

Reduction of the wind erosion potential in dried-up lakebeds using artificial biocrusts

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Abstract The artificial creation of biocrusts can be a rapid and pervasive solution to reduce wind erosion potential (WEP) in dried-up lakes (e.g., Lake Urmia). So, in this study, we created a biocrust by the inoculation of bacteria and cyanobacteria on trays filled by soils collected from the dried-up bed of Lake Urmia, Iran, to reduce WEP in laboratory conditions. We used the wind erodible fraction of soil (*EF*) and soil crust factor (*SCF*) equations to calculate the WEP of the treated soils. *EF* and *SCF* were decreased ($p < 0.05$) through applying the co-inoculation of bacteria and cyanobacteria by 5.6% and 10.57%, respectively, as compared to the control; also, the “cyanobacteria alone” inoculation decreased *EF* by 3.9%. Our results showed that the artificial biocrusts created by soil inoculation, especially with the co-using of bacteria and cyanobacteria, significantly reduced the WEP of a newly dried-up lakebed. Furthermore, we found that inoculation decreased the WEP of the study soil by increasing the soil organic matter content from 3.7 to 5 fold. According to scanning electron microscopy images, the inoculated microorganisms, especially cyanobacteria, improved soil aggregation by their exopolysaccharides and filaments; thus, they can be used with other factors to estimate the soil erodibility in well-developed biocrusts. The inoculation technique could be considered as a rapid strategy in stabilizing lakebeds against wind force. However, it should be confirmed after additional experiments using wind tunnels under natural conditions.

Keywords biological soil crust, dried-up lakes, dust storms, flowing-sands, soil cyanobacteria

1 Introduction

The drying up of Lake Urmia, the world’s sixth-largest

saline lake (~5000 km²), in the northwestern part of Iran, is known as one of the most apparent indices of unsustainable development and ecosystem health threats. In the dried-up beds of this lake, as well as other lakes with similar conditions, wind erosion is a widespread phenomenon (Whitney et al., 2015) because of lacking natural barriers (Duniway et al., 2019). Wind erosion from dried-up lakebeds causes ecosystem instability degradation in detachment, transportation, and deposition areas (Farebrother et al., 2017).

Sand dunes, moving wind-blown sands, and dust hotspots are new-born landforms that have emerged around the bed of Lake Urmia, like other world’s dried lakes. Moreover, salt sediments and dust are another problem this lake faces currently (Ahmady-Birgani et al., 2018). Accordingly, along with the Lake Urmia restoration programs, reducing the wind erosion potential (WEP) of the dried-up beds can prevent the degradation of ecosystems in this region.

Increasing cohesion of soil particles and continuing the rehabilitation of the vegetation coverage can reduce WEP in the dried-up beds (Maleki et al., 2016; Fan et al., 2018; Vacek et al., 2018). In addition to vegetation, biological soil crusts (biocrusts) can also play this role in the drylands (Belnap et al., 2014). However, the natural formation of biocrusts in the dried-up beds is time-consuming because of their continually changing nature (Rozenstein et al., 2014).

Biocrusts are communities of living organisms (i.e., bacteria, cyanobacteria, microfungi, lichens, mosses, and bryophytes) on the tiny layer of the upper soil (Belnap et al., 2014). Biocrusts play a critical role in accelerating the development of the ecosystem in the early stages (Cutler et al., 2008; Kheirfam et al., 2017a). Decrease of the soil WEP in biocrusts arises from some capabilities of some microorganisms, including exopolysaccharide secretions (EPSs; Costa et al., 2018), formation of filament networks on the soil surface (especially

cyanobacteria; Chamizo et al., 2018), nitrogen fixation, and carbon sequestration (Kheirfam et al., 2017a; Kheirfam, 2020), and soil moisture retention (Rossi and De Philippis, 2015).

Biocrusts play an essential role in improving the stability of topsoil against erosive agents. Therefore, the creation of artificial biocrusts in the dried-up lakebeds can significantly help to reduce the soil WEP. As recently reported, biocrust formation by inoculating microorganisms can lead to controlling water erosion (Kheirfam et al., 2017b), stabilizing bare sandy beds (Mugnai et al., 2018), improving infiltration (Sadeghi et al., 2017), and increasing the soil nitrogen and carbon content (Muñoz-Rojas et al., 2018; Roncero-Ramos et al., 2019; Kheirfam, 2020).

In this study, we hypothesized that creating artificial biocrusts through inoculating soil bacteria and cyanobacteria could be regarded as a quick way to reduce WEP in dried-up lakebeds. It was also hypothesized that the co-inoculation of bacteria and cyanobacteria could play a greater role in improving the soil properties, especially soil organic matter, thus reducing WEP more, as compared to their separate inoculation.

In this study, we also attempted to investigate biocrust formation by inoculating soil bacteria and cyanobacteria to reduce WEP in dried-up lakebeds, with a particular focus on the newly dried Lake Urmia. However, before any widespread application of this technique on a large scale, laboratory experiments were considered to control possible environmental interferences.

2 Materials and methods

2.1 Soil collection

Soil was collected from the upper 0–20 cm of the dried-up areas of the western (Jabal-Kandi region) Lake Urmia (Fig. 1; NW Iran; 36°45'N to 38°20'N longitude and 44°50'E to 46°10'E latitude; elevation: ~1270 m a.m.s.l) in December 2018. The area of Lake Urmia is about 5000 km² (with a length of ~140 km length and a width of ~55 km); Lake Urmia is known as the world's sixth-largest saline lake (ranging from 140 to 380 g·L⁻¹; Zeinoddini et al., 2009). Currently, about 70% of this lake has been dried up due to indiscriminate dam-building, climate change, and especially uncontrolled exploitation of surface- and ground-water resources for agricultural irrigation purposes (Danesh-Yazdi and Ataie-Ashtiani, 2019). Crystalline salt formation in the north, fine-grained sediment-salt formations in the east and south, and sand-salt sediments in the west of Lake Urmia have led to various phenomena, including moving sands, dunes, and salt dust (Kheirfam and Roohi, 2020). Our recent analysis of 200 points of all dried-up beds of Lake Urmia (unpublished data) showed that the amount of soil organic matter varied from 0.03 to 5 g·kg⁻¹; the lowest values were observed in the western and northern regions of the lake. Despite the appropriate content of organic matter in some dried beds of the lake, the high salt concentration led to susceptibility to erosion in these areas.

The recent channel deposits (~44%), alluvial fans and

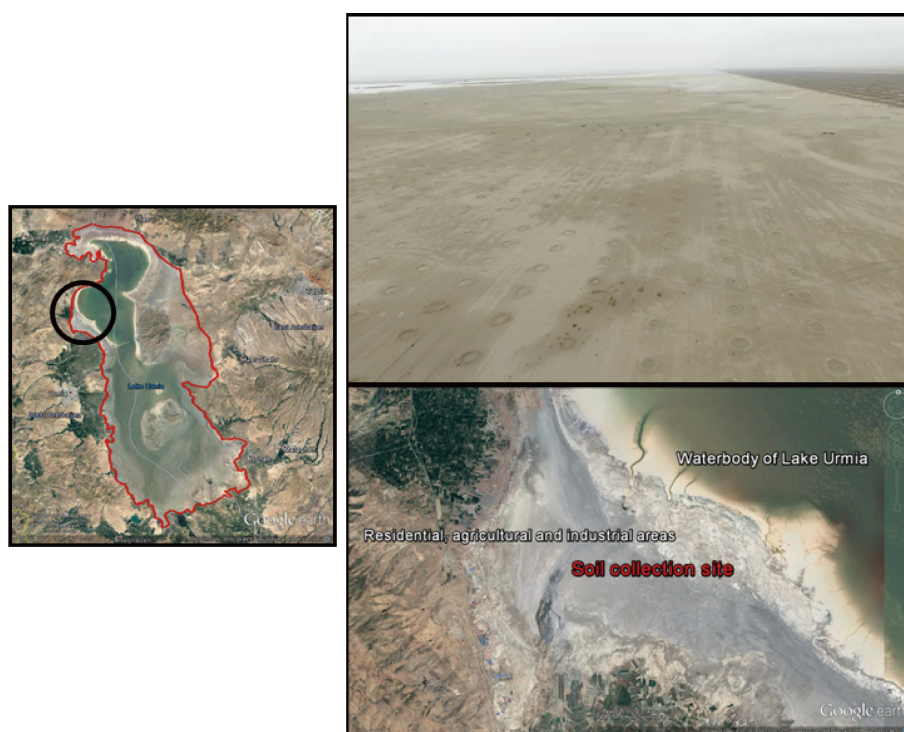


Fig. 1 The location of Lake Urmia, dried-up beds of the lake, and soil collection site for the experiment.

terraces (~33%), salty sandy flats (~14%), and the Rhyolite and marginal facies of granitic gabbro (~9%) geomorphological/lithological units have contributed to the formation of the western shore of Lake Urmia (Ahmady-Birgani et al., 2018). The dried-up beds of Lake Urmia, especially the western parts, can be regarded as a newly-born and unstable ecosystem. Surface soil instability due to the insufficient content of organic matter and, also, the high concentration of salt have reduced the chance of biocrust formation in the dried beds (Kheirfam and Roohi, 2020). Therefore, the western parts of the dried-up beds of Lake Urmia have a relatively significant potential for wind erosion; moving sands and dunes fields are known as one of the most critical new-born wind erosion landscapes rapidly advancing toward residential, industrial, and agricultural areas (Ahmady-Birgani et al., 2018).

A series of small galvanized trays with the length, width, and depth of 0.5, 0.3, and 0.1 m, respectively, were used to simulate the soil profile. The field-collected soils were poured into them and then compacted to achieve the bulk density of $1.67 \text{ g}\cdot\text{cm}^{-3}$, equal to that measured at the field site (Kheirfam et al., 2017a). The properties of the study soil are presented in Table 1. The study soil properties were the same throughout the sampling soil depth, without any specific stratifications.

2.2 Bacteria and cyanobacteria proliferation

To prepare inoculum, we used a *Bacillus subtilis* strain bacteria, and *Nostoc sp.* and *Oscillatoria sp.* cyanobacteria; these existed in the collection of Lake Urmia bed microorganisms in the Environmental Science Laboratory, Urmia Lake Research Institute, Urmia University, Iran. The microorganisms, as mentioned above, were selected according to their ability to secrete exopolysaccharides and network growth, the viability in different soil conditions, and none-pathogenicity, as previously reported by Kheirfam et al. (2017a and 2017b). We then proliferated and grew the bacteria and cyanobacteria

using the liquid Luria Broth (Garbeva et al., 2011) and CHU10 (Whitton and Potts, 2012) media, respectively. The inoculums were grown until a density of $1.5 \text{ g}\cdot\text{L}^{-1}$ of dry weight was obtained (Kheirfam, 2020). To determine the desired inoculum weight, we took 20 mL of each bacteria and cyanobacteria liquid inocula and then centrifuged them at 8000 rpm for 10 min; after that, they were freeze-dried and weighed (Ansari and Fatma, 2016). When the desired density of the inoculums was achieved, we used the optical density (OD) in the spectrophotometry and Neubauer chamber cells counting under high-resolution optical microscopes to count the bacteria and cyanobacteria, respectively (Janssen et al., 2002).

2.3 Soil inoculation

After the preparation of soil inoculums and trays (with the 0.5 m (length), 0.3 m (width) and, 0.1 m (depth) dimensions), based on a completely randomized factorial design, we inoculated 0.5 l (~0.75 g dry weight) of the bacteria ($\sim 3.33 \times 10^{11} \text{ CFU}\cdot\text{cm}^{-2}$) and cyanobacteria ($\sim 3.33 \times 10^6 \text{ CFU}\cdot\text{cm}^{-2}$), separately and in combination (0.25 L (~0.375 g dry weight) of each bacteria and cyanobacteria), on the soil by the spraying method (Wang et al., 2009; Kheirfam et al., 2017a, 2017b).

Accordingly, we had three replicates: 1) no inoculation (control), 2) inoculation of bacteria, 3) inoculation of cyanobacteria and 4) inoculation of bacteria+cyanobacteria treatments. The study was planned under laboratory experiment to better control the study conditions. After inoculation, the experimental trays were placed in the Environmental Sciences Laboratory of the Urmia Lake Research Institute, Urmia University, Iran, 10 km near the study site (from February to June 2019). Based on the recorded data from the meteorological station in the soil collection site, the temperature and relative humidity for the study period were $(25\pm 5)^\circ\text{C}$ and $(60\pm 10)\%$, respectively. We created environmental (temperature and relative humidity) conditions in the laboratory similar to the study area. We

Table 1 Description of the soil properties of the study region

Property	Description	Property	Description
Sand (%)	85.67	Organic N ($\text{g}\cdot\text{kg}^{-1}$)	0.08
Silt (%)	7	Available phosphor ($\text{mg}\cdot\text{kg}^{-1}$)	7.47
Clay (%)	7.33	Available potassium ($\text{mg}\cdot\text{kg}^{-1}$)	247
Texture	Sandy	CO_3 ($\text{mEq}\cdot\text{L}^{-1}$)	9.87
Bulk density ($\text{g}\cdot\text{cm}^{-3}$)	1.67	SO_4 ($\text{mEq}\cdot\text{L}^{-1}$)	9.42
Mean weight diameter (mm)	0.39	Cl ($\text{mEq}\cdot\text{L}^{-1}$)	4.30
Geometric mean diameter (mm)	0.067	Ca ($\text{mEq}\cdot\text{L}^{-1}$)	2.90
pH	8.47	Mg ($\text{mEq}\cdot\text{L}^{-1}$)	1.57
EC ($\text{ds}\cdot\text{m}^{-1}$)	1.45	Na ($\text{mEq}\cdot\text{L}^{-1}$)	11.38
Organic C ($\text{g}\cdot\text{kg}^{-1}$)	0.075	CEC ($\text{mEq}\cdot 100\text{g}^{-1}$)	4.23

also set the daily 14:10 h light/dark cycles in the laboratory environment based on the study site conditions.

2.4 Calculation of the wind erosion potential

Chepil (1950) and Chepil and Woodruff (1954) found a relationship between WEP and the soil surface properties (i.e., soil's texture and chemical content); based on the soil sieving and wind tunnel experiments data, we used the wind erodible fraction of soil (*EF*; Fryrear et al., 1994, 2000) and soil crust factor (*SCF*; Fryrear et al., 2000) equations (Eqs. (1) and (2), respectively) to calculate the WEP of the inoculated and non-inoculated soils. These commonly accepted equations have been widely applied to calculate WEP (e.g., Colazo and Buschiazzi, 2010; Borrelli et al., 2014, 2016; Jiang et al., 2019). However, aggregates larger than 0.84 mm in diameter have no potential for wind erosion (Borrelli et al., 2014). Evaluation of Eqs. (1) and (2) in estimating WEP by using wind tunnel data are, therefore, suggested to achieve more reliable results. However, the efficiency of these equations have already been confirmed by the wind tunnels experiment data (Chepil, 1950; Pásztor et al., 2016):

$$EF = \frac{29.09 + 0.31S_a + 0.17S_i + 0.33S_c - 5.9OM - 0.95CaCO_3}{100}, \quad (1)$$

$$SCF = \frac{1}{1 + 0.0066(\text{clay})^2 + 0.21(\text{OM})^2}, \quad (2)$$

where S_a , S_i , S_c , OM, and $CaCO_3$ are the soil sand (%), silt (%), sand to clay ratio, organic matter (%) and calcium carbonate contents (%), respectively. *EF* and *SCF* values vary from 0 to 100%, with higher values being indicative of a higher WEP (Borrelli et al., 2014).

EF and *SCF* represent the resistance of the soil crust against erosive factors (Borrelli et al., 2014); soil organic matter plays a critical role (as a cement) in adhering the soil particles together. This is despite the fact that, in the bare soils (without any vegetation), the soil microorganisms are responsible for providing organic matter in them (Kheirfam and Roohi, 2020). Therefore, the creating artificial biocrusts in the bare soils (e.g., dried-up lakebeds) through inoculating soil microorganisms could be a strategy to increase the content of the soil organic matter (Kheirfam, 2020), thus leading to strengthening the soil crust. However, it should be noted that the *EF* and *SCF* only reflect the potential of soil (inoculated or uninoculated) to wind erosion.

To measure the variables of the equations, the texture (% of sand, silt, and clay), organic matter content, and calcium carbonate content of the treatments soil surface

(0–2 cm) were measured using the flat sieve method (López et al., 2007), dichromate oxidation (Walkley and Black, 1934), and calorimetric (Loeppert and Suarez, 1996) methods, respectively. We also took scanning electron microscopy (SEM) images from the soil surface samples to show their particles connection.

2.5 Statistical analyses

After measuring sand, silt, clay, organic matter, and calcium carbonate content, *EF* and *SCF* values were calculated from the treatments. We generated scatterplots with regression lines to show the relationship between the measured variables and *EF* and *SCF* values, using Microsoft Excel 2013. Afterward, to explain the best-fit relationship between each soil variable and *EF* and/or *SCF* in the scatterplots, the squared correlation coefficient, R^2 value, was adjusted. We also used the Shapiro-Wilk and Levene's tests to test the data normality and homogeneity of variance, respectively. After confirming that our data followed a normal distribution ($p > 0.05$) and had equal variances ($p > 0.05$), one-way analysis of variance (ANOVA), which was followed by the Tukey's HSD test at the 95% confidence level, was applied to analyze the significant differences in the soil variables (S_a , S_i , S_c , OM, and $CaCO_3$), as used in Eqs. (1) and 2 (Table 2); as well, *EF* and *SCF* values among treatments (Table 3, and Figs. 2 and 3) were considered. When the Tukey value was less than 0.05 ($p < 0.05$), we accepted the hypothesis that the means of the groups (soil variables and, or *EF* and *SCF* values) significantly differed. The IBM SPSS Statistics 23 software package was then used for the analyses.

3 Results

The statistical analyses of the soil property values, according to Eqs. (1) and (2), showed that *EF* and *SCF* could be assumed as important indicators to estimate the soil, susceptibility to wind erosion, according to the treatments, as presented in Tables 2 and 3, and Figs. 2 and 3. The sand, silt, clay, OM, and $CaCO_3$ contents for the control soils were (85.67±1.15)%, (7±1)%, (7.33±0.58)%, (0.13±0.01)%, and (8.83±1.04)%, respectively (Table 2). The resulting *EF* and *SCF* values for the control trays were (51.97±0.57)% and (73.61±3.00)%, respectively (Figs. 2 and 3).

In the bacteria treatment, the contents of sand, silt, clay, OM, and $CaCO_3$ were (86.67±0.58)%, 6%, (7.33±0.58)%, (0.25±0.02)%, and 9%, respectively (Table 2). The estimated *EF* and *SCF* in the inoculated bacteria trays were 51.70 and 73.06%, respectively (Figs. 2 and 3). We also found that the bacteria inoculation did not have a significant effect ($p > 0.05$) on *EF* and *SCF*, as compared to the control.

Table 2 Measured soil properties for use in Eqs. (1) and (2) and statistical tests to evaluate their continuous variation

Treatments	Plot No. and statistical criteria	Properties				
		Sand ^{ns} /%	Silt ^{ns} /%	Clay ^{ns} /%	OM ^{**} /%	CaCO ₃ ^{ns} /%
No Inoc. (Control)	1	85	7	8	0.124	8
	2	87	6	7	0.138	10
	3	85	8	7	0.129	8.5
	Average	85.67 ^a	7.00 ^a	7.33 ^a	0.13 ^c	8.83 ^a
	SD	1.15	1.00	0.58	0.01	1.04
	CV (%)	1.35	14.29	7.87	5.34	11.78
Ba Inoc.	1	87	6	7	0.241	9
	2	87	6	7	0.224	9
	3	86	6	8	0.272	9
	Average	86.67 ^a	6.00 ^a	7.33 ^a	0.25 ^c	9.00 ^a
	SD	0.58	0.00	0.58	0.02	0.00
	CV (%)	0.67	0.00	7.87	9.89	0.00
Cy Inoc.	1	87	5	8	0.527	10
	2	84	7	7	0.696	8.2
	3	86	5	7	0.603	10
	Average	85.67 ^a	5.67 ^a	7.33 ^a	0.61 ^b	9.40 ^a
	SD	1.53	1.15	0.58	0.08	1.04
	CV (%)	1.78	20.38	7.87	13.89	11.06
Ba+Cy Inoc.	1	85	6	8	0.827	10
	2	85	7	7	0.782	10
	3	86	6	8	0.762	9
	Average	85.33 ^a	6.33 ^a	7.67 ^a	0.79 ^a	9.67 ^a
	SD	0.58	0.58	0.58	0.03	0.58
	CV (%)	0.68	9.12	7.53	4.23	5.97

Notes: No Inoc. (Control): no inoculation; Ba Inoc. : bacteria inoculation; Cy Inoc. : cyanobacteria inoculation; Ba+Cy Inoc. : combined inoculation of bacteria and cyanobacteria. “ns” is non-significant differences; “***” is significant difference (Tukey, $p < 0.01$). Averages with the same letter show non-significant differences (Tukey, $p > 0.05$), otherwise, they show a significant difference (Tukey, $p < 0.05$) within subjects (properties).

Sand, silt, clay, OM, and CaCO₃ contents for cyanobacteria inoculated soils were (85.67±1.53)%, (5.67±1.15)%, (7.33±0.58)%, (0.61±0.08)%, and (9.40±1.04)%, respectively (Table 2). We also observed that the estimated EF and SCF in the inoculated cyanobacteria trays were 50.06 and 69.71%, respectively (Figs. 2 and 3). The results, therefore, showed that the inoculation of cyanobacteria decreased EF (3.9%), as compared to the control.

In the inoculated bacteria + cyanobacteria trays, the contents of sand, silt, clay, OM, and CaCO₃ were (85.33±0.58)%, (6.33±0.58)%, (7.67±0.58)%, (0.79±0.03)%, and (9.67±0.58)%, respectively (Table 2). The results indicated that the estimated EF and SCF in the bacteria + cyanobacteria treatment were 49.97 and 65.83%, respectively (Figs. 2 and 3). We also found that the bacteria + cyanobacteria inoculation had a positive effect ($p < 0.05$) on the decrease of both EF (5.6%) and SCF (10.57%), as compared to the control (Figs. 2 and 3). However, the variance among treatments (displayed as

error bars) indicated a slight difference between the treatments; this could be attributed to the low values of standard deviation.

According to the one-way ANOVA results (Table 3), significant changes ($p < 0.05$) were only found for EF, SCF, and OM between treatments, while no significant changes were observed for other components (i.e., S_a , S_p , S_c , and CaCO₃).

The scatterplot graphs of the treatments soil properties used for WEP estimation equations, as well as EF and SCF values, are presented in Fig. 4. We observed that the R^2 values for the relationship between sand-EF, silt-EF, clay-EF, OM-EF, and CaCO₃-EF were 0.03, 0.18, 0.094, 0.82, and 0.47, respectively. Also, the R^2 values for the relationship between silt-SCF and OM-SCF were 0.57 and 0.62, respectively.

The SEM images obtained from the experimental tray’s soil surface showed no binding between soil particles in the control treatment (Fig. 5(a)). We also observed an almost good relation between soil particles in the bacteria

Table 3 Results of the one-way ANOVA comparing the variation of the wind erodible fraction of soil (EF ; %) and soil crust factor (SCF ; %) as well as sand (S_a ; %), silt (S_i ; %), sand/clay (S_c ; %), organic matter (OM; %), and calcium carbonate ($CaCO_3$; %) content that used for calculating the EF and SCF due to the various treatments

Variable		df	Mean square	F-value	p-value
EF	Between Groups	3	5.816	14.839	0.001
	Within Groups	8	0.392		
	Total	11			
SCF	Between Groups	3	38.454	4.956	0.031
	Within Groups	8	7.760		
	Total	11			
S_a	Between Groups	3	1.000	0.923	0.472
	Within Groups	8	1.083		
	Total	11			
S_i	Between Groups	3	0.972	1.458	0.297
	Within Groups	8	0.367		
	Total	11			
S_c	Between Groups	3	0.285	0.362	0.782
	Within Groups	8	0.786		
	Total	11			
OM	Between Groups	3	0.285	127.773	0.000
	Within Groups	8	0.002		
	Total	11			
$CaCO_3$	Between Groups	3	0.430	0.688	0.584
	Within Groups	8	0.624		
	Total	11			

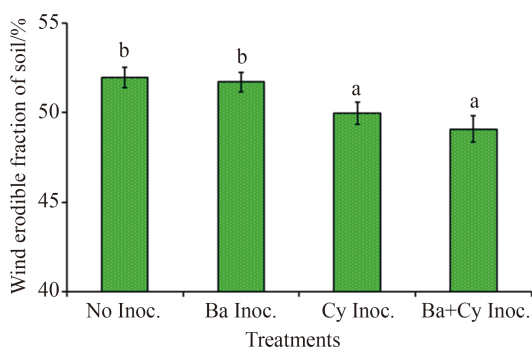


Fig. 2 Wind erodible fraction of soil (EF) variation in the treatments. No Inoc. (Control; no inoculation); Ba Inoc. (bacteria inoculation); Cy Inoc. (cyanobacteria inoculation); and Ba + Cy Inoc. (combined inoculation of bacteria and cyanobacteria). Bars with the same letter show non-significant differences (Tukey, $p > 0.05$); otherwise, they show a significant difference (Tukey, $p < 0.05$).

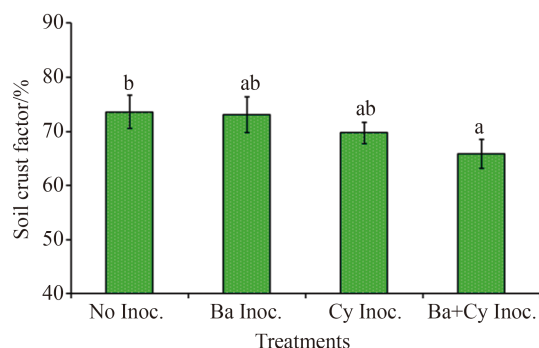


Fig. 3 Soil crust factor (SCF) variation in the treatments. No Inoc. (Control; no inoculation); Ba Inoc. (bacteria inoculation); Cy Inoc. (cyanobacteria inoculation); and Ba + Cy Inoc. (combined inoculation of bacteria and cyanobacteria). Bars with the same letter show non-significant differences (Tukey, $p > 0.05$); otherwise, they show a significant difference (Tukey, $p < 0.05$).

treatment (Fig. 5(b)). Also, the soil particles were well-aggregated in the cyanobacteria and bacteria + cyanobacteria treatments, as compared to the control (Figs. 5(c) and 5(d)).

4 Discussion

4.1 WEP from dried-up lake beds

According to the soil WEP classification proposed by López et al. (2007), the collected soil (control) could be

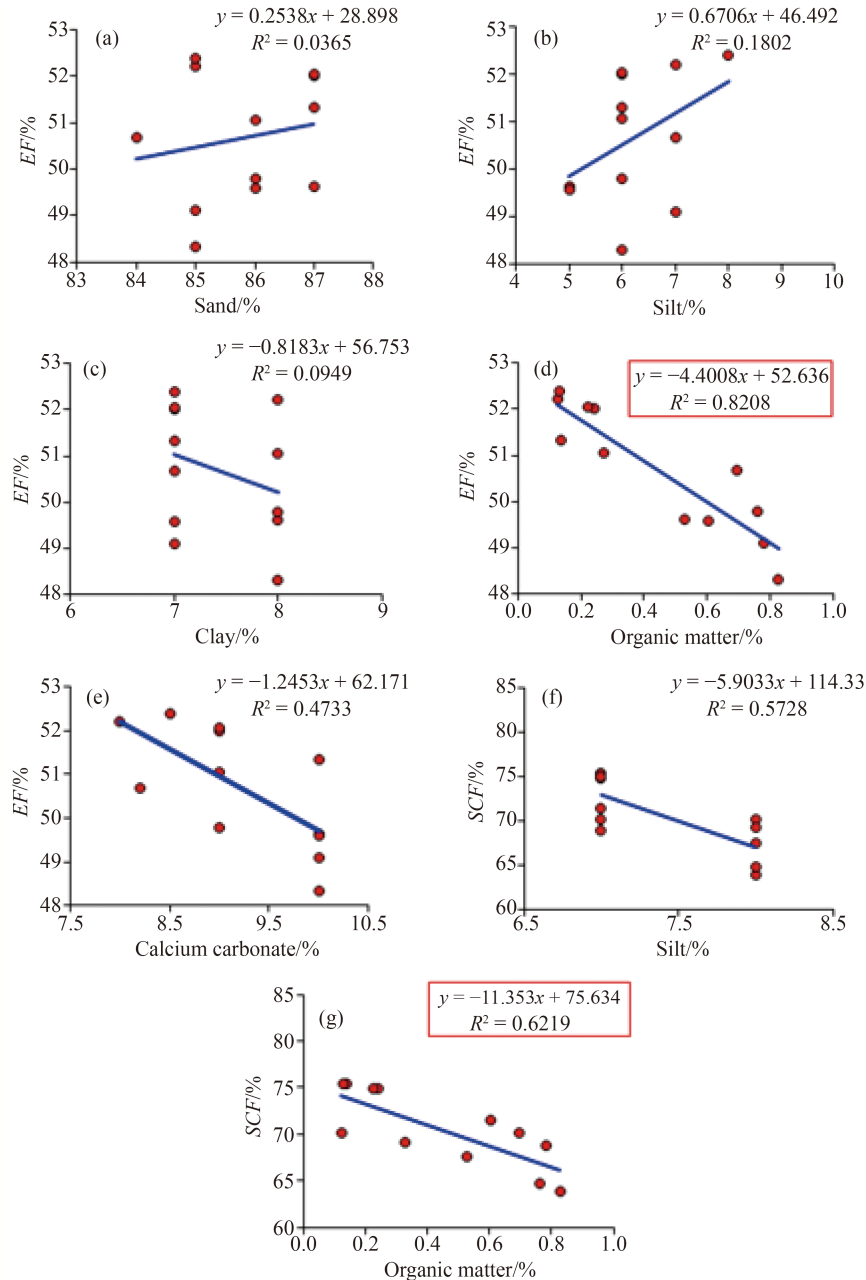


Fig. 4 Scatter plot graph of the treatments soil properties used for WEP estimation equations and the *EF* and *SCF* values. The linear (blue) trendlines (the line of best fit) indicate the general pattern and overall direction of the data set, drawn using Microsoft Excel 2013. The upward and downward direction lines indicate indirectly and reverse the relationship between soil variables and *EF* and/or *SCF* values. The R^2 values also show the strength of the relationship between each soil variable and *EF* and/or *SCF* in the scatterplots, in which the high R^2 indicates a high correlation between the two dependent and independent variables.

characterized by high erodibility ($EF \geq 50\%$); this result was also observed based on the *SCF* value. In addition to wind force factors, soil surface conditions and soil properties (i.e., physical, chemical, and biological properties) play a significant role in the soil susceptibility to wind erosion. The soil particles size distribution (Shahabinejad et al., 2019), aggregation (Borrelli et al., 2014), moisture content (de Oro et al., 2019), organic matter content (Zou et al., 2018), chemical elements content (e.g., calcium carbonate; Zou et al., 2018), and

biocrust developing state (Gao et al., 2017) have been reported as the most critical soil factors.

In the bare sandy soils, as in our case, the high participation of coarse particles in the soil texture could be an advantage, increasing the soil resistance to wind force, provided that the clay content would be above 20% (Gillette et al., 1980); however, this condition was not observed in the case of our origin soil (Table 2; clay < 8%). On the other hand, soil particle size distribution could affect the WEP rate by contributing to the

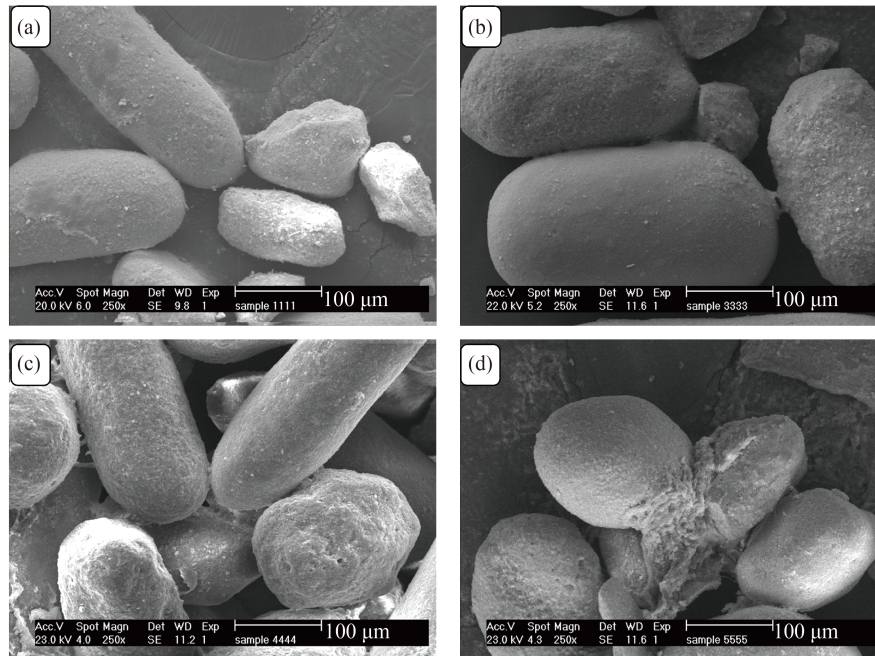


Fig. 5 The scanning electron microscopy images of the control (a), inoculation of bacteria (b), inoculation of cyanobacteria (c), and co-inoculation of bacteria and cyanobacteria (d) treatments.

formation of soil aggregates (Yan et al., 2018). Coarse-textured soils are more susceptible to the erosive force of wind because of the more frequent poor aggregation with lower density and weak binding, as well as inter binding forces (Avecilla et al., 2015). These conditions were also observed in the soil we studied.

According to the criterion suggested by Le Bissonnais (2016), the aggregations of the soil could be classified as very unstable, unstable, medium stable, stable, and very stable, based on the MWD values of <0.4, 0.4–0.8, 0.8–1.3, 1.3–2 and >2, respectively. As presented in Table 1, the soil collected from the dried-up beds of Lake Urmia could be categorized as very unstable aggregation soils (with the mean weight diameter (MWD) = 0.39 mm).

Soil organic matter has a negative charge that can adsorb cations from other organic carboxylic and phenolic groups by forming micelles capable of hydrating and adsorbing cations (Sequeira and Alley, 2011). Therefore, soil organic matter plays an indirect role in determining the WEP rate by affecting the soil properties (i.e., nutrient availability, soil porosity, water retention capacity, and water infiltration rate). Additionally, soil chemical elements and components (e.g., calcium carbonate) can control the WEP rate by the absorption of water (Zou et al., 2018). The low content of organic matter (0.075 g·kg⁻¹; Table 1) and calcium carbonate (8.83%; Table 2) in the collected soil could be regarded as one of the reasons for the high-susceptibility of our soil to wind erosion.

4.2 Impacts of the artificial creation of biocrusts on WEP in dried-up lake beds

The obtained results indicated that the artificial creation

of biocrusts by the inoculation technique, especially the co-inoculation of bacteria and cyanobacteria, could reduce the WEP of a newly dried-up lakebed (Lake Urmia, Iran).

According to Tables 2 and 3, among the soil variables measured in the trays (sand, silt, clay, organic matter, and calcium carbonate), only soil organic matter had significant differences in different treatments ($p < 0.01$). Therefore, the role of the creation of biocrust through inoculation in increasing the soil organic matter content was confirmed. As shown in Fig. 4, the WEP indices in this study had a significant inverse correlation with the soil organic matter (*EF*-organic matter, $R^2 = 0.82$, and *SCF*-organic matter, $R^2 = 0.62$). It is important to note that 58% of the soil's organic matter is made of organic carbon (Kheirfam, 2020). In the bare soils, as our soil, biocrust is known as the only supplier of the soil organic matter through carbon storage (Kheirfam, 2020). Carbon storage in biocrusts is done in different ways, including decomposition of dead microorganisms (Rossi et al., 2015), photosynthetic and bioelectrochemical processes (Kheirfam et al., 2017a). However, photosynthetic microorganisms (i.e., cyanobacteria) play a critical role.

In the photosynthetic process, cyanobacteria can fix atmospheric CO₂ and then convert it to oxygen and carbon, as the C_x-H_y-O_z chains form, with the help of photon energy (Mager and Thomas, 2011). This process can also be performed by chemosynthetic bacteria, although limited (Rossi et al., 2015). In this regard, Naik et al. (2010) found that some species of bacteria could increase the soil organic matter using electrochemical processes. Our results also showed that the organic matter

was significantly increased in the cyanobacteria and bacteria + cyanobacteria inoculated trays by 3.7 and 5 folds, respectively, compared to the control (Table 2). It has been reported that cyanobacteria could increase the soil organic carbon by 40% (after 60 days; Kheirfam et al., 2017a) and 83% (after 90 days; Chamizo et al., 2018). Furthermore, Kheirfam (2020) found that the co-inoculation of bacteria and cyanobacteria increased the sequestered C in the erosion-prone soil by 24 folds. Although it may be part of the soil carbon content increases due to the inoculated microorganisms cells, it has been estimated to be less than 2.2×10^{-10} g·m⁻² for the inoculum volume used in the present study (Mahlmann et al., 2008; Kheirfam, 2020). Thus, it had no notable effect on the soil organic matter.

Besides the direct impact, biocrust living microorganisms, especially cyanobacteria, are capable of producing and secreting polysaccharide materials (Stuart et al., 2016); these exopolysaccharides are also a notable source of organic matter (Rossi and De Philippis, 2015). In this regard, Chamizo et al. (2018) have reported that ~22% of cyanobacterial exopolysaccharides are composed of organic matter. Soil inter-particle bonding can be one of the impacts of the secreted exopolysaccharides of cyanobacteria, as shown in Figs. 5(c) and 5(d) for our inoculated soils, which was because of their adhesion properties (Bullard et al., 2018). Additionally, the filaments of cyanobacteria could bind the fine particles of soil together like a spider's web (Pagliai and Stoops, 2010; Figs. 5(c) and 5(d)), which is known as one of the functions of biocrusts (Belnap et al., 2013).

Overall, the results indicated that the inoculation of cyanobacteria and co-inoculation of bacteria and cyanobacteria decreased the WEP of the dried-up bed of Lake Urmia by increasing the soil organic matter in laboratory conditions. However, the biocrust artificially created by the inoculation technique could not improve other soil variables affecting the wind erodibility of soil (i.e., sand, silt, clay, and calcium carbonate content). The results, therefore, confirmed that the soil inoculation technique improved the soil aggregation with the help of inoculated microbial exopolysaccharides and filaments. Therefore, the biocrust artificially created by inoculated microorganisms increased the soil resistance and stability against wind force.

5 Conclusions

Newly dried-up lakebeds like Lake Urmia are prone to wind erosion; thus, they are subject to drying up. Artificial rapid creation of biocrusts can provide a novel strategy to control the potential of wind erosion; in this study, bacteria and cyanobacteria inoculation was used to achieve this goal. We found that the sandy soil of the dried-up beds of Lake Urmia was highly susceptible to

wind erosion; however, the amount of WEP was reduced with the creation of biocrust by using the inoculation technique. Our results also showed that bacteria and cyanobacteria reduced WEP by increasing the soil organic matter content, with no effect on the soil texture. However, exopolysaccharides and filaments of cyanobacteria improved the soil particle adhesion and aggregation; thus, the involvement of this factor in WEP estimation equations (e.g., *EF* and *SCF*) could be considered for drylands with well-developed biocrusts. However, despite the good results obtained by the experiment in this study, much further research is needed to investigate this technique under field conditions along with the wind tunnel experiments data.

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