

# Enhancing soil resistance to wind erosion: effects of sodium alginate on dust source stabilization in southeastern Lake Urmia.

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## Abstract

Climate change, accelerated by human activities, has led to the shrinkage and disappearance of salt lakes worldwide. In northwestern Iran, the gradual drying of Lake Urmia has exposed lakebed sediments to wind erosion, turning sandy-saline areas in its southeastern region into a primary source of dust generation. This study examines the effects of various concentrations and application methods of sodium alginate on increasing the resistance of soil samples from these sandy-saline areas against wind erosion. Sodium alginate was applied at four concentrations (0%, 0.5%, 1%, and 2%) using three methods: dry spraying, wet spraying, and mixing with soil, followed by compaction. Key properties such as crust thickness, compressive strength, and changes in compressive strength with soil depth were evaluated. Wind tunnel experiments were conducted to measure soil loss, while electron microscopy imaging and elemental analysis were used to investigate the structural bonds formed between soil particles. Results revealed that a 0.5% sodium alginate concentration produced thicker crusts across all application methods. The highest compressive strength (up to 13,053 kPa) was achieved using the 2% sodium alginate concentration with the mixing and compaction method. Wind tunnel tests demonstrated a significant reduction in soil loss, decreasing from 47.29% in the distilled water treatment (control) to 10.75% and 6.37% with 0.5% and 1% sodium alginate treatments, respectively. Microscopic and elemental analyses of the crusts, conducted three months after application, showed that sodium alginate remained effectively integrated into the soil samples. By forming a durable surface coating on soil particles, sodium alginate enhanced the soil's resistance to wind erosion. Overall, this study shows that sodium alginate can be used as a practical and environmentally friendly stabilizer to increase soil resistance to wind erosion and reduce dust emissions from the southeastern Lake Urmia playa, providing a promising tool for sustainable land management in arid regions.

**Keywords:** Sodium Alginate, Wind Erosion, Soil Stabilization, Sandy-Saline Soils, Lake Urmia

## Introduction

Arid and semi-arid regions cover approximately 40% of the Earth's surface and are characterized by limited water resources, extreme temperatures, and low soil fertility (Huang et al., 2016). These regions are particularly vulnerable to the impacts of climate change, such as altered precipitation patterns and rising temperatures, which exacerbate desertification and land degradation. Recent studies indicate that intensified drought cycles and prolonged heatwaves have accelerated land degradation and expanded dust-source areas in many drylands (Liang et al., 2021). Furthermore,

increased dust-storm frequency has been associated with heightened respiratory and public health risks (Dehghanisanij and Bashi-Azghadi, 2026; Lian et al., 2025; Fussell and Kelly, 2021).

In Iran, human activities, including deforestation, agricultural expansion, and unsustainable water management, have further intensified environmental degradation. Over the past three decades, Iran has experienced a clear increase in both minimum and maximum temperatures compared with the selected climatic normal period, with the rise in minimum temperature being more pronounced (Fakhri, 2024). In addition, analysis of satellite-based drought indices (SPI, TCI, VCI, and VHI) revealed intensified and prolonged drought conditions across several regions of Iran during the 2001–2021 period (Sadat Fakhari and Nazari, 2024). These climatic changes have contributed to the drying of critical water bodies, including Jazmourian, Bakhtegan, and Lake Urmia, transforming their lakebeds into significant dust source areas (Hajipour et al., 2024; Motamedi et al., 2023; Mansouri Daneshvar et al., 2019).

Globally, dried lakebeds contribute up to 30% of the world's dust emissions, with the dust containing fine particles and salts that degrade soil fertility, threaten human health, and reduce ecosystem stability (Abbas et al., 2024; Darvishi Bolorani et al., 2023; Abuduwaili et al., 2010). These desiccated lakebeds have recently been identified as emerging regional dust hotspots contributing substantially to transboundary aerosol pollution (Li et al., 2022; Akbari et al., 2022). In the case of Lake Urmia, located in northwest Iran, over 90% of the lake has dried up since the 1990s due to a combination of reduced precipitation, high evaporation rates, and excessive water extraction (Emami and Zarei, 2021; Sharifi et al., 2018). This has exposed expansive salt-rich playa surfaces with limited vegetation cover, creating ideal conditions for wind erosion and dust generation. Recent hydrological and remote-sensing analyses have further confirmed that the expansion of salt crusts and exposed sediments has accelerated over the past decade, increasing their vulnerability to wind erosion (Esmailzadeh et al., 2023; Parsinejad et al., 2022; Hamzehpour and Marcolli, 2024). Studies have shown that areas in the southeastern parts of Lake Urmia are highly susceptible to wind erosion, with erodible materials comprising up to 95% of the soil in some locations (Hamzehpour et al., 2022; Motaghi et al., 2020). Dust storms originating from these areas transport saline particles that degrade nearby agricultural lands and threaten regional public health (Ahmady-Birgani, 2025; Darvishi Bolorani et al., 2025; Ahmady-Birgani, 2020). Comparable degradation patterns have been documented in other desiccated lakes such as the Aral Sea, Owens Lake, and the Great Salt Lake, where exposed saline sediments act as major sources of severe dust storms (Alkhayer et al., 2023).

To mitigate the environmental and agricultural impacts of wind erosion, various stabilization methods have been explored, including mechanical, chemical, and organic approaches. Traditional stabilizers, such as cement, lime, and chemical compounds, are often effective in reducing soil erosion but have significant environmental drawbacks, including high costs, potential toxicity, and persistence in the soil (Marques and Syahril, 2021). Recent evaluations suggest that mineral- and chemical-based stabilizers can alter soil physicochemical properties and exhibit limited long-term ecological compatibility, reducing their suitability for fragile dryland landscapes (Soleimani et al., 2024; Latifi et al., 2016). Organic stabilizers, such as bio-based polymers, have emerged as

environmentally friendly alternatives. Sodium alginate (SA), a natural polysaccharide extracted from brown algae, is particularly promising due to its biodegradability, low cost, and ability to form stable crusts on soil surfaces (Beaucamp et al., 2019; Guilherme et al., 2015).

Recent studies have demonstrated the efficacy of SA in improving soil resistance to wind and water erosion. For example, Zhao et al. (2020) showed that the application of SA in loess soil formed aggregates by filling the pores between soil particles, thereby enhancing soil stability. Similarly, Wade et al. (2021) reported that SA increased soil aggregate diameters and reduced wind erosion sensitivity. In sandy soils, Lemboye et al. (2021) found that SA could stabilize dunes against wind speeds of up to 16.2 m/s, while Peng et al. (2017) showed that SA enhanced the development of biological crusts on soil surfaces, increasing their compressive strength without negatively affecting soil properties. The addition of SA also improved soil cohesion and water retention, making it a versatile solution for addressing erosion in arid and semi-arid environments (Lemboye et al., 2021; Arab et al., 2019). The binding capacity, film-forming behavior, and moisture-retention properties of SA are increasingly recognized as key mechanisms contributing to its performance as a nature-based soil surface stabilizer (Almajed et al., 2020).

In the context of Lake Urmia, SA offers a sustainable alternative for stabilizing the exposed playa surfaces, which consist largely of sandy-saline soils prone to wind erosion. These soils are particularly challenging due to their low organic matter content, high salt concentration, and limited vegetative cover. While traditional stabilizers such as magnesium chloride and cement have been applied in other regions, their environmental impact and compatibility with agricultural systems remain concerns. SA, on the other hand, can form protective crusts on the soil surface, reducing dust generation while supporting long-term soil health (Lemboye et al., 2021; Almajed et al., 2020). Considering the fragility and erosion susceptibility of the exposed Urmia playa, the use of bio-based stabilizers such as SA represents a practical and environmentally compatible strategy for dust-control applications.

Despite the growing body of research on chemical and organic soil stabilizers, significant limitations and knowledge gaps persist, particularly concerning their application to highly saline, sandy-loam playa surfaces characteristic of desiccated lakebeds. Most existing studies on sodium alginate have focused on non-saline sandy soils, leaving a critical need for research on its efficacy in saline environments like the southeastern Lake Urmia playa. Furthermore, few studies have explicitly evaluated active dust source areas like this playa, where frequent wind events and saline dust emissions pose severe environmental and agricultural risks. There is also a lack of integrated evaluations that simultaneously assess soil strength, crust formation, and dust emission under controlled wind tunnel conditions for SA-treated saline soils. Therefore, the primary objective of this study is to address these critical research gaps by:

(a) investigating the effects of various concentrations and application methods of sodium alginate on the physical properties (crust thickness, compressive strength) of saline sandy-loam soils from the Lake Urmia playa, (b) quantifying the reduction in wind erosion and dust emissions using wind tunnel experiments, and (c) examining the long-term structural stability and bonding mechanisms of sodium alginate in these challenging soil conditions.

By doing so, this research aims to provide crucial insights into the potential of sodium alginate as a sustainable dust mitigation strategy for arid regions affected by large-scale lake desiccation.

## **Material and methods**

### **Climate, soil moisture, and thermal regimes**

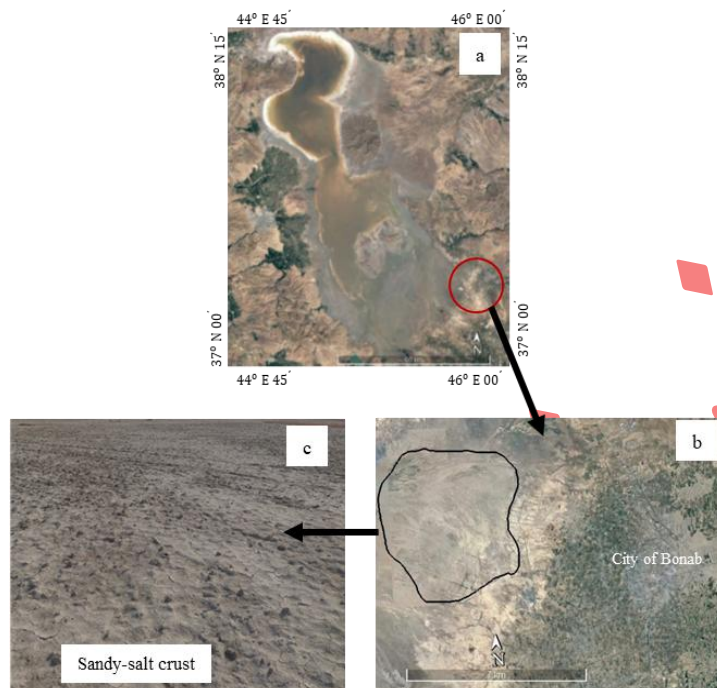
According to the Köppen climate classification, this region is categorized as a semi-arid cold zone, characterized by a xeric moisture regime and a mesic thermal regime. These climatic conditions are crucial in understanding the vulnerability of sandy-saline soils to wind erosion and the effectiveness of stabilizing agents. Data from the Bonab synoptic station indicate an average wind speed of 2.8 m/s over ten years (2013–2023), with peak wind speeds reaching 5.7 m/s. The region experiences an average annual temperature of 15.01°C and average annual precipitation of 264.73 mm, contributing to limited vegetation cover and increased susceptibility to wind deflation (<https://data.irimo.ir>).

### **Preparation of wind rose maps for the study area.**

To characterize the wind dynamics in the study area, wind speed and direction data were obtained from the nearest meteorological station (Bonab station) for the summer months (July to September 2021), including the sampling period in August 2021. These data were reviewed for completeness and accuracy before being processed using WRPLOT View Freeware 8.0.2 to generate windrose maps for both the summer season and the sampling month. The resulting windrose maps provide a visual representation of predominant wind directions and speeds during the dry season, which are critical for understanding the dust emission potential and validating the experimental setup. This analysis ensures that the sampling sites are accurately aligned with the region's prevailing wind erosion patterns (<https://data.irimo.ir>).

### **Location and area of the study region**

The study area is situated on the southeastern edge of Lake Urmia, near the Bonab Plain, in the Akhund-Qeshlaq region (Figure 1). Previous studies have classified this region as a sandy-saline playa surface (Motaghi et al., 2020). The geographical coordinates range from 45°53'14" to 45°59'34" E longitude and from 37°19'36" to 37°22'47"N latitude. Spanning approximately 30 square kilometers, the study area is relatively flat, with an elevation of about 1270 meters above sea level.



**Fig 1. Study area on the southeastern edge of Lake Urmia, adjacent to the Bonab Plain near Akhund-Qeshlaq Village. (a) General view of Lake Urmia in August 2021 during the sampling period. (b) Detailed location of the study area to the east of the Bonab Plain. (c) Close-up image of the sandy-saline surfaces sampled for analysis.**

### Soil sampling and laboratory analyses

Soil samples were collected from various sections of the study area at a depth of 0–5 cm from the surface (Figure 1). Soil samples collected from the study area were transported to the Soil Science Laboratory at the University of Maragheh. After air-drying, the samples were crushed and sieved through a 2 mm mesh to prepare them for physical and chemical analyses. The analyses were conducted following established methodologies outlined in Methods of Soil Analysis, as detailed below:

Soil texture was determined using the hydrometer method. Organic carbon content was measured using the wet combustion method (Smith et al., 1996). Electrical conductivity and pH were measured in a 1:2.5 soil-to-water suspension using an electrical conductivity meter (Jenway, Model 4510) and a pH meter (VWR Symphony SB70P), respectively. Calcium carbonate equivalent (CCE) was determined via titration. Soluble sodium was measured in a 1:2.5 soil-to-water extract using a flame photometer, while soluble calcium and magnesium were determined via EDTA titration.

Wet aggregate stability (WAS) was assessed using a wet sieving apparatus. To determine the erodible material, a 100 g air-dried soil sample was sieved (8 mm) to remove debris and placed on a 0.84 mm sieve. The sample was shaken for 3 minutes, and the remaining aggregates were dried at 120°C for 24 hours and weighed. Soil moisture content was adjusted using an additional subsample. The percentage of stable aggregates larger than 0.84 mm ( $AS_{0.84}$ ) and the erodible material fraction (EF) were calculated using the following formulas (Equ. 1):

$$AS_{0.84} = (W_2 / W_1) \times (1 - \theta) \quad (1)$$

Where:

$W_1$  is the initial weight, and  $W_2$  is the weight of remaining aggregates after drying at 120°C for 24 hours (Equ. 2).

$$EF = [(100 - AS_{0.84}) / TW] \times 100 \quad (2)$$

where:

EF: Percentage of erodible material, and TW is the Initial weight of the soil sample.

The mineralogy of the soil samples was analyzed using X-ray diffraction (XRD). Measurements were conducted with a Bragg-Brentano X-ray diffractometer (D8 Advance, Bruker AXS, Germany) employing  $CoK\alpha$  radiation (35 kV, 40 mA). The instrument featured an automatic beam optimization system, including a theta divergence compensation slit, an automatic air scattering plate, and a Lynx-Eye XE-T detector. Powder samples were scanned over a range of 5° to 70° 2 $\theta$ , with a step size of 0.02° 2 $\theta$  and a 2-second count time per step.

**Use of sodium alginate in stabilizing sandy-saline surfaces.** Sodium alginate was applied to the soil at four concentrations (0%, 0.5%, 1%, and 2%), with three replicates, using two methods: spraying (dry spraying (DSp) and spraying on soil with optimal moisture (WSp)) and mixing with soil followed by compaction (MC). The crust thickness was measured with a caliper with a precision of 0.1 mm.

To assess the surface strength of the natural crusts, an automatic penetrometer (Model MP11, Iran) was employed to measure the maximum and average penetration pressure in the crust samples. Measurements were conducted at a penetration rate of 0.3 mm per second to a depth of 30 mm, with a maximum applied pressure of 12,000 kPa.

The wind erodibility of the treated samples was evaluated in a wind tunnel capable of generating wind speeds up to 20 m/s.

### **Scanning electron microscopy imaging and point analysis (SEM-EDAX)**

Untreated soil samples, along with the dry sodium alginate-treated samples that exhibited the best results in terms of crust thickness and compressive strength, were analyzed using scanning electron microscopy (SEM). SEM imaging was performed with a TESCAN MIRA3 Scanning Electron Microscope equipped with an energy-dispersive X-ray spectroscopy (EDX) detector. A 1x1 cm crust sample was mounted on a stub, evacuated in a vacuum chamber for 10 minutes, and coated with a thin layer of gold to prevent charging under the electron beam during imaging.

Additionally, Fourier-transform infrared (FTIR) spectroscopy was conducted to identify functional groups within the range of 400 to 4000  $cm^{-1}$ . The analysis was carried out using a Spectrum Two FTIR Spectrometer (Perkin Elmer, USA) on both untreated and treated soil samples.

### **Wind tunnel studies**

A type 9 blower wind tunnel system from Shahid Beheshti University, Tehran, was employed for the experiments. The setup comprised two primary sections: a wind generation unit and a test compartment. The wind generator was equipped with a 95 kW jet fan operating at a rotational speed of 2400 rpm, capable of generating wind velocities ranging from 0.9 to 20 m/s at a height of 90 cm. In this study, the highest wind speed available was applied. To achieve consistent

airflow, a conical section was positioned ahead of the generator, followed by a honeycomb structure to standardize the wind profile. The test compartment, fabricated from galvanized iron, measured 100 cm in length, 95 cm in width, and 95 cm in height, and included openings on its upper surface for wind velocity measurements. Soil samples were weighed before and after 15 minutes of exposure in the wind tunnel, and the reduction in sample weight was used as a measure of soil erosion.

### Statistical design

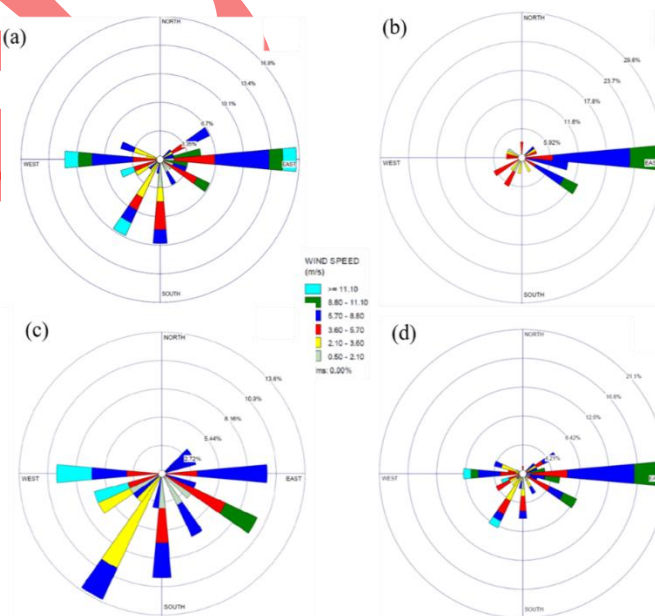
To evaluate the effect of sodium alginate on enhancing soil resistance to wind erosion, a factorial experiment was conducted in a completely randomized design (CRD) with two factors. The first factor was sodium alginate concentration at four levels (0, 0.5%, 1%, and 2%), and the second factor was the application method at three levels (dry spraying, wet spraying, and mixing followed by compaction). Each treatment was replicated three times. The experimental data were analyzed using SAS software, and mean comparisons were performed using Duncan's Multiple Range Test (DMRT) at a significance level of  $P < 0.05$ .

### Results and discussion

#### Wind rose map, dominant wind direction, and speed in the study area

Figure 2 illustrates the wind rose maps for the summer of 2021 (July to September) along with the overall average wind rose for this period (Figure 2d). Figure 3 presents the frequency distribution of wind speed classes for the specified time frame.

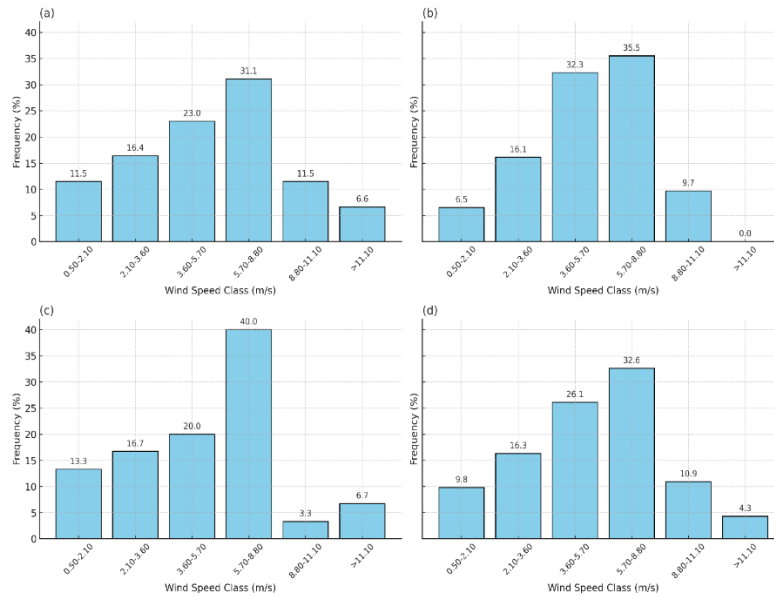
According to Figure 2, the prevailing wind direction during the summer months of 2021 is from east to west (Figure 2d). However, strong winds exceeding 11 meters per second from the west are observed in both July and September. Given the geographical context, with the Bonab Plain located to the east of Lake Urmia, these strong west-to-east winds (blowing from Lake Urmia toward the Bonab Plain) pose a significant risk of dust transport from the exposed playa surfaces of the drying lake toward agricultural lands and the city of Bonab.



**Fig 2. Wind Rose Map for Maximum Wind Speed and Direction for the Dry Months (July to September, 2021). The wind rose maps are prepared using data from the nearest weather stations to the sampling area**

(Bonab station). The wind rose maps for: (a) July; (b) August; (c) September; (d) Average from July to September.

Furthermore, Figure 3 indicates that over 40% of the maximum wind speeds recorded in the region exceed 6 meters per second. Since 6 meters per second is the threshold speed at which soil particles begin to move in most environments, the study area is frequently exposed to wind speeds sufficient to cause wind erosion. Consequently, there is a substantial potential for dust transport to more distant areas, including the Miandoab Plain (southwest of the study area) and the cities of Mahabad and Naqadeh (west of the study area), as well as the agricultural lands near these locations.



**Fig 3. Diagrams of wind speed classes in the study area during the summer of 2021. The diagrams were created using data from the nearest weather station to the sampling area (Bonab station). (a) July; (b) August; (c) September; (d) average from July to September.**

### Physicochemical properties of soil samples from the sandy-saline surface

Table 1 presents the physicochemical properties of soil samples collected from the sandy-saline surface in the southeastern region of Lake Urmia, near the village of Akhund-Qeshlagh, adjacent to the Bonab Plain. The results reveal high levels of soluble sodium (1250 mmol/L) and a sodium adsorption ratio (SAR) of 139.65. Furthermore, the soil exhibits notably high electrical conductivity (EC) at 40 dS/m, indicating significant salinity. The equivalent calcium carbonate (CaCO<sub>3</sub>) content was measured at 17.25%, classifying the soil as calcareous.

**Table 1. Physicochemical properties of soil samples from the sandy-saline surface in the Southeastern Playa of Lake Urmia.**

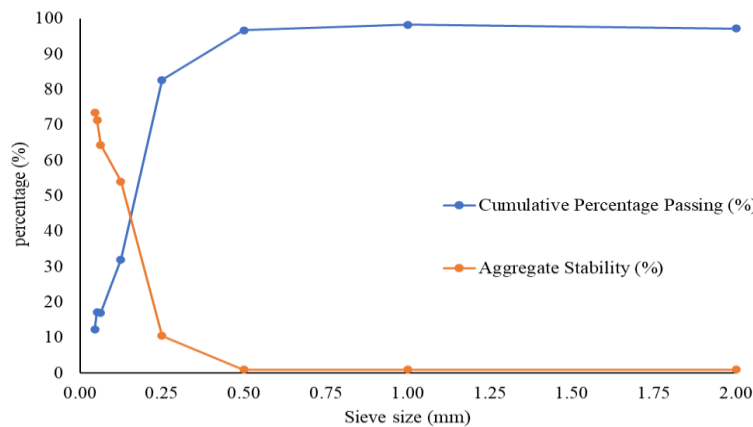
Sandy-Saline surface	S <sub>Na</sub>	S <sub>Mg</sub>	S <sub>Ca</sub>	SAR	pH	EC
	(mmol/L)					(dS/m)
	0.1250	23.100	0.060	65.139	7.80	40.00
	CCE	OM	EF	Clay	Silt	Sand
	(%)					
	17.25	0.36	84.50	6.60	14.00	79.40

S: soluble; SAR: Sodium Adsorption Ratio; EC: electrical conductivity; CCE: Calcium Carbonate Equivalent; OM: Organic Matter; EF: Erodibility Fraction

The organic matter content was found to be very low (0.36%), which is unsurprising given the soil's high salinity and lack of vegetation cover. The erosion susceptibility (EF) percentage is exceptionally high at 84.50%, reflecting the soil's vulnerability to wind erosion. This is primarily due to the high sand content (79.40%), low clay content (6.60%), and limited organic matter.

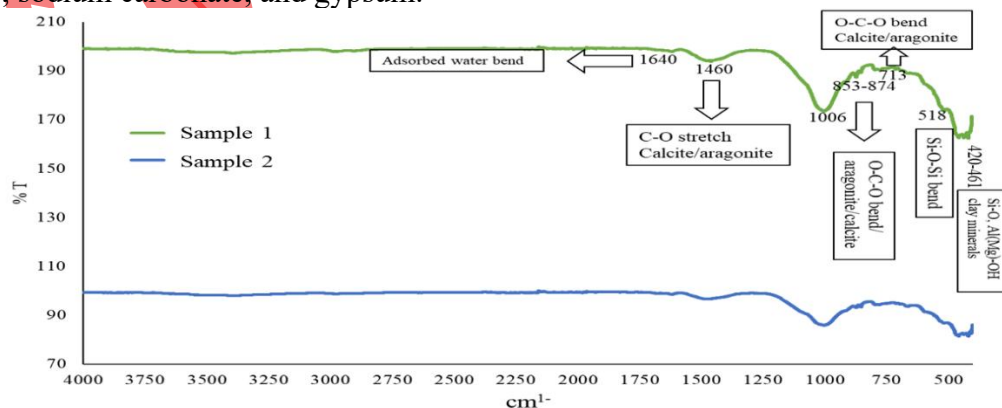
A related study by Motaghi et al. (2020) in a similar area identified high sand content, insufficient organic matter, and minimal clay percentages as critical contributors to the soil's susceptibility to wind erosion. Combined with wind speeds exceeding 6 m/s in this region, these factors emphasize the urgent need for stabilization measures to mitigate dust generation from this key source area in the southeastern playa of Lake Urmia.

As shown in Figure 4, the soil stability in the wet state is remarkably low, with no particles larger than 0.5 mm remaining. Over 96% of the sample passes through the 0.5 mm sieve, and more than 82% passes through the 0.25 mm sieve.

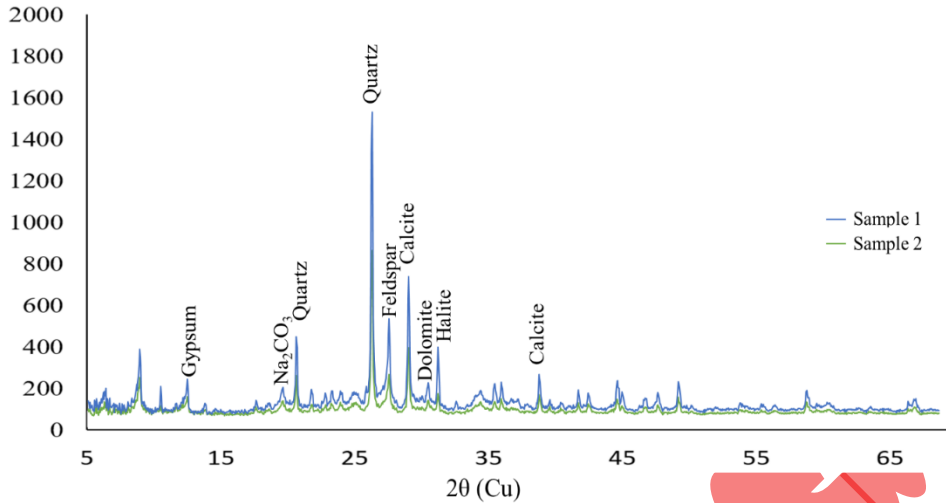


**Fig 4. Particle Size Distribution and Its Stability Using the Wet Sieving Method**

Figures 5 and 6 present the FTIR and XRD spectra of two samples collected from the sandy-saline surface under study. These results indicate that silicates and carbonates are the primary components of the soil. The dominant minerals identified include quartz, calcite, feldspar, halite, dolomite, sodium carbonate, and gypsum.



**Fig 5. FTIR spectra of two soil samples from the sandy-saline surface located in the southeastern part of Lake Urmia.**



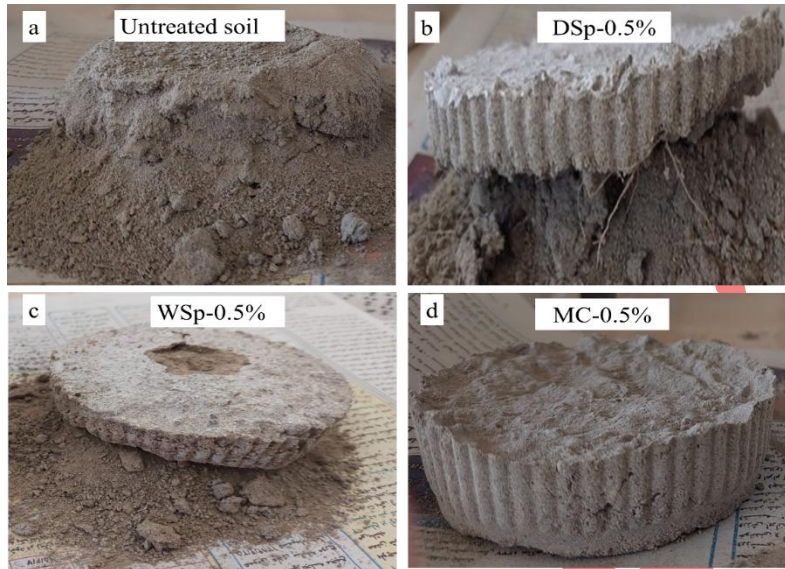
**Fig 6. XRD spectrum of a soil sample from the sandy-saline surface located in the southeastern part of Lake Urmia. The intensity of each peak indicates the abundance of the corresponding mineral in the sample.**

Although previous studies on the Urmia Playa have demonstrated that highly saline playa surfaces, due to the formation of salt crusts primarily composed of sodium chloride (NaCl), exhibit increased resistance to wind erosion (Hamzhepour and Macolli, 2024; Taghizadeh et al., 2021; Motaghi et al., 2020), the surface under investigation does not form stable crusts despite its high salinity. Mineralogical analysis reveals that this instability can be attributed to the presence of carbonate compounds, such as sodium carbonate. Unlike sodium chloride, sodium carbonate not only fails to facilitate the formation of stable crusts but also contributes to surface swelling, thereby increasing the soil's susceptibility to wind erosion.

### **Stabilization of sandy-saline surface with sodium alginate**

#### **Crust thickness and compressive strength**

Based on the results from this study, the application of sodium alginate significantly altered the crust formation on sandy-saline soils, as shown in Figure 7 for untreated soil and 0.5 % concentration of sodium alginate (SA). The untreated soil (Figure 7a) exhibited no cohesive crust, maintaining a loose, granular structure. In contrast, the dry spraying method (DSp<sub>0.5</sub>, Figure 7b) produced a moderately cohesive crust, while the wet spraying method (WSp<sub>0.5</sub>, Figure 7c) resulted in a thinner crust with visible fractures, reflecting weaker cohesion. The mixing with compaction method (MC<sub>0.5</sub>, Figure 7d) generated the thickest and most uniform crust, demonstrating superior stabilization. These results highlight the effectiveness of MC in enhancing soil crust thickness and cohesion compared to spraying methods.



**Fig 7. Visual comparison of crust development on untreated soil and treated soils using different application methods of sodium alginate at a 0.5% concentration. (a) Untreated soil shows a loose, granular structure with no crust formation. (b) Dry spraying (DSp<sub>0.5</sub>) resulted in a moderately thick and cohesive crust. (c) Wet spraying (WSp<sub>0.5</sub>) produced a relatively thin but cohesive crust with visible fractures. (d) Mixing with compaction (MC<sub>0.5</sub>) formed the thickest and most uniform crust, indicating superior soil stabilization.**

In Table 2, the results of the variance analysis for the interaction effects of the three methods (DSp, WSp, and MC) on crust thickness, average compressive strength, and maximum compressive strength are presented. The data indicate that the applied treatments significantly influenced crust thickness, average compressive strength, and maximum compressive strength, with all effects being significant at the 1% level.

**Table 2. Analysis of variance for physical properties of crusts formed by sodium alginate application methods (dry and wet spraying, mixing and compaction) under laboratory conditions**

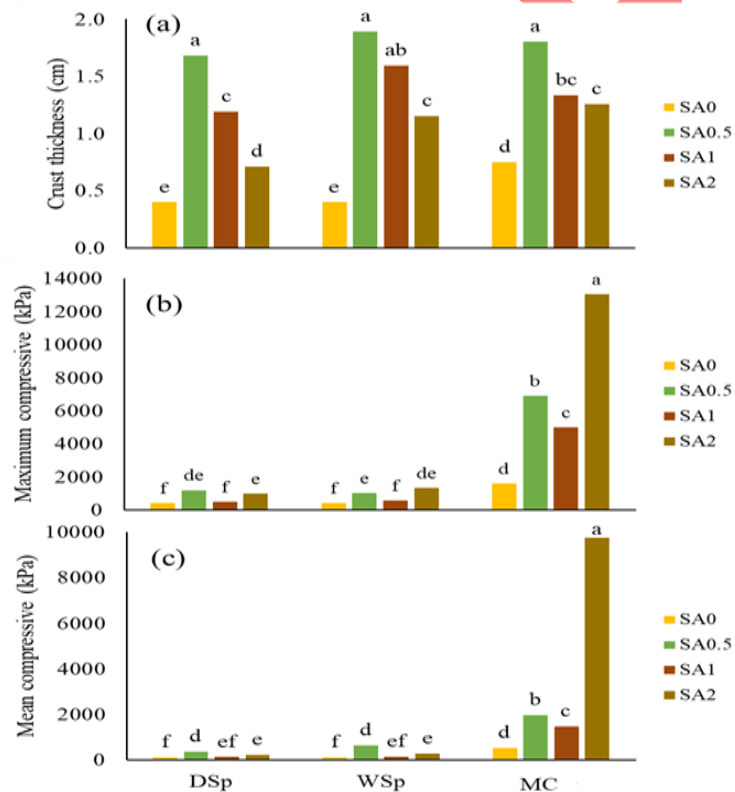
Source of Variation	Degrees of Freedom	Crust Thickness (cm)	Maximum Compressive Strength (kPa)	Average Compressive Strength (kPa)
DSp * WSp * MC	11	0.77	4,374,256.5	2,232,187.9
Error	24	0.26	106,883.7	83,169.3
Coefficient of Variation	-	13.56%	11.82%	22.21%
Significance Levels	-	*p < 0.05	p < 0.01	p < 0.01

Figure 8 presents the mean comparison results illustrating the effects of three application methods—dry spraying (DSp), wet spraying (WSp), and mixing with compaction (MC)—on crust thickness and compressive strength of the sandy–saline soil samples collected from the southeastern margin of Lake Urmia. Figure 9 complements these results by presenting heatmaps that summarize the average values of crust thickness, mean compressive strength, and maximum compressive strength for the same treatments.

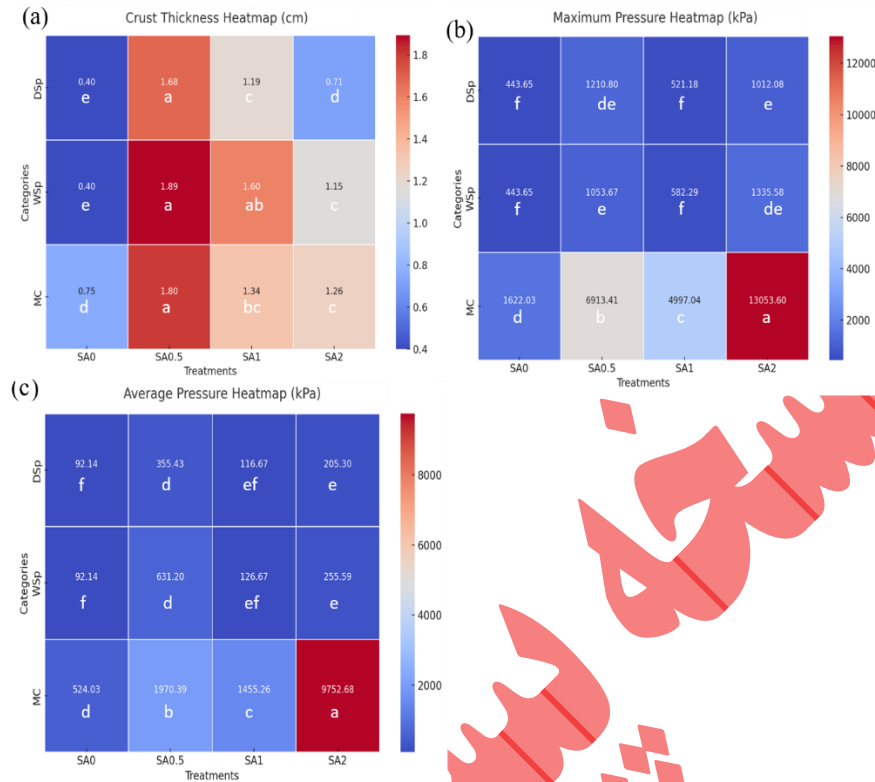
Both Figure 8 and Figure 9 show that the MC method achieved the greatest crust thickness at the 0.5% sodium alginate concentration (SA0.5), with no statistically significant difference compared

to the 0.5% dry and wet spraying treatments (Figure 8a; Figure 9a). Similar patterns were observed for maximum and mean compressive strengths (Figures 8b, 8c; Figures 9b, 9c), with the MC method consistently outperforming the other treatments, particularly at higher sodium alginate concentrations.

A key distinction between the Sp and MC methods is evident in the performance of the control samples. In the spraying treatments, the crust thickness for Sp0 was 0.4 cm, with mean and maximum compressive strengths of 92 kPa and 443 kPa, respectively. In contrast, the MC control samples (MC0) exhibited a crust thickness of 0.75 cm, and the compressive strengths increased to 506 kPa (mean) and 1,667 kPa (maximum). This indicates that even without sodium alginate, simply mixing the soil with distilled water and applying compaction significantly enhanced the physical properties of the soil, improving its resistance to compression and potential wind erosion.



**Fig 8. Mean-comparison charts of the measured properties, including crust thickness, mean compressive strength, and maximum compressive strength, in the crusts developed on the sandy-saline soil from the southeastern playa of Lake Urmia under three application methods: spraying sodium alginate onto dry soil (DSp), spraying onto soil at optimum moisture content (WSp), and mixing sodium alginate solution with the soil followed by compaction (MC). Treatments marked with different lowercase letters represent statistically significant differences at the 1% level.**

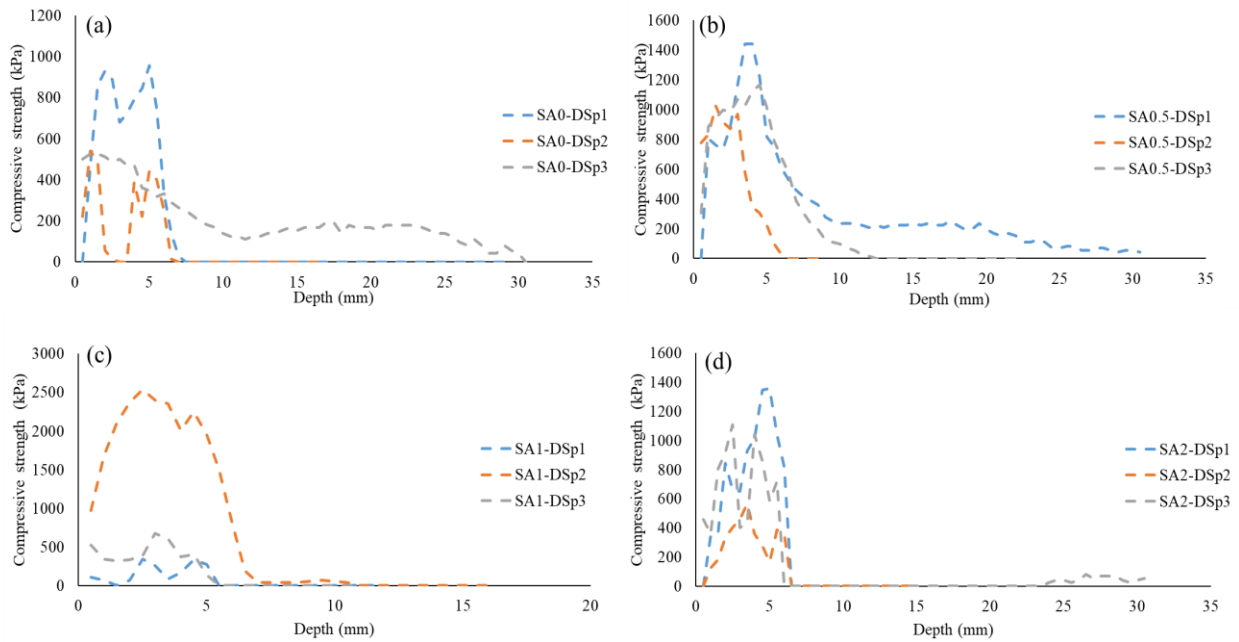


**Fig 9. Heatmaps comparing mean crust properties (thickness, average compressive strength, and maximum compressive strength) developed on sandy-saline soils in southeastern Lake Urmia using three methods: dry spraying (Dsp), wet spraying (WSp), and mixing with compaction (MC). Different lowercase letters within each heatmap indicate statistically significant differences at the 1% level.**

Overall, the MC method outperformed the spraying treatments, achieving significantly better results in crust thickness and compressive strength. The highest compressive strength was observed in the MC<sub>2</sub> treatment, reaching 13,052 kPa—approximately 13 times greater than the maximum strength recorded in the Sp treatments. Even the lowest compressive strength in the MC treatments (1,667 kPa in MC<sub>0</sub>) exceeded the maximum strength in the spraying methods. These findings align with previous studies on sandy soils in the western Lake Urmia region, highlighting the MC method as a superior approach for enhancing soil stability compared to spraying methods (Hamzhepour et al., 2024).

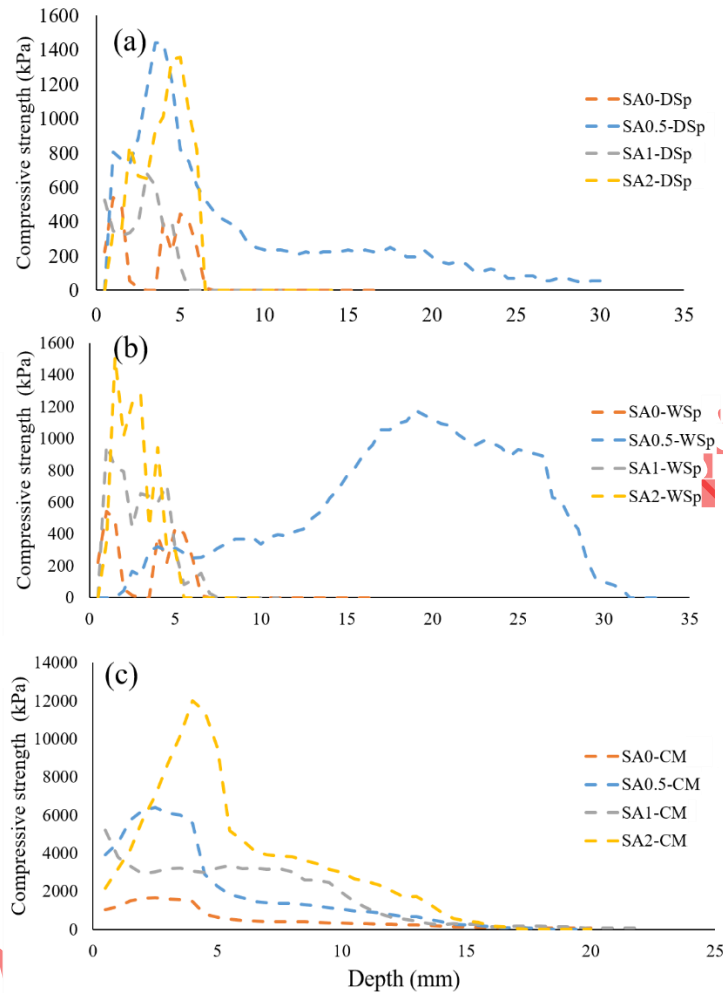
### Compressive strength curves and resistance against wind

In Figure 10, compressive strength curves for the dry spray method (Dsp) with three repetitions illustrate the variability across different replicates. The results indicate that compressive strength was highest within the top 5–10 mm of the crust, followed by a significant decrease with depth.



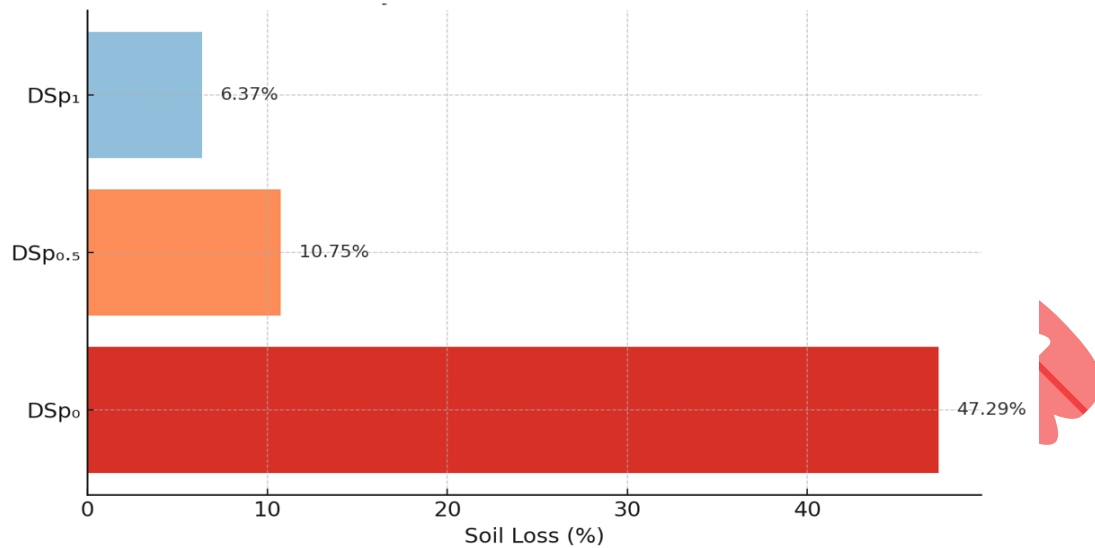
**Fig 10. Penetration force versus penetration depth in crusts developed on sandy-saline soil from the southeastern Lake Urmia region, treated with dry-spray sodium alginate (DSp) at four concentrations (0%, 0.5%, 1%, 2%) across three repetitions: (a) DSp<sub>0</sub>, (b) DSp<sub>0.5</sub>, (c) DSp<sub>1</sub>, and (d) DSp<sub>2</sub>. Each curve illustrates the variation in compressive strength with increasing depth.**

As shown in Figure 11, the compressive strength of crusts formed under the CM treatments was consistently much higher than those of the DSp and WSp treatments across all sodium alginate concentrations. This trend remained consistent at all depths of measurement (Figure 11c). In contrast, the WSp<sub>0.5</sub> treatment exhibited an irregular compressive strength curve (Figure 11b, blue line). Initially, compressive strength was low, increased between 15 and 25 mm depth, and then decreased. This irregularity is likely due to deeper penetration of the sodium alginate solution into the moist soil, forming thicker crusts but with reduced surface strength due to lower concentrations at the surface. Consequently, this could compromise its resistance to wind erosion. Overall, the DSp<sub>0.5</sub> treatment and all CM treatments demonstrated more uniform and effective improvements in compressive strength across depths. These results highlight their potential to stabilize sandy-saline soils by forming robust crusts, thereby reducing susceptibility to wind erosion.



**Fig 11. Penetration force versus penetration depth in crusts developed on sandy-saline soil from the southeastern Lake Urmia region, showing variations with depth under three sodium alginate application methods: (a) dry spray (DSp), (b) wet spray (WSp), and (c) mixing and compaction (CM).**

In Figure 12, the soil loss data obtained from the wind tunnel experiments for the different SA treatments are illustrated in detail. It is important to note that the highest concentration, SA<sub>2</sub>, was excluded from the wind tunnel tests due to its poor performance in preliminary evaluations, likely owing to challenges in forming effective surface crusts under this treatment. According to the results, the control treatment (DSp<sub>0</sub>), which lacked sodium alginate application, experienced a soil loss of 47.29%, reflecting the high susceptibility of the untreated sandy-saline surface to wind erosion. However, the application of sodium alginate at concentrations of 0.5% (DSp<sub>0.5</sub>) and 1% (DSp<sub>1</sub>) significantly reduced soil loss to 10.75% and 6.37%, respectively. These results demonstrate reductions in soil loss of 77% and 87%, underscoring the considerable potential of these treatments to mitigate wind erosion. The findings highlight the role of sodium alginate in stabilizing the soil surface, particularly at concentrations that effectively balance soil penetration and crust strength, making it a viable and environmentally friendly option for reducing wind erosion in arid and semi-arid regions.

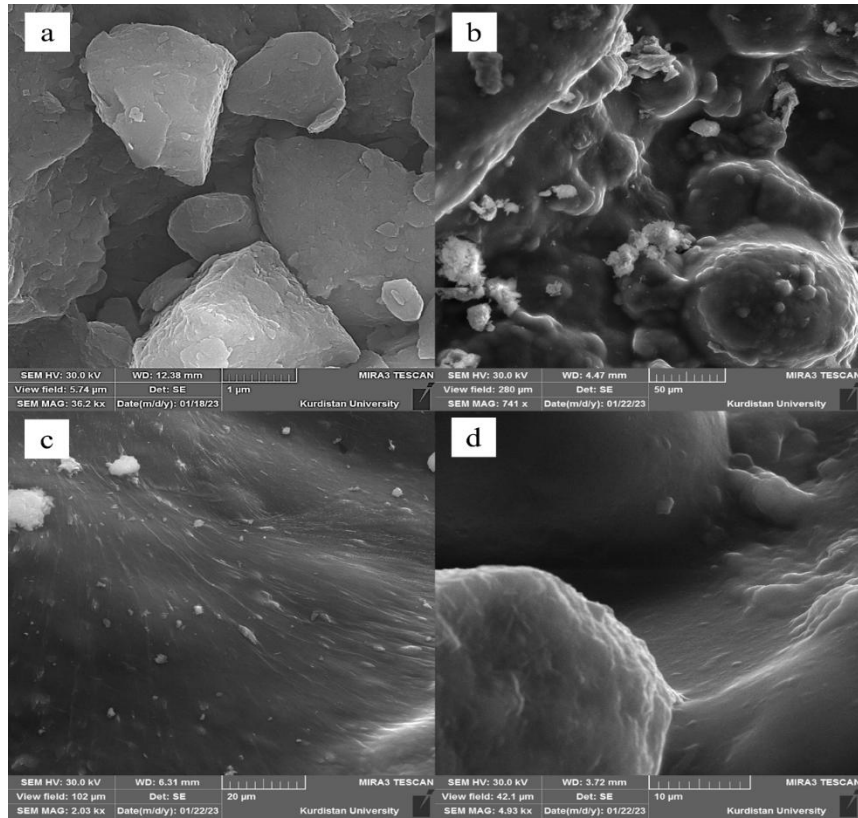


**Fig 12. Soil erosion under different sodium alginate treatments (DSp method) in a wind tunnel with a maximum wind speed of 20 m/s.**

### 3.3.3. Morphological and Elemental Composition Characteristics

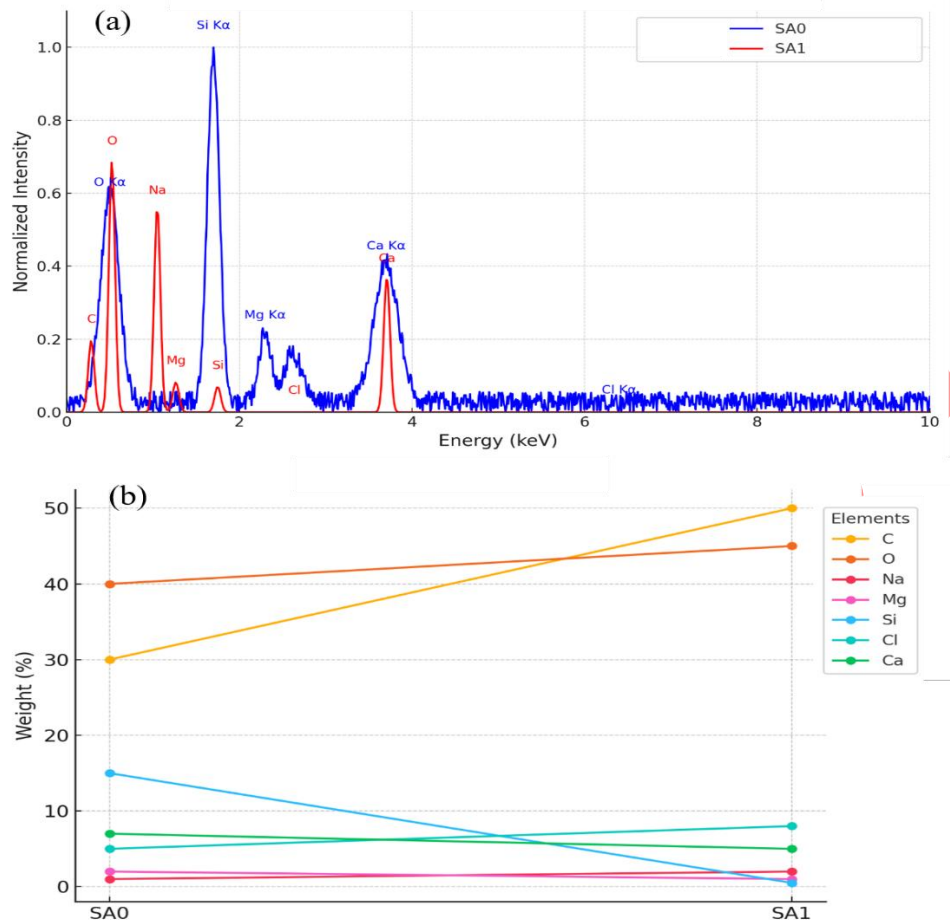
Figure 13 presents scanning electron microscopy (SEM) images of the surface of sandy-saline soil samples from the southeastern region of Lake Urmia, treated with 1% sodium alginate (DSp<sub>1</sub>) and analyzed three months after treatment. For reference, Figure 12a shows an untreated control sample (DSp<sub>0</sub>), which exhibits a loose arrangement of soil particles with minimal cohesion and a lack of any evident crust formation. This arrangement is indicative of the soil's inherent vulnerability to wind erosion and surface destabilization due to the absence of any binding agents. In contrast, the treated samples (DSp<sub>1</sub>), as shown in Figures 13b, 13c, and 13d at varying magnifications, reveal significant structural changes. The images clearly demonstrate that the sodium alginate treatment facilitated the formation of a continuous polymeric layer on the soil surface. This layer effectively binds the soil particles together, bridging large particles with smaller ones, which contributes to the development of a stable and cohesive crust. Such particle aggregation is a key mechanism for improving the soil's resistance to mechanical forces, such as wind erosion.

The observed crust formation in the treated samples is consistent with the known properties of sodium alginate, a natural polysaccharide capable of forming strong gels and cross-linked structures. These structures reduce the mobility of soil particles and enhance surface stability. The sodium alginate layer not only provides a physical barrier against erosive forces but also contributes to a reduction in pore spaces on the soil surface, thereby limiting the detachment and transport of particles by wind.



**Fig 13. Scanning electron microscope (SEM) images of sandy-saline soil samples from the southeastern Lake Urmia region, three months after treatment. (a) Untreated sample (DSp0), showing a loose particle arrangement; (b), (c), and (d) Soil samples treated with 1% sodium alginate (DSp1) at different magnifications, illustrating enhanced particle bonding and crust formation resulting from the treatment.**

Figure 14 provides the results of the energy-dispersive X-ray (EDX) elemental analysis for the same soil samples, highlighting the differences in elemental composition between the untreated ( $SA_0$ ) and treated ( $SA_1$ ) soils. The normalized spectra reveal a significant enhancement in sodium, oxygen, and carbon peaks in the treated sample ( $SA_1$ ) compared to the control ( $SA_0$ ). These increases are attributed to the introduction of sodium alginate, a compound rich in sodium and carbon. The elevated oxygen content further reflects the polymer's chemical structure and its interaction with soil particles. Conversely, the noticeable reduction in the silicon peak, a dominant component of the untreated soil matrix, indicates that the sodium alginate coating partially obscures the underlying mineral structure. This coverage likely plays a critical role in reducing soil erodibility by shielding individual particles and enhancing cohesion within the soil matrix.



**Fig 14. (a) Overlay of normalized spectra for SA<sub>0</sub> (blue) and SA<sub>1</sub> (red). The spectra were collected under identical experimental conditions and normalized to their respective maximum intensities to enable relative comparison. Key peaks corresponding to elements (e.g., O K $\alpha$ , Si K $\alpha$ , Mg K $\alpha$ , Ca K $\alpha$ ) are labeled. This visualization highlights the relative differences in elemental composition between SA<sub>0</sub> and SA<sub>1</sub>. (b) Quantitative comparison of elemental concentrations, highlighting changes in key elements such as sodium (Na), calcium (Ca), and magnesium (Mg) between untreated (DSp<sub>0</sub>) and treated (DSp<sub>1</sub>) samples.**

The results of this study demonstrate that sodium alginate (SA) is highly effective in enhancing the structural stability of sandy-saline soils typical of the southeastern Lake Urmia playa. The SEM and EDX analyses clearly indicated the successful integration of SA within the soil matrix, as reflected by increased carbon, oxygen, and sodium content in treated samples. The polymer formed a continuous coating over soil grains, leading to reduced visibility of silicon peaks and suggesting partial coverage of mineral surfaces. This coating appears to act as a flexible binding network that improves particle cohesion, supports the formation of stable aggregates, and limits particle detachment under aerodynamic stress. These microstructural observations align with earlier studies that reported SA creates a thin polymer film capable of reinforcing soil crusts and improving wind resistance (Peng et al., 2017; Arab et al., 2019).

The substantial reduction in soil loss (77% and 87% in DSp<sub>0.5</sub> and DSp<sub>1</sub>, respectively) is consistent with Zhao et al. (2020), who demonstrated that SA improves interparticle bonding by filling void spaces and reducing pore continuity. The persistence of SA after three months under

semi-arid conditions suggests a level of durability necessary for stabilization efforts in highly erosive environments. This is especially relevant in playa margins of Lake Urmia, where high salinity, strong winds, and extreme dryness frequently degrade mechanically weak surface crusts. A key finding of this study is the superiority of the mixing and compaction (MC) method relative to surface spraying (DSp, WSp). Incorporation of the polymer into the soil matrix produced thicker, stronger crusts with greater resistance to mechanical disruption. This trend matches observations from Lemboye et al. (2021), who found that uniform distribution of biopolymers enhances long-term soil bonding. However, spraying approaches remain relevant for large-scale operational use when minimal soil disturbance is required.

Although this study focused solely on sodium alginate, insights from previous work on Lake Urmia playa soils provide valuable context for interpreting SA's performance. Mineral-based stabilizers such as bentonite and zeolite—which have been tested extensively across hotspot soils show strong but mechanism-specific behavior. Bentonite forms thick, cohesive crusts due to its swelling and hydration capacity, achieving maximum compressive strengths (Bani Baker et al., 2022). However, its performance is strongly dependent on clay content and water availability, making it less effective in coarse or carbonate-rich soils. Zeolite, while chemically stable, forms thinner crusts due to its rigid non-swelling framework.

These contrasts help highlight the unique advantages of SA. Unlike bentonite and zeolite, SA does not rely on mineral hydration or water-driven swelling; rather, it forms an organic polymer network stable even under low-moisture conditions. This property is particularly valuable in arid playas where rapid surface drying prevents mineral stabilizers from fully expressing their swelling potential. Similar results are reported by Hamzhepour et al. (2024). In that study, sodium alginate also achieved thick, highly resistant crusts on sandy soils from northwestern part of Lake Urmia. Moreover, combining polymers with minerals—as shown in previous studies—can result in gel formation that increases pore space and weakens crust strength (e.g. Alkhayer et al., 2024; Alkhayer et al., 2024). The present results demonstrate that SA alone can generate stable bonds without interfering with mineral packing, making it a more reliable stabilizer for sandy and saline soils.

Recent research on geopolymers provides additional comparative insight, especially regarding their vulnerability to sulfate and magnesium attack. Geopolymer-stabilized soils deteriorate when exposed to high concentrations of  $\text{Na}_2\text{SO}_4$  or  $\text{MgSO}_4$ , showing softening, mass loss, and microstructural breakdown (Luo & Zhang, 2023; Yi et al., 2023).  $\text{Mg}^{2+}$ , in particular, disrupts the aluminosilicate network, causing pronounced surface scaling and internal cracking. These deterioration patterns parallel processes commonly observed in Lake Urmia's sulfate- and chloride-rich playa surfaces (Alkhayer et al., 2024; Hamzhepour and Marcolli, 2024).

In contrast, the stabilization mechanism of SA is largely independent of sulfate–mineral reactions. SA binds particles through physical film formation and hydrogen bonding rather than chemical precipitation or ionic gelation, making it less susceptible to sulfate-induced degradation. This distinction is important because playa soils exposed to long-term evaporation cycles commonly accumulate sulfate minerals, which can undermine the performance of geopolymer and salt-based

stabilizers. The durability of SA observed in this study over a three-month period suggests it may offer advantages in saline environments where many mineral stabilizers show rapid decay.

Moreover, while chemical stabilizers such as Mg-brine can rapidly produce hard but brittle salt crusts, these crusts typically lack depth and are sensitive to moisture dissolution and recrystallization cycles (Alkhayer et al., 2024). The polymer-based mechanism of SA avoids brittleness and instead generates flexible crusts with better resistance to cracking under thermal and mechanical stress.

Sodium alginate's biodegradability and non-toxicity provide further justification for its application in environmentally sensitive regions. Unlike synthetic stabilizers or high-concentration brines, SA does not introduce persistent chemical residues or increase soil salinity—critical considerations for the degraded ecosystems surrounding Lake Urmia. Biopolymers have been shown to enhance soil physical properties without disrupting soil biological activity (Guilherme et al., 2015), making SA particularly aligned with ecological restoration goals.

Taken together, these findings show that sodium alginate offers a promising balance of mechanical effectiveness, environmental compatibility, and durability under saline–arid conditions. Compared with mineral-based, geopolymer, and salt-induced stabilizers studied previously, SA presents a fundamentally different and potentially more resilient stabilization mechanism for playa soils. Future research should evaluate long-term performance under natural wetting–drying–crystallization cycles, investigate synergistic combinations of SA with low-dose mineral amendments, and conduct field-scale trials to validate laboratory findings across different soil textures.

## **Conclusion**

The desiccation of Lake Urmia has resulted in the exposure of vast sandy–saline surfaces, transforming these areas into significant dust source regions. Among these, the Akhund-Qeshlagh region exhibits a high susceptibility to wind erosion due to its poor soil structure, characterized by high sand content, low clay and organic matter levels, and elevated salinity. This study investigated the potential of sodium alginate as an eco-friendly stabilizer to enhance the resistance of these soils to wind erosion under varying concentrations and application methods.

The results demonstrated that sodium alginate is effective in improving soil stability. The mixing and compaction (MC) method yielded the highest compressive strength, making it suitable for applications requiring long-term stability. Spraying sodium alginate, particularly on wet soil (WSp), also produced promising results, offering a practical option for large-scale or temporary stabilization efforts. The wind-tunnel experiments confirmed that even the dry spraying method (DSp) reduced soil loss by up to 86%, highlighting the potential of sodium alginate for erosion control in high-wind environments.

Although this study provides valuable insights into the effectiveness of sodium alginate in stabilizing sandy–saline soils of the southeastern Lake Urmia playa, several limitations should be acknowledged. First, the experiments were carried out under controlled laboratory and wind tunnel conditions, which may not fully represent the complexity of natural field environments, including

variable moisture, temperature, and wind dynamics. Second, the study evaluated short- to medium-term performance (three months), whereas the long-term durability and environmental behavior of sodium alginate under repeated wetting–drying and salt-crystallization cycles remain uncertain. Third, only a limited range of concentrations and application methods were tested, and additional formulations or field-scale application strategies may yield different results. Future field-based investigations are therefore necessary to validate the scalability, persistence, and practical feasibility of sodium alginate as a dust-control agent in active playa systems.

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