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Interaction of petroleum mulching, vegetation restoration and dust fallout on the conditions of sand dunes in southwest of Iran

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A R T I C L E I N F O

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A B S T R A C T

In the past half-century, petroleum mulching-biological fixation (PM-BF) practices have been employed to stabilize sand dunes in Iran. However, the effects of PM-BF practices on the attributes of sand dunes and the dispersion of heavy metals of mulch have been poorly understood. To this end, three regions treated with PM-BF for 5, 20, and 40 years and a control region with no PM-BF were studied. Samples of soil properties were taken at the depths of 0–10 cm and 10–50 cm, with three replications, in Khuzestan Province. The results showed that PM-BF practices promoted the restoration of vegetation cover in the sand dunes. In addition, these practices increased the deposition of dust particles, gradually increasing the magnitudes of palygorskite and smectite clays over time. The interactions between dust deposition and PM-BF practices significantly altered the chemical and physical properties of the dunes. PM-BF practices increased soil organic matter (184–287%), cation exchangeable capacity (142–209%), electrical conductivity (144–493%), clay content (134–196%), and penetration resistance (107–170%) compared to the region with no PM-BF practices. Furthermore, petroleum mulching significantly increased the amount of Ni (1.19%), Cd (1.55%), Pb (1.08%), Cu (1.34%), Zn (1.38%), Mn (1.66%), and Fe (1.15%). However, in the long term, these elements will probably leach linearly as a consequence of an increase in organic matter and soil salinity in the light texture of sand dunes.

1. Introduction

Sand dunes (Ahmadi et al., 2002) and dust storms (Zarasvandi et al., 2011) are two of the most serious problems of arid regions in Iran because they cause damage to cities, villages, communication lines, installations, and various factories each year. According to current estimates, wind erosion has affected more than 400,000 ha of land area in Khuzestan province, more than 270,000 ha of which are sand dunes. Therefore, in the past half-century, approximately 70,000 ha of these lands have been stabilized with PM-BF practices (Khalilimoghadam et al., 2015).

Various types of mulch are widely used around the world for sand dune stabilization. Although the biological establishment of sand dunes is one of the fixation methods for stabilization, in many cases, the establishment of plant species requires the initial stabilization of sand dunes (Rezaie, 2009). Thus far mulches such as heavy petroleum products, bitumen emulsion, sodium chloride solution, sodium or potassium carbonates, fiber, stone, glass wool, thin layers of plastic, polyethylene, and cellophane have been utilized to stabilize sand dunes (Homauoni and Yasrobi, 2011). Mulches are compounds that can increase soil strength against wind shear forces and prevent the separation of particles of sand dunes (Wuddivira et al., 2013). The mulch compounds can increase sand cohesion and inter-particle friction in sand dunes. Due to their cohesion properties, clay, polymer, petroleum, and organic matter mulches cause the particles of sand dunes to stick together (Khalilimoghadam et al., 2015). Moreover, owing to their lower ionic double layers, salts cause the flocculation of particles of sand dunes. Li et al. (2014) showed that soils with higher salinity have lower wind erodibility than non-saline soils.

The main base of the petroleum mulch is a wide range of compounds of heavy petroleum hydrocarbons that are divided into different parts, which have a different chemical composition that includes saturated naphthene, polar aromatics, and asphaltenes (Akbarnia, 2009). Crude oil is a colloidal mixture in which metals are present in organic and inorganic forms (Wang et al., 2010). The chemical decomposition of petroleum compounds with different viscosities and concentrations of asphaltenes showed that higher oil residuals result in higher heavy metals. When soil and live tissues contaminated with the crude oil were analyzed, Ni, V, Pb, Cu, and Cd were extracted (Duyck, 2009). Li et al. (2014) concluded that petroleum mulching increases soil quality due to the increase in the nutrient matter (N, P, K, and micronutrients). They demonstrated that petroleum mulch creates pores in the soil, thus

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enhancing plant growth. Akbarnia et al. (2005) concluded that the use of petroleum mulch in some regions of Khuzestan increases sand dune stabilization as well as vegetation. According to their results, the decomposition of molecules of petroleum hydrocarbon in the soil causes an increase in the amount of organic matter.

In addition to the phenomenon of sand dunes, the phenomenon of dust storm has been observed and exacerbated in recent decades due to climate change and human factors such as the construction of large dams, intensive grazing in pastures, lack of crop rotation, monoculture, drying wetlands, and regional conflicts in the Middle East region. Accordingly, Khuzestan province is affected by dust storms arising from internal and external sources such as Iraq, Syria, and Saudi Arabia. The effects of dust storms may continue at a distance of 4000 km from the main source and cause biotic effects and great damages in the fields of agriculture, industry, transport, and telecommunication systems (Zarasvandi et al., 2011).

The results obtained from many samples of dust storms in Khuzestan province confirm that the constituent minerals of the samples investigated are generally in the three phases of main minerals, including carbonate (mainly calcite), silicate (mainly quartz), and phyllosilicate (mainly kaolinite). The clay minerals, as the secondary mineral phase, play a role in the absorbance of some heavy metals (Zarasvandi et al., 2011). These findings indicate that in the majority of samples, the frequency of calcite and quartz as the main products in the destructive sediment environments demonstrates rather a sedimentary source for dust storm particles in Khuzestan (Zarasvandi et al., 2011).

Hojati et al. (2012) stated that the majority of minerals in the dust storm striking Jandagh to Koohrang contain more quartz and calcite and less dolomite, gypsum, and halite. Mahmoudi and Khademi (2014) demonstrated that the clay mineralogy compound of dust storm particles contains palygorskite, smectite, chlorite, illite, kaolinite, feldspars, and quartz. Other researchers reported that the constituent minerals of dust storm particles are quartz (Cattle et al., 2002; Hojati et al., 2012), palygorskite and feldspars (Fiol et al., 2005), micas (Küffmann, 2003), and magnetite (Reynolds et al., 2006). Dust storms in lowlands result from multiple mechanisms of natural and anthropogenic disturbance and can be transported far from the source (Steenburgh et al., 2012; Vandenberghe, 2013; Inmaculada et al., 2014). After their deposition, dust storms cause serious effects on ecosystem, including changes in the hydrological cycle (Painter et al., 2007, 2010; Jeffrey et al., 2015), the chemical characteristics of surface water (Brahney et al., 2014; Moser et al., 2010; Psenner, 1999), and soil formation processes (Dahms, 1993; Lawrence et al., 2011).

Although petroleum mulching-biological fixation (PM-BF) practices aimed at stabilizing sand dunes have a history of more than a hundred years, there are few research reports in this regard, and what is on hand is more indicative of the utility of this type of mulch for temporary mechanical stabilization of sand. However, the long-term effects of PM-BF practices and their interactions with dust storms on different characteristics of sand dunes have not been investigated yet. Therefore, this research was carried out in stabilized regions of sand dunes in Khuzestan province with a history of 2 to 50 years. The aim was to address the long-term effects of PM-BF practices on the physical and chemical properties of sand dunes and heavy metals and the trend of changes in clay minerals.

1.1. Study area (Physiographic conditions and history)

In this region, there are three morphologies of sand dunes. The dominant morphology is the seif dunes created due to the presence of western and southeastern winds with acute angles. In addition, the morphology of transverse ridges is obseved in this region, which has been formed owing to the movement of barchans under the influence of the collision of two dominant winds in the region with obtuse angles and their connection with each other. Single barchans are also scattered throughout the region (Iranian Institute of Forest and Rangelands Research, 2005). Fig. 1 shows the frequency distribution of the direction of the winds in the region. Based on morphoscopy studies, the mode diameter of sand dunes in this region is approximately 166–214 μm. These almost equal diameters indicate the existence of a concentric source for the sand dunes in this region. The most frequent diameter of the sand dune particles is 180 μm, and the displacement distance of these particles is estimated to be approximately 20–25 km, indicating the nearness of the source of the sand dunes. The sorting of the samples is very good (0.1–3) and the skewness of their particles is toward fine grain. The sand dunes have not been moved from a far distance and are mainly originated to discontinuous sandstones in the west and northwest regions. Calcareous materials constitute more than 60% of these sands whose compounds are almost the same as those of Aghajari formation sand stones (Iranian Institute of Forest and Rangelands Research, 2005).

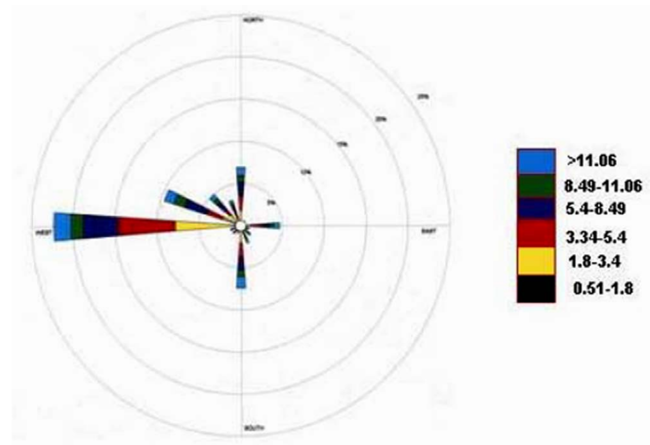

Fig. 1. The frequency distribution of the direction of the winds in a 30 year time period.

2. Materials and methods

2.1. Experimental area

The present study was conducted in the stabilized sand dunes of Khuzestan province in the southwest of Iran (Fig. 2). The average annual air temperature in this region is 24.5 °C. In addition, the mean monthly maximum air temperature of 45.9 °C is observed in July and the average annual minimum air temperature of 5.98 °C is observed in January. The average maximum temperature of the warmest month (July) is 50 °C and the mean minimum temperature of the coldest months (January and February) is 3.2 °C. The average annual rainfall of 261.7 mm and the mean monthly maximum rainfall are reported in January and December. In this station, there are 6.1 days with less than one millimeter of rainfall in a single year, 25.6 days with more than one millimeter of rainfall, and 7.9 days with more than 10 mm of rainfall.

In Khuzestan province, for sand dune stabilization, petroleum mulch of 1 mm thickness could be sprayed on sand dunes, a process known as petroleum mulching (PM). The mulches consumed are mostly petroleum-based and are produced by Abadan Oil Refineries. Petroleum mulch is a colloidal mixture of a wide range of heavy hydrocarbon compounds which are classified into the following four fractions: saturates, naphthene, polar aromatics, and asphaltenes (Akbarnia, 2009). After that tree seedlings such as *Prosopis cineraira* and *Tamarix hispida* are planted. Due to its cohesive property, petroleum mulch prevents the movement of sand particles and helps the tree seedling to grow by the full establishment. The stabilized region was excluded for several years and the entrance of livestock was prevented for many years. The practice of tree planting and exclosure after mulching is called biological fixation (BF). A significant part of the mulch sprayed was decomposed by the biological activity of soil organisms and chemical

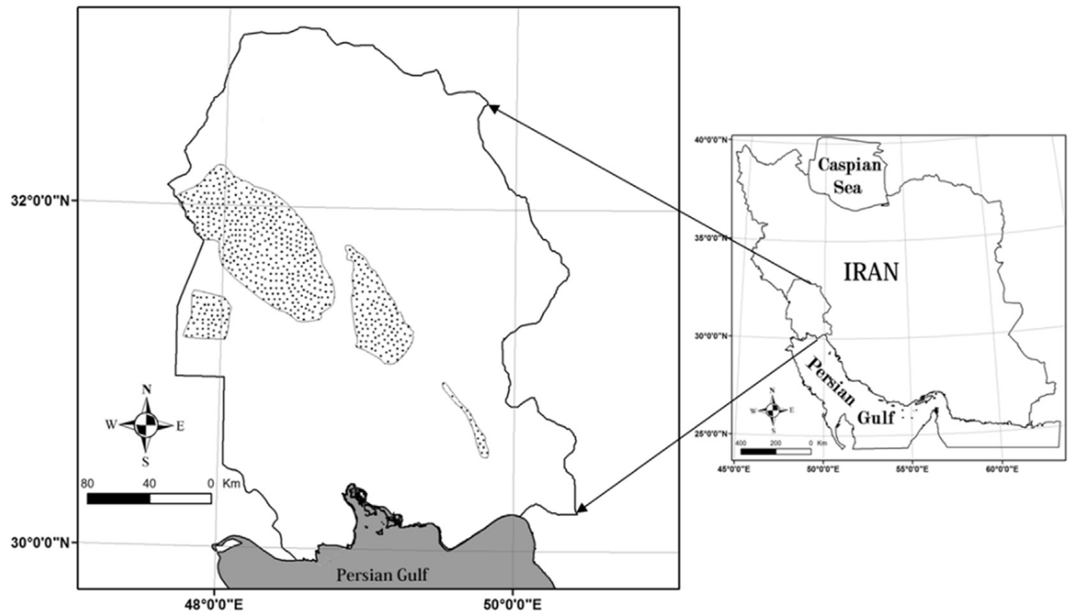

Fig. 2. Geographical location of the area under study.

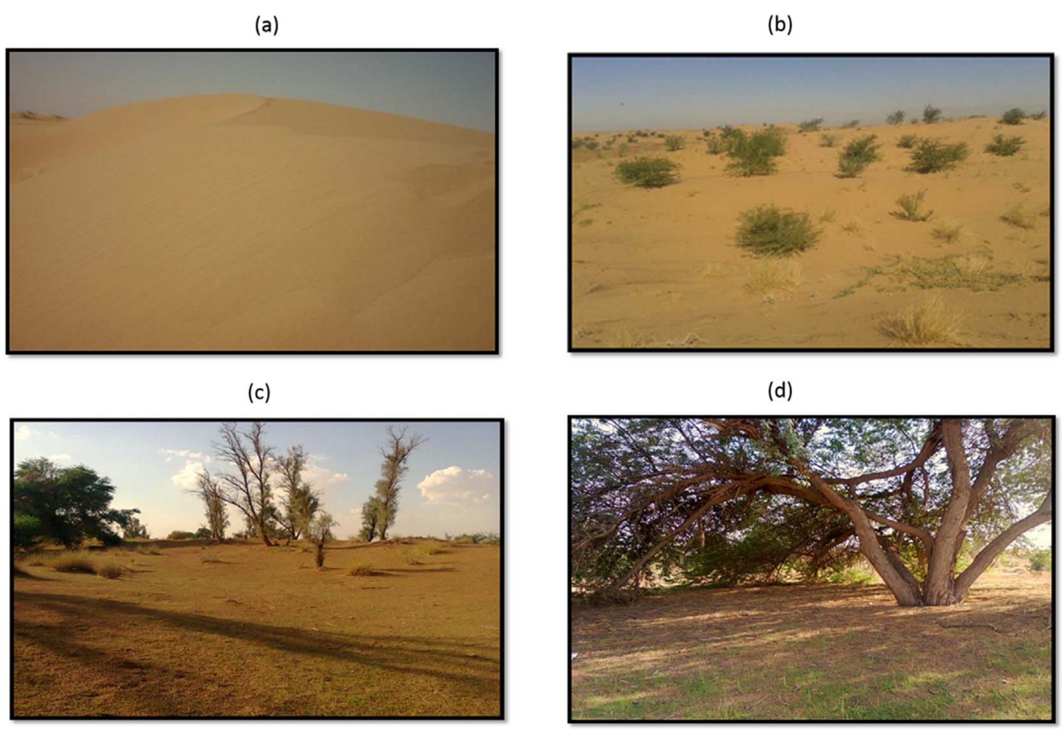

Fig. 3. A view of the general landscape and vegetation cover in study regions with a different history of PM-BC practices (a) T0 – no PM-BC practice, b) T5 – 5 years old practice, c) T20 – 20 years old practice and d) T40 – 40 years old practice).

reactions over three years. The cultivation of vegetables and cereal products boomed in this region in the lands around of the stabilized sand dunes.

2.2. Sampling and analysis

Based on 50-year-old petroleum mulching-biological fixation (PM-BF) practices in the southwest of Iran, three regions of T5, T20 and T40 that are 5, 20 and 40 years old for PM-BC practices, respectively, in the neighborhood of a control region of T0 (no PM-BC practices) at the depths of D1(0–10 cm) and D2(10–50 cm) in three replications—disturbed and undisturbed—were selected. To ensure the representativeness of the soil profiles, the plots examined were identified after preparatory surveys on the morphology, slope degree, and vegetation cover of the sand dunes and three samples were obtained from each region. Aggregate stability was conducted by the dry sieving strategy (Chepil, 1962). The hand penetrometer (Eijkelkamp model) was utilized to decide the penetration resistance (PR) of soil. The principle of the hand penetrometer depends on measuring the most noteworthy PR of a cone over an approximately 10 cm. The PR was measured by the method for a pressure spring. Various cones and pressure springs were accessible. In addition, a number of cones and

Table 1
Mean comparisons of sand dune properties in the study regions with a different history of PM-BC practices.

Parameter		T0	T5	T20	T40
pH	–	7.89a	8.02a	8.05a	8.13a
EC(dS m^{-1})	–	0.49b	0.71b	1.24b	2.42a
Clay%))		4.7c	6.38bc	7.42ba	9.25a
Sand(%)		93.82b	90.79ab	87.78b	86.8a
	Coarse sand	0.35b	1.20ab	0.355b	3.23a
	Moderate sand	8.64b	31.19a	30.92a	38.01a
	Fine sand	84.80a	58.45bc	56.94bc	45.60c
Silt(%)		1.7a	2.81a	4.89a	4.03a
	Coarse silt	0.76 a	1.72a	2.89a	2.97a
	Fine & Moderate silt	0.94a	1.093a	1.99a	1.06a
D50	–	0.135d	0.17 cd	0.22b	0.31a
MWD(mm)	–	0.189b	0.268b	0.403b	0.859a
PR(MPa)	–	270b	290b	420a	460a
CEC(C mol kg^{-1})	–	2.73c	3.89b	4.56b	5.73a
N(%)	Total	0.0165c	0.03b	0.037b	0.047a
P(ppm)	Olsen method	20.10a	21.5a	23.8a	60c
OM(%)	–	0.331c	0.61b	0.73b	0.95a
$CaCO_3$ (%)	–	40a	35.20b	34.20b	33.10b
Fe(ppm)	Total	3247.5b	3637.5a	3737.3a	3309.4a
Fe(ppm)	DTPA-extractable	3.46b	5.88a	4.68ab	5.99a
Mn(ppm)	Total	617.81b	1026.27ba	802.13a	685.19a
Mn(ppm)	DTPA-extractable	15.63b	24.21ab	27.91a	34.02a
Zn(ppm)	Total	717.77c	995.92a	851.84b	682.04c
Zn(ppm)	DTPA-extractable	1.13b	3.035a	3.009a	3.68a
Cu(ppm)	Total	82.13c	110.50a	93.85bc	82.98c
Cu(ppm)	DTPA-extractable	3.76c	4.74b	5.53ab	6.81a
Ni(ppm)	Total	192.32c	230.41a	223.62b	200.74c
Ni(ppm)	DTPA-extractable	0.129b	0.877a	1.44a	1.19a
Cd(ppm)	Total	3.15b	4.89a	4.45ab	3.91ab
Cd(ppm)	DTPA-extractable	0.06ab	0.078a	0.089a	0.099a
pb(ppm)	Total	129.44b	140.97a	130.45b	127.71b
pb(ppm)	DTPA-extractable	0.218b	0.486ab	0.523a	0.524a

[a]: Figures followed by similar letters in each row are not significantly different at $p < 0.05$ (LSD).
EC: electrical conductivity; OM: organic matter; MWD: mean weight diameter; CEC: cation exchangeable capacity.

compression springs were accessible. A certain combination of a cone and a compression spring was chosen in accordance with the expected penetration resistance. If the expected PR was high, a cone with a small surface and a compression spring with a large maximum force was chosen, and vice versa.

Each disturbed sample was obtained from various places and combined into a composite example to lessen the impacts of miniaturized scale varieties on the properties of sand dunes. Acidity reaction of the sand dune samples was investigated in a water-saturated paste using a glass electrode. The electrical conductivity of the saturated extract of the soil samples was measured by the electrical conductivity meter device. Organic carbon was measured by the Walkley–Black method (Nelson and Sommers, 1986). To measure the phyto-availability of heavy metals (lead, cadmium, and nickel) and micronutrients (iron, zinc, copper, and manganese) in sand dunes, DTPA (diethylene-triamine-penta-acetate) as per Lindsay and Norvell (1978)—in combination with atomic absorption spectrophotometry—was employed, and the solution pH was set at 7.3. Afterwards, the elements in the extract were measured by atomic absorption device (Lindsay and Norvell, 1978). Particle size distribution was determined by pipette method (Gee and Bauder, 1986). Available phosphorus was measured by Olsen method using a spectrophotometer (Olsen et al., 1954). Calcium carbonate was measured by HCl and back titration by NaOH (Nelson et al., 1982). To measure the concentrations of heavy metals, chemical digestion method was done by HNO3, HClO, and HF (1:1:2, v/v/v) and was analyzed by AAS.

Discrimination of the clay minerals in sand dunes was performed by Mehra and Jackson (1960) and Kittrick and Hope (1963) using X-ray diffraction (XRD) after removing the soluble carbonates, organic matter and iron oxides and free manganese. Pure clays were discriminated by XRD device (Siemens, D-500 model) with radiation Cukα with the energy of 40 kV and 30 mA from 2 to 30° (2θ). The oriented samples were analyzed for K saturated slides at 25 °C (K_{25}), potassium saturated with 550 °C (K_{550}), magnesium saturated (Mg_{25}) and magnesium saturated with ethylene glycol (EG). Furthermore, another thermal treatment of 300 °C was used to distinguish the dioctahedral from trioctahedral 2:1 minerals with a base area of 060. Also, semi quantitative estimation of clay minerals was performed through calculating the first order peak height of minerals in Mg treatments (Jones, 1965). The intensity of peaks obtained was used as an index to indicate the proportion of each clay.

2.3. Statistical analysis

The experiments were carried out using a factorial experiment with a completely randomized design which was replicated three times. Factors in this research include 3 mulching regions with different histories (5, 20, and 40 years) and a control region (no PM-BF practices). The data obtained were analyzed using the general linear models (PROC GLM) of SAS Institute (SAS, 1999). Mean comparisons were conducted using Fisher's LSD test

3. Results and discussion

The study area in the present research constitutes a part of the stabilized dunes with different petroleum mulching-biological fixation (PM-BF) practices that are 2 to 50 years old. In recent years, the climate changes and human factors (construction of large dams, intensive grazing in pastures, lack of crop rotation, monoculture, drying wetlands, and regional conflicts in the Middle East) have led to the dust phenomenon. As Fig. 3 shows, by increasing the period of PM-BF practices, the seedlings of *Prosopis cineraira* and *Tamarix hispida* grow more, and endemic herbaceous vegetation is restored. Accordingly, since 40 years ago (Fig. 3D), trees have grown and developed, and dense forests have been planted in this region. Petroleum mulching practices prevent the accumulation of sand on the seedlings planted and the percussion of fine sand particles with the leaves. The percussion of fine sand particles causes the perforation of leaves and the spread of pests and diseases in plants. Therefore, sand dune stabilization fulfills the requirements for plant growth. These hand-planted forests, which have a low fertility rate and small leaves due to environmental stresses such as low rainfall and sandy texture, have covered the soil surface well and have created a shade for another vegetation cover. Since dust storm particles are mainly silt- and clay-sized, these particles are trapped on the leaves of trees, are washed from the leaves and trunks of trees by rainfall, and are added to the sand dunes. This plant species (*Prosopis cineraira* and *Tamarix hispida)* with small leaves have lower efficiency for dust storm trapping compared to broad-leaved plants. The size and structure of trees affect the deposition of particle matter on the leaf surface. Increased leaf surface roughness due to three-dimensional structures such as grapes, scales, glands, furrows, and veins affect the accumulation of dust storm in the air (Jamil et al., 2009; Mitchell et al., 2010).

3.1. Chemical properties of sand dunes

Table 1 lists a number of chemical properties of sand dunes stabilized at different intervals, including no PM-BF practices (T0) and 5- (T5), 20- (T20), and 40-year-old (T40) PM-BF practices. As it is observed, the mean pH of T0 to T40 PM-BF practices follows an increasing trend. This suggests that petroleum mulch increases soil pH. Wang et al. (2013) showed that soil pH significantly increases in soil contaminated with crude oil. Hydrocarbon pollution can also cause changes in pH and

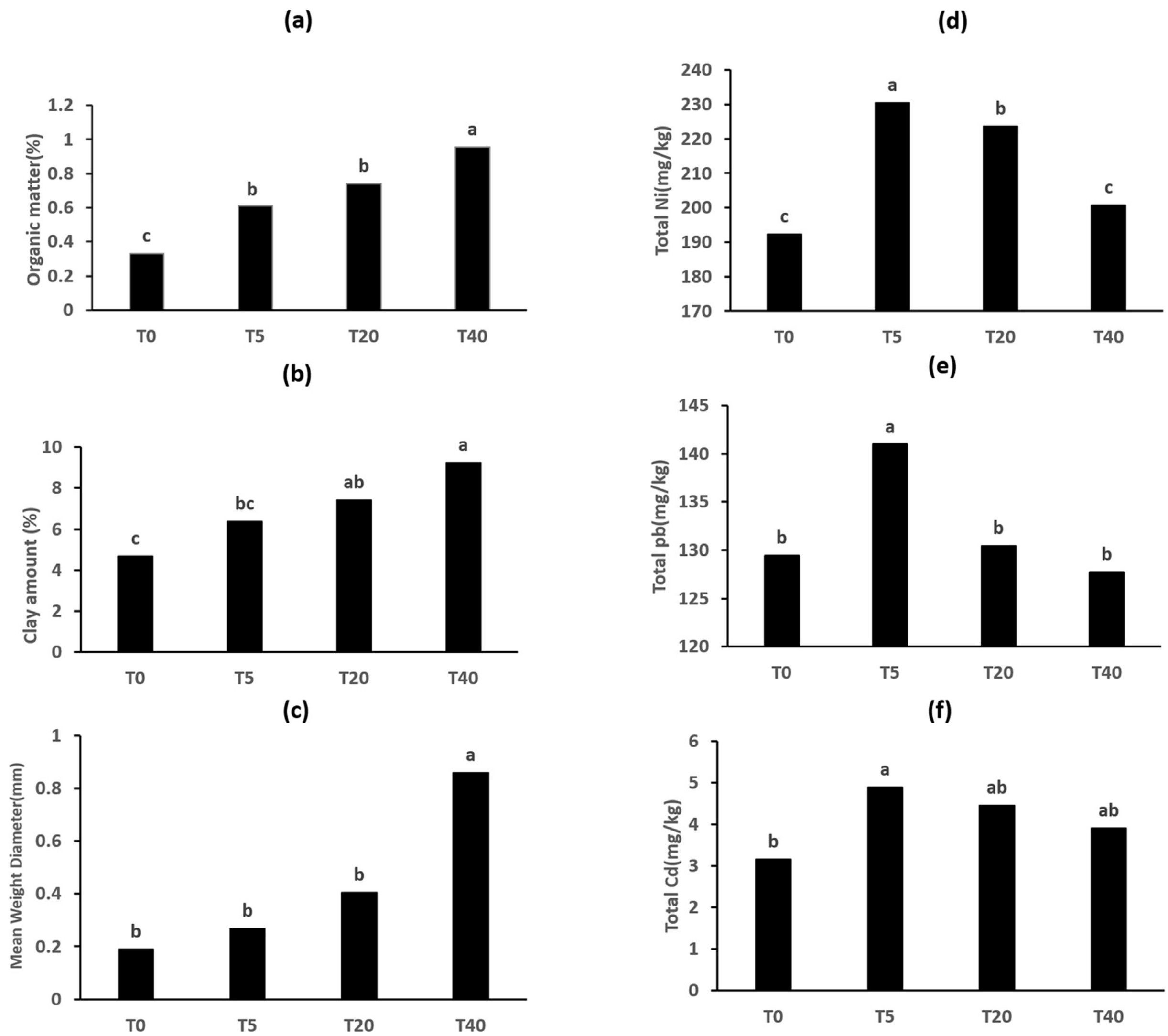

Fig. 4. The mean comparison between the different regions(T0, T5, T20 and t40) on the organic matter, clay percentage, ped mean weight diameter, total havy metal(NI, PB, Cd) using Duncan test at 1% level probability. The different letters (a, b and c) at the tops of the bars indicate significant differences.

other chemical properties of soil (Hu et al., 2006; Wang et al., 2009 & 2010). Nejoko et al. (2009) stated that salinity and the accumulation of exchangeable sites of sodium and calcium are the reasons for the increase in pH in petroleum-contaminated soil. Furthermore, salinity in sand dunes significantly increases from T0 to T40 to an extent that salinity values in T40, T20, and T5 are 4.93, 2.53, and 1.44 times greater than those of T0, respectively. Higher salinity due to PM-BF practices in the sand dunes in the southwest of Iran could be because of the following reasons:

A) Dust trapped on the leaves contains a lot of minerals, thus increasing soil salinity.
B) Although the soil texture is light, the leaching potential of the chemical minerals in the region is low due to low rainfall, and the minerals are not easily removed from the soil profile.
C) Development of tree roots over time leads to mineral absorption from the lower layers of sand dunes and shoot growth. Returning the litter of these plants to the soil surface increases soil salinity.

PM-BF practices have significantly increased organic matter. Average soil organic matter in T40, T20, and T5 is 2.88, 2.20, and 1.84 times more than that of T0, respectively. Soil organic matter increases owing to an increase in the canopy and the return of organic matter to the sand dunes (Akbarnia, 2009). Moreover, the decomposition of petroleum matters increases soil hydrocarbons and organic matter (Akbarinia et al., 2009). Akbarnia (2009) concluded that moisture (rainfall) and temperature are two influential factors in the decomposition of petroleum mulch in Khuzestan province. Since there is a direct relationship between TN and soil organic matter, TN and organic matter follow a similar trend. TN in T40, T20, and T5 is 2.8, 2.31, and 1.81 times more than that of T0, respectively. The mean P from T0 to T40 follows an increasing trend. The decomposition of petroleum compounds over time and the release of elements and ions in sand dunes account for the increase in phosphorus and potassium available in sand dunes. Over time and as a result of soil particle stabilization and the establishment of plant species after petroleum mulching, soil nutrients such as phosphorus increase (Zhenghu et al., 2004). The activities of the degrading bacteria of petroleum contaminants in the sand dunes increase the amount of phosphorus (Shahi et al., 2016) and potassium (Cheraghi et al., 2015). Su et al. (2002) investigated the effect of shrubberies on soil fertility. They concluded that the establishment of area species exacerbates soil fertility, especially the amount of nitrogen whose increase depends on the nitrogen fixation by the plant species and its release after the decomposition of leaves.

The average amount of lime ($CaCO_3$) in sand dunes shows an increasing trend from T0 to T40. It appears that the phenomenon of dust is the reason for the growth in lime after increasing the post-mulching period. According to the findings reported by Zarasvandi et al. (2011)

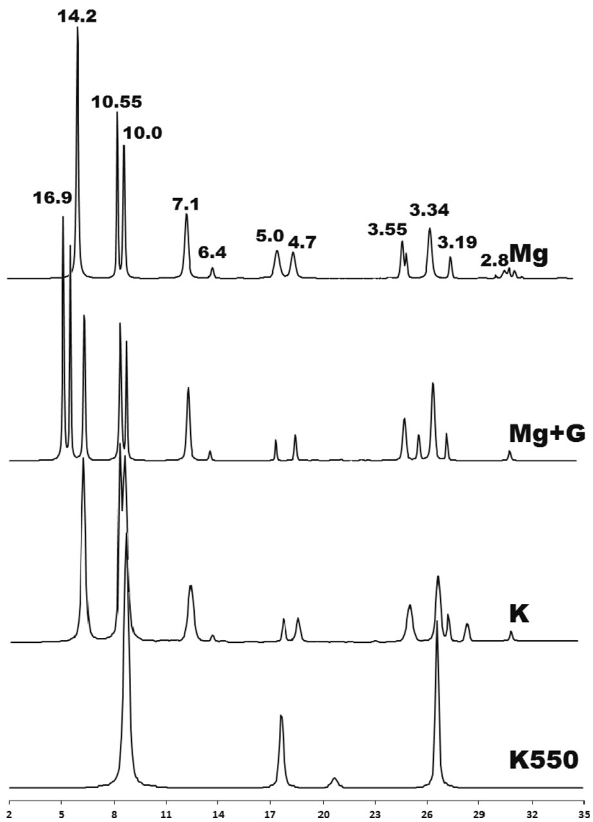

Fig. 5. X-ray diffraction patterns of the clay fraction of T0.

on the constituent minerals of the studied samples from the dust storms in Khuzestan province, carbonates, especially calcite, were identified as one of the main mineral phases. CEC of sand dunes has a direct and positive relationship with clay percentage and soil organic matter. Therefore, the older the mulching due to increased clay percentage (Table 1) and organic matter, the more the CEC.

3.2. Soil physical properties

Table 1 lists some of the physical properties of sand dunes in the study area. PM-BF practices significantly change PSD. The average clay percentage in T40, T20, and T5 is 1.96, 1.57, and 1.35 times more than that of T0. In contrast, the average percentage of sand and fine sand significantly decreases in T40, T20, and T5 compared to T0. Additionally, the average percentage of silt increases over time. D_{50} of sand dunes indicates that particle size distribution significantly changes. The phenomenon of dust storms in recent years in the study area has shown that the fine particles of soil, generally clay particles, have been trapped by plant foliage, have been washed by rainfall, and have been added to the sand dunes. Clays are the active component of sand dunes and, with organic matter derived from plant litter, have given rise to increasing CEC, chemical interactions, and microbial activity. Clay particles improve the physical and chemical conditions and, thereby, the fertility of sand dune surfaces and the restoration of endemic herbaceous vegetation cover. These results are consistent with the findings reported by Akbarinia et al. (2005).

MWD and PR in T40, T20, and T5 are 4.55, 2.13, 1.41 and 1.70, 1.55, 1.1 times more than those of T0, respectively. As the age of PM-BF practices increases, the petroleum mulch loses cohesion and decomposes, but organic matter and clay increase, thus increasing MWD and PR. The results of this research showed that petroleum mulch causes the cohesion of sand particles and increases particle cohesion resistance. Owing to its liquid and low viscosity properties, petroleum mulch can penetrate below the surface of sand dunes, can increase the depth of stabilization, and protect the thickness of sand particles against erosive winds. Moreover, due to its hydrophobic property, petroleum mulch infilters rainwater into inferior layers of sand dunes. Sand dune can transfer water easily because of its high hydraulic conductivity and prevent water vapor because its capillary property is not as significant as that of clay soils. Hence, petroleum mulch decreases water stress in arid ecosystems. However, in less than 5 years and due to its decomposition, petroleum mulch loses its cohesive properties. As Fig. 3 shows, increasing clay and organic matter, which are two cement agents, results in increasing aggregate stability. Since there is a direct relationship between aggregate stability and soil shear strength, an increase in aggregate stability leads to an increase in soil strength and a decrease in erodibility. These results correspond with the findings reported by Zhenghu et al. (2004). They investigated the gradual development of soil properties of stabilized sand dunes in Tengo Desert, China. They also studied the changes in the physical and chemical properties of soil after sand dune stabilization. They found that sand stabilization improves soil texture and the mechanical change of initial soil moisture and increases water retention capacity and water infiltration in sand dunes. They stated that sand stabilization leads to the development of microbial organisms from a simple to a more complex status. They also found that sand stabilization and the establishment of plant species significantly increase the organic matter and nutrients of sand dunes such as nitrogen and phosphorus.

3.3. Heavy metals and micronutrient elements of sand dunes

Table 1 presents the heavy metals and micronutrient elements of sand dunes stabilized by PM-BF practices at different times after mulching. By reason of the decomposition of petroleum mulch by microorganisms and chemical methods in the environment, the average available amount of Fe, Cu, Mn, Zn, Ni, Pb, and Cd in the regions of T40, T20, and T5 are significantly different from that of T0. The

Table 2
The relative abundance of minerals in the clay fraction of studied sand dunes.

Region	Depth	Mineralogical composition of clay fraction %						
		Chlorite	Illite	Kaolinite	Palygorskite	Smectite	Vermiculit	Quatrtz
T0	0–10 cm	+ +	+ +	+ +	+	ND	+	+ +
	10–50 cm	+ +	+ +	+ +	+	ND	+	+ +
T5	0–10 cm	+ +	+ +	+ +	+ +	+	+	+ +
	10–50 cm	+ +	+ +	+ +	+ +	+	+	+ +
T20	0–10 cm	+ +	−/+	+ +	+ +	−	+	+ +
	10–50 cm	+	+	+ +	+ +	−/+	+	+ +
T40	0–10 cm	+	+	+ +	−/+	+ +	+	+ +
	10–50 cm	+	+ +	+ +	+ +	+	−/+	+ +

Relative abundance of clay minerals is shown by: − (> 3%), −/+ (3–5%), + (5–10%), + +(10–25), and ND: not detected.

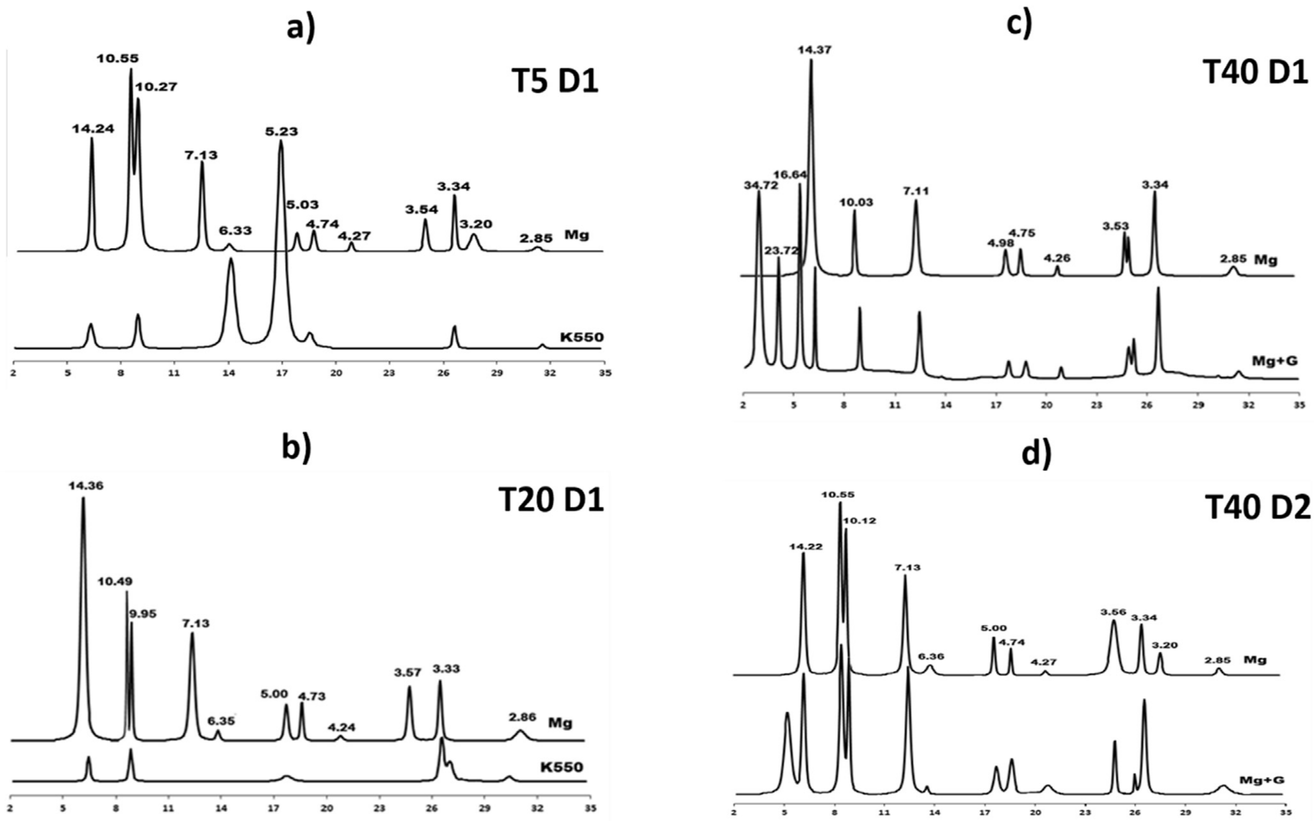

Fig. 6. X-ray diffraction patterns of the clay fraction of T5 D1, T20 D1, T40 D1 and T40 D2.

average amount of Fe, Cu, Mn, Zn, Ni, Pb, and Cd available in the region of T40 was 1.73, 1.81, 2.18, 3.25, 9.22, 2.40, and 1.65 times more than that of T0, respectively. By increasing salinity, the percentage of clay and soil organic matter gives rise to an increase in the solubility of these elements over time. Katyal and Sharma (1991) showed that by increasing the percentage of clay, the amount of Cu and Zn-DTPA increases. Adams and Sanders (1984) found that Ni has the ability to chelate in the presence of organic matter, and in such circumstances, its available amount can increase and become poisonous to plants. Saeedi et al. (2012) showed that by adding organic matter to the soil, the availability of heavy metals increases due to a large specific surface of organic matter and the presence of Lewis acids and bases such as carboxyl and phenol groups. Soil salinity can increase the solubility of metals and their uptake by plants (Amini et al., 2011).

The total average amount of heavy metals of Ni, Pb, and Cd in the regions of T40, T20, and T0 was 1.14, 1.03, 1.19; 1.10, 1.08, 1.09; 1.25, 1.09,1.55 times more than that of T5, respectively (Fig. 4). The total highest concentrations of these elements are observed in the region of T5. However, the concentration of these elements is reduced over time, which can be due to the leaching of heavy metals. Since the soil texture is light, the leaching of these elements has occurred and these elements have been transferred to the lower layer despite the low rainfall. Many researchers have suggested that dust storms contain the critical level of heavy metals (Zarasvandi, 2011). Despite the higher dust deposition in the region of T40, the amount of heavy elements in this region is lower than that of T5, indicating that petroleum mulch is the origin of heavy element. The average amount of total concentration of heavy metals of Ni, Pb, and Cd in the regions of T40, T20, T5, and T0 was 200.74, 223.62, 230.41, 192.32; 127.71,130.45, 140.97, 129.44; 3.91, 4.45, 4.89, 3.15 mg/kg, respectively. The critical level of concentration of heavy metals will vary depending on their use and pH. According to the Soil Pollution Standards and its guide (Iranian Environment Protection Agency, 2012), the standard levels of pollution of Pb, Cd, and Ni for the uses of environmental protection, agriculture, forest, and rangeland in Iran are equal to 300, 75, 290; 3.9, 5, 8; 50, 110, 530 mg/kg, respectively. Therefore, the average amount of total concentrations of heavy metals of Ni, Pb, and Cd in the regions of T5, T20, and T40 with regard to forest and rangeland is lower than their critical level of pollution. However, for the agricultural use, the concentrations of all three elements are more than their critical level of pollution, and for the environmental protection use, the concentrations of Ni and Cd are more than their critical level of pollution (Iranian Environment Protection Agency, 2012).

3.4. Assessment of changes in clay minerals

In the present study, the X-ray diffraction patterns of clay in sand dunes showed that there are the minerals of chlorite, illite, kaolinite, quartz, palygorskite, and vermiculite with a little amount of smectite in the region of T0 (Fig. 5, Table 2). According to the terms of sand dunes that are always moving, it can be stated that all of these minerals are inherited and soil-forming factors do not play a significant role in the alteration of these minerals. As a result of sand dune stabilization for 5 years in the region of T5, the amount of smectite and palygorskite slightly increased (Fig. 6a). The increase in this type of clay can be due to dust particles trapped by the vegetation cover. Fiber minerals such as palygorskite are dominant minerals in arid and semi-arid regions due to their fine size, and the fiber shape is easily separated from the surface of the soil of the source region by the wind shear force. In addition, sodium in the soil of the source region gives rise to the depression of soil particles. As a result of this process, smectite clay particles, that are very fine, are dispersed, and lower wind shear force suspends these particles. As a result, these particles are transported by the wind for miles, are trapped on their way by vegetation cover, and are added to the surface layer of sand dunes by rainwater. Palygorskite and smectite minerals were distinguished below the 10–50 cm surface in the region of T5, similar to the 0–10 cm surface, with the difference that the amount of smectite clay was a little higher and the vermiculite clay was added (Table 2). The clay alteration process can be due to the leaching of clay from the surface layer to the subsurface. In both regions of T20 and T5, a similar trend was dominated. Hence, in the region of T20, the palygorskite increased and the expanding clays of smectite and vermiculite were added (Table 2). In the region of T20, the results showed that smectite minerals in the surface layer were severely added, but the peak rate of the palygorskite mineral was reduced or virtually eliminated. Therefore, it can be concluded that the palygorskite clay in the sand dunes was developed and transformed into smectite owing to the leaching flow of the profile of sand dunes. Furthermore, the smectite clay was added to the sand dunes as a result of dust storms. The smectite clay was accumulated in these sand dunes, especially in their surface layers. In the K-saturated treatment and at a temperature of 550 °C, the intensity of the 14 Å peak significantly decreased, while the intensity of the 10 Å peak increased. Therefore, it can be concluded that as a result of leaching, illite was transformed into vermiculite. In other words, due to low levels of fine particles of illite in the structure of the coarse particles of sandy soil that have low weathering potential, the ability to transform these clay minerals improved and illite clay minerals were transformed into intermediate minerals and finally vermiculite or smectite (Fig. 6b). In the T40 region, creating the desirable conditions for leaching on the one hand and plant growth on the ground surface, especially seasonal pasture plants, on the other hand exacerbated the process of the formation of vermiculite or smectite minerals (Fig. 6c). However, in the subsurface layers in the T40 region, the vermiculite and smectite contents were reduced, which can exacerbate the hypothesis of trapping these minerals on the ground surface of sand dunes (Fig. 6d).

4. Conclusion

The phenomena of sand and dust storms have intra and extra-regional damaging effects. Petroleum mulching-biological fixation (PM-BF) practices in the ecosystem of sand dunes in the southwest of Iran date back to more than 50 years ago, but the interactions between these practices and the phenomenon of dust in the ecosystem have not been considered to date. Long-term PM-BF practices have given rise to improving the physical (PSD, MWD, and PR) and chemical properties (OM, CEC, and micronutrients) of sand dune ecosystems. However, according to the standard of Iranian Environmental Protection Agency, the amount of heavy metals of Pb, Cd, and Ni has not exceeded the critical level. Increasing the time interval of mulching has added to the relative intensity of palygorskite and smectite clay minerals on the surface of sand dunes. Furthermore, PM-BF practices have increased the transformation of illite clay minerals due to the high potential of leaching and potassium uptake by plants. Hence, forest restoration and vegetation cover have led to the deposition of particles suspended in the air, especially needle-shaped particles of the palygorskite clay. This type of clay can cause human respiratory allergies (Zarasvandi et al., 2011). In general, PM-BF practices give rise to the restoration of sand dune ecosystems and reducing different dust storm consequences for citizens. However, concerns about the release of Pb, Cd, and Ni into the environment are still remain. It is not recommended to apply petroleum mulching (PM) for productive ecosystems such as the sand dunes of southwestern Iran.

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