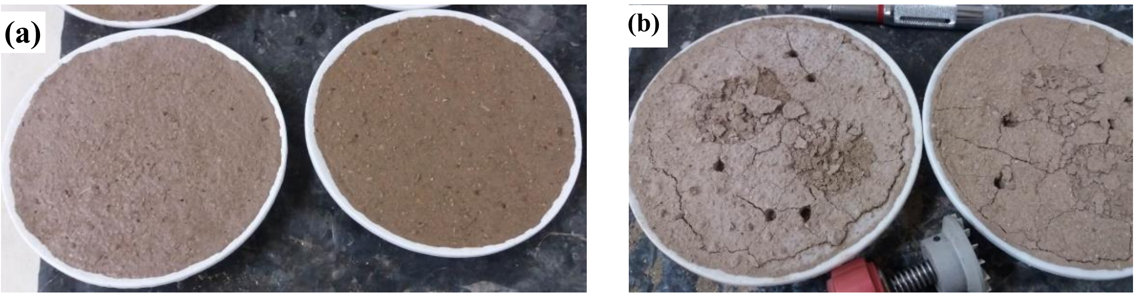

Figure 4. Photographs of wet (a) and dry (b) samples: control (right) and clay-mulched (left) samples.

3.4. Morphology of the surface seal

Figure 4 shows photographs of the soil surface immediately after clay spraying and it dried. The shinier color in the wet state and lighter color in the dry state of the clay-mulched sample compared to the control indicate that the sprayed clay likely formed a thin veneer on the soil surface. Based on this, clay penetration into subsurface the layers is unlikely. This is beceause upon spraying the suspension, a surface seal formed immediately on the soil surface, and with the pores blocked, infiltration of clay particles (10-20 μm in size) was not possible.

In the optical microscopy images (Figure 5), a significant number of salt crystals are visible, often covering surrounding soil particles. In the subsurface layer (Figures 5a and b), soil particles and salt crystals range in size from fractions of a millimeter to several millimeters, and the soil appears porous. The mulched sample (c) has a smooth, continuous surface without visible pores and features fine salt crystals. In contrast, the control sample (d) displays coarser, non-uniform crystals and a rougher surface. The crust images (e and f) illustrate the differences between surface seals with and without a clay film. Surface roughness and smoothness depend on whether a clay layer was sprayed on. In the control sample, coarser pores facilitate greater salt transport through water to the surface, which leads to the formation of larger crystals. However, in the clay mulch sample, finer pores restrict salt transport, resulting in much smaller crystals. In some clay-mulched samples, pressure beneath the surface layer caused ruptures in the seal, leading to the formation of explosive salt cavities (Figures 5g and h), which were not observed in the control samples.

4. Discussion

4.1. Effect of clay mulch and salt crust on the mechanical strength of the surface seal

The findings of this study indicate that rainfall and water spraying on the surface of the soil in the Segzi region led to the formation of a dense and resistant surface seal (Table 1). This phenomenon occurs as a result of raindrop impact (Assouline, 2004) in soils characterized by low aggregate stability and medium-to-fine texture (Rafahi, 2012; Avizehgan et al., 2021; Assouline and Thompson, 2023; Laker and Nortjé, 2019). In the examined soil, this effect was intensified by very high salinity-sodicity and likely low aggregate stability due to high sodium concentration.

The application of bentonite clay mulch significantly enhanced both the strength and morphology of the surface seal (Figures 2, 3 and 5, and Table 1). This finding aligns with the results of Majdi et al. (2006), who showed that clay mulches are resistant to wind flow. However, a key finding of this study is that a substantial portion of the effect of the clay mulch, particularly at higher application levels, can be attributed to the influence of the sprayed water rather than the clay itself. This conclusion is supported by two observations: (1) a 66% increase in the volume of sprayed water in the control treatment resulted in a 79% increase in shear strength, whereas the same increase in suspension volume within the mulch treatment only led to a 39% rise in strength; (2) as the application level increased from 30 to 50 g m^{-2}, the difference in strength between the control and mulched samples sharply diminished, the effects of clay itself becomes negligible. This diminishing effect can be explained by the inherent susceptibility of the tested soil to surface sealing. Given that the soil is medium-textured and structurally weak, the kinetic energy of water droplets (or sprayed water) alone is sufficient to disaggregate surface particles and form a dense, compacted seal. Consequently, once this initial water-induced seal is established, the marginal contribution of the bentonite clay to further strength enhancement drops considerably. In other words, the physical consolidation from drop impact already addresses the primary mechanism of strength gain, so adding extra clay on top of this pre-formed seal yields progressively smaller returns, which is why the strength gap between the control and mulched treatments narrows sharply at higher application levels.

The formation of a mixed clay-salt crust is one of the most important findings of this study, induced by the very high salinity-sodicity of the tested soil. The observation of abundant salt crystals in microscopic images and their morphological differences in the presence of clay mulch indicate a complex interaction between clay and salts in surface seal formation (Figure 5). In contrast, the

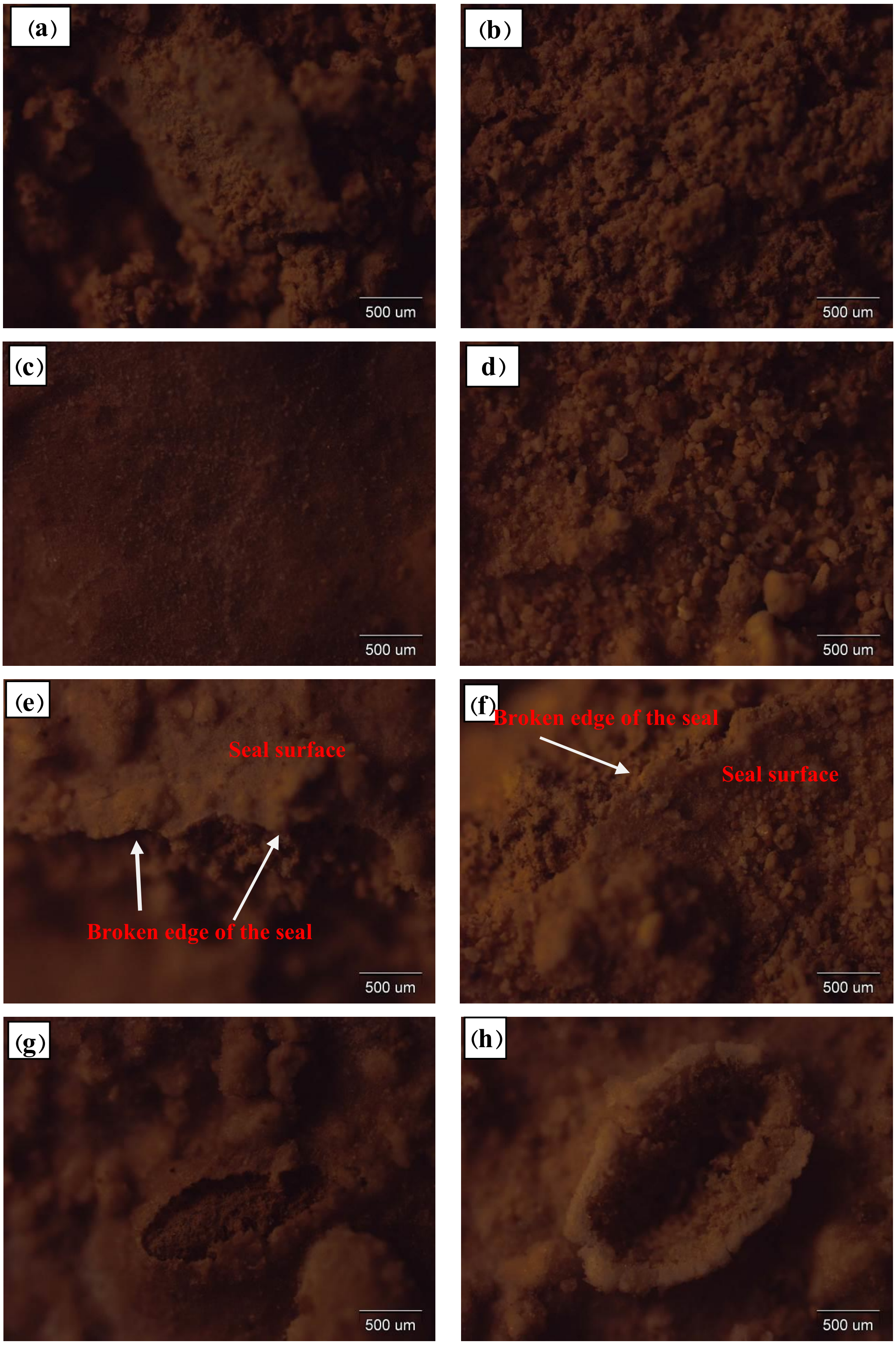

Figure 5. Optical microscopy images: (a) and (b) soil subsurface layer; (c) surface of mulched sample; (d) surface of control sample; (e) surface and edge of surface seal of mulched sample; (f) surface and edge of surface seal of control sample; (g) and (h) explosive salt cavities in the seal layer

observation of explosive cavities in the clay-mulched sample (Figures 5g and h) suggests pressure buildup beneath the seal layer and its potential for long-term degradation. Nield et al. (2015) have also reported to the degradation of salt crusts under specific conditions.

The formation of a surface seal in arid and semi-arid region soils is exacerbated by very high salinity-sodicity and low aggregate stability. On salt-rich playas, salts accumulate at the soil surface and form a thin layer known as a salt crust (Rafahi, 2012). This salt crust serves as a natural barrier that prevents soil erosion caused by wind (Nield et al., 2016a). Research results have shown that sodium chloride at high or supersaturated concentrations, in both fine and coarse soil textures, leads to the formation of salt crusts and increases soil stability against wind erosion (Ekhtesasi et al., 2003). Extensive studies have also confirmed that parts of dried lakes covered with evaporative-salt crusts significantly reduce dust emission (Baddock et al., 2011; Houser and Nickling, 2001; King et al., 2011; Nickling and Ecclestone, 1981; Nickling, 1984; O'Brien and Neuman, 2012; Sweeney et al., 2011; Webb and Strong, 2011). Therefore, the formation of a surface seal or salt crust is recognized as a natural protective mechanism in arid and semi-arid regions. However, salt crusts are inherently dynamic and may degrade under specific conditions (moisture and temperature changes) and become intense dust sources (Nield et al., 2016a).

4.2. Effect of clay mulch on hydraulic conductivity and permeability

A significant reduction in saturated hydraulic conductivity due to water spraying, rainfall, and clay mulch (Table 3) indicates the formation or strengthening of a surface seal and clogging of soil pores. This finding is consistent with the theoretical foundations of surface seal formation (Assouline, 2004). The development of a soil surface seal consists of a very thin (<0.1 mm) "skin seal" on the surface, formed by the compaction and structural reorientation of dispersed clay particles parallel to the soil surface (McIntyre, 1958a, 1958b; Valentin & Bresson, 1992), underlain by a 2- to 3-mm "washed-in" zone, where dislodged fine particles are carried downward by infiltrating water and deposited within the soil pores, effectively clogging them and forming a low-permeability layer (McIntyre, 1958b; Slattery and Bryan, 1992; Assouline, 2004; Assouline & Mualem, 2006). In the current study, while the physical breakdown of soil aggregates by raindrop impact of sprayed water (Slattery and Bryan, 1992; Geeves, 1997) and/or by slaking due to fast wetting (Li et al., 2024) is responsible for the underlying seal layer, spraying clay mulch would provide or enhance the skin seal. Some studies have shown that physical mechanisms account for approximately 93% of the sealing process (Geeves, 1997). Clay particles can penetrate surface pores and create chemical bonds between particles, thereby strengthening the surface seal (Lado et al., 2007; Mamedov and Levy, 2001).

4.3. Effect on moisture retention and water vapor absorption

The lower evaporation intensity observed in the clay-mulched sample (Table 3) suggests that clay mulch may help retain soil moisture by blocking surface pores. Moreover, the reduced water-vapor adsorption recorded for the clay-mulched samples (Table 3) provides further evidence of this surface sealing effect. The dense, compacted layer formed by the clay and water impact appears to physically occlude soil pores, thereby limiting the soil's exposure to atmospheric moisture and restricting vapor-phase uptake. This raises an important practical question: does this vapor barrier impede soil rewetting through dew or high-humidity events, particularly in dry periods when liquid rainfall is scarce? Given that such water-vapor inputs can be ecologically significant in arid environments, this potential trade-off between mechanical reinforcement and atmospheric moisture exchange clearly merits dedicated investigation.

The formation of surface seals and crusts can reduce evaporation from the soil surface, however, this effect depends on the type and conditions of the crust. Modeling studies have shown that under dry conditions, the soil profile beneath a crust can retain on average 17-20% more moisture than uncrusted soil (Shoshany and Assouline, 2013). The main mechanism underlying this reduction is the formation of a soil surface seal which acts as a physical barrier (shield) against water vapor loss by trapping moisture below the surface (Assouline, 2004; Sela et al., 2012). However, it is important to consider the dual effect of the crust. Although the crust reduces evaporation and retains soil moisture, it severely reduces permeability and increases runoff on the other side. The net effect of the crust on the soil water balance depends on the balance between these two opposing processes. Unlike physical crusts and seals, biological crusts may not create such a conflict (Kakeh et al., 2021a, b). Studies have shown that biological crust formation can reduce evaporation rates by up to 50% (Ji et al., 2024). In general, in arid and semi-arid regions where water stress is a major issue, reduction in evaporation due to seal formation can be considered an effective natural mechanism for soil moisture conservation (Shoshany and Assouline, 2013).

4.4. Limitations and recommendations

The main limitation of this study is the very high soil salinity-sodicity of the soil. The presence of a strong salt crust in this soil naturally increases its resistance to wind erosion. Consequently, the effectiveness of bentonite clay mulch in low-salinity or salt-free soils, which are not susceptible to salt crust formation, may differ significantly. Thus, generalizing these findings to other areas requires further investigation of soils with similar texture but varying salinity-sodicity levels. Additionally, the long-term behavior of the clay mulch, such as its durability against wetting-drying cycles and strong winds, was not assessed in this study and needs to be examined through extended field studies.

5. Conclusion

In general, the results of this study showed that water spraying, rainfall application, and clay spraying on the surface of the Segzi region soil, independently and in combination, led to the formation of a surface seal characterized by higher shear strength, greater penetration resistance, and lower saturated hydraulic conductivity. Furthermore, the use of bentonite clay mulch significantly enhanced the strength of the surface seal and altered its morphology. This improvement is demonstrated by the increased shear strength and penetration resistance, as well as the reduced saturated hydraulic conductivity. The effectiveness of clay mulch is influenced by the initial resistance of the surface seal. For the studied medium-textured saline-sodic soil, a substantial part of the impact of clay mulching is attributed to the sprayed water. As the amount of clay applied increases (and consequently the applied water volume), the relative contribution of the clay in enhancing the strength of the seal diminishes. The combination of "rainfall and clay spraying" has the most significant effect, reducing saturated hydraulic conductivity to less than 20% of its initial value. Additionally, increasing the volume of water and suspension directly correlates with increased sealing intensity. Although this phenomenon is beneficial for controlling wind erosion, it also raises the potential for runoff and water erosion, factors that should be considered in the land management of arid and semi-arid regions. Based on these findings, an application rate of 20 g/m² of bentonite clay is recommended, as it maintains a suitable balance between increased resistance and reduced permeability.

Soil in the eastern part of Isfahan Province including Segzi region is basically saline, which with a small amount of water a mixed clay-salt crust will be produced. Extreme sodicity, also develops this crust that substantially influences its resistance to wind erosion. The high sodium concentration promotes clay dispersion and facilitates the formation of a dense surface seal upon drying, while the low organic carbon content provides minimal structural binding, making the crust formation highly dependent on salt crystallization dynamics. The morphology of salt crystals differs markedly in the presence of a bentonite clay mulch, suggesting that the applied clay interacts with the native soil matrix to modify crust structure and stability. The effectiveness of the mulch in enhancing soil resistance may thus be attributed, at least in part, to the synergistic effects of clay addition and salt-induced crusting, rather than solely to the mulch itself. Given the extreme salinity and sodicity of this soil, further investigation is needed to determine whether similar results can be generalized to non-saline or low-salinity soils, where salt crusts do not form and clay dispersion mechanisms differ considerably.

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