

Research Article

Effects of wind erosion and aeolian sediments caused by drought on the distribution and diversity of clay minerals in a part of Mesopotamia, Iran

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ABSTRACT- This study evaluated the effects of drought-induced wind erosion and aeolian sediments on clay mineral distribution and diversity in the Mesopotamia region of Iran. Soil and sediment samples were collected from 15 locations, representing different land-use types. Clay minerals were identified using X-ray diffraction (XRD). Standard laboratory procedures enabled the measurement of soil physicochemical properties: pH, electrical conductivity (EC), sodium adsorption ratio (SAR), and organic matter (OM). The results indicated that soils in the study area are strongly saline-sodic with pH values ranging from 7.8 to 9.2, their EC between 12 and 45 dS m⁻¹, and SAR values between 15 and 45 (meq L⁻¹)^{0.5}. These conditions, combined with very low organic matter content (< 1%), significantly increased soil susceptibility to wind erosion. Clay mineralogical analysis revealed that kaolinite (20–30%) is the most abundant mineral, followed by illite (15–25%), and smectite (20–30%). Sepiolite or similar fibrous clay minerals occur in smaller proportions (2–10%). The expansion and contraction behavior of smectite contributes to soil cracking and structural instability, facilitating wind erosion processes. In addition, highly saline groundwater (> 32 dS m⁻¹) restricts vegetative growth, further exposing soil surfaces to erosion. The results demonstrated that wind erosion plays an important role in redistributing clay minerals through aeolian transport, thereby influencing mineralogical diversity across the region. These findings provide important insights into soil degradation mechanisms in arid environments and emphasize the need for sustainable land management strategies to reduce wind erosion.

INTRODUCTION

Changes in the hydrological regime of arid and semi-arid regions can trigger a cascade of environmental degradation, including soil salinization and sodification, vegetation loss, wind erosion, sediment deposition, and wetland desiccation. Khuzestan Province is particularly vulnerable because of its extreme temperatures, high evaporation rates, and 1.27 million hectares of desert landscapes. Historically, seasonal flooding across the Mesopotamian Plain sustained vegetation and soil hydrological processes (UNEP/UN, 2001). Winter and spring floods supported irrigation, groundwater recharge, and vegetation growth, thereby helping to control soil salinity and limit wind erosion. Over recent decades, however, dam construction and declining precipitation have substantially reduced river inflows and disrupted natural flood cycles (Jafari, 2014). The impoundment of Gotvand Dam in 2011 further intensified salinity problems. At the Gotvand monitoring station, Karun River salinity increased from 0.85 dS m⁻¹ in 2002 to 1.26 dS m⁻¹ in 2012 (Rangzan and Jafari, 2017). Soil salinity subsequently exceeded 32 dS m⁻¹ in some areas, restricting vegetation establishment and contributing to the loss of

halophytic species such as *Artemisia*, *Salsola*, and *Tamarix* (Jafari, 2020). The resulting reduction in vegetation cover has increased soil exposure and intensified wind erosion. Clay mineralogy is closely linked to these degradation processes because clay minerals influence potassium retention, shrink–swell behavior, aggregate stability, pollutant adsorption, and soil moisture dynamics. Wind erosion can preferentially transport fine soil particles, including silt-sized material, thereby altering the mineralogical composition of both eroded soils and aeolian sediments (Colazo and Buschiazzi, 2015; Zarasvandi et al., 2011). The mineral composition of deposited dust can therefore provide a useful fingerprint for identifying sediment sources (Hassanizadeh and Jafari, 2021). Previous studies of Khuzestan have reported carbonate minerals as the dominant component (> 50%) of aeolian deposits, followed by quartz, kaolinite, and gypsum (Zarasvandi et al., 2011), whereas soils in southwestern Iran are dominated by quartz and calcite (Broomandi et al., 2017). However, the effects of intensified wind erosion on the distribution and diversity of clay minerals in the region remain insufficiently understood.

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Ahvaz's dune systems contain distinctive assemblages of carbonate minerals, palygorskite, and smectite (Hassanizadeh and Jafari, 2021). Despite extensive research on mineral amendments in arid environments, the diversity and distribution of clay minerals in dust source areas remain poorly understood (Azough et al., 2016). Aeolian transport is controlled by interactions among particle size, soil cementation, emission rates, transport processes, and vegetation cover (Jiao et al., 2018). Among clay minerals, smectite, sepiolite, and palygorskite may be particularly susceptible to aeolian transport (Hassanizadeh and Jafari, 2021). Sodium-induced dispersion of smectite can further increase soil erodibility, whereas the relatively coarse particles of illite and chlorite may complicate source identification. The region's soils contain approximately 40–50% soluble salts and carbonates, with carbonates greatly exceeding gypsum and other salts, together with silicate clay minerals. However, conventional X-ray diffraction (XRD) analysis generally focuses on the clay fraction and may not fully characterize clay minerals associated with the silt and sand fractions. Consequently, the contribution of aeolian processes to the redistribution of clay minerals remains poorly constrained. This study therefore investigates the effects of wind erosion on clay mineral diversity and distribution across the plains of southwestern Iran. Understanding these changes is particularly important under increasing drought and climate variability, which can alter surface mineral composition and accelerate land degradation. The findings may contribute to improved land management and erosion-control strategies in these vulnerable ecosystems.

MATERIALS AND METHODS

Study area and methodology

The study was conducted across approximately 1.3 million hectares of the southern plains of Khuzestan Province, within the Mesopotamian region of Iran. The area has an arid to ustic soil-moisture regime and a hyperthermic soil-temperature regime (Banaei, 1999), with mean annual precipitation of 180–210 mm. It extends from southeastern Khuzestan to the Iran–Iraq border, while the northern part comprises an east–west alluvial plain (Fig. 1). Given its large extent, the study area was divided into four sections: West Karun (Region 1), East Karun (Region 2), East Hendijan (Region 3), and West Hendijan (Region 4) (Fig. 1).

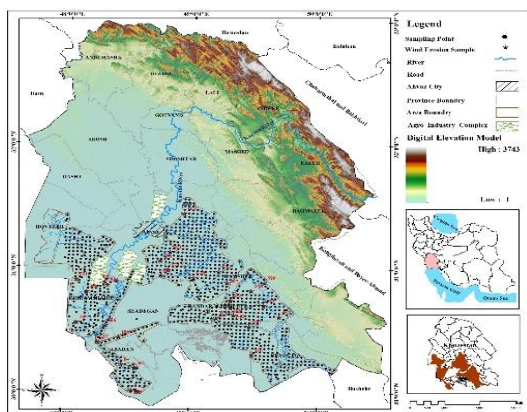


Fig. 1. Sampling points and location of the study area in Khuzestan Province and Iran.

Geologically, the study area lies within one of the three major zones of the Zagros Mountains. Its surface is covered by thick alluvial deposits that obscure the underlying geological formations. These Quaternary sediments were deposited primarily by floods of the Karun, Dez, and Karkheh rivers (Jafari and Nadian, 2014). The four study sections are nearly flat, with slopes of 0–1%. The soils are young and developed mainly from alluvial deposits of the Karun, Zohreh, and Jarahi rivers. Gypsum is more abundant in the parent materials of the eastern plain and occurs across a range of particle sizes. Carbonate contents range from 35% to 50% throughout the soil profile (Jafari et al., 2021). Recurrent flooding also buries older soils beneath younger sediments. The soil-moisture regime is Aridic in the south and Ustic in the north, while the soil-temperature regime is hyperthermic throughout the study area (Banaei, 1989). Low elevations and shallow groundwater, typically 1–2 m below the surface for most of the year, promote salinization and sodification through intense evaporation. These conditions are further aggravated by high evaporation and limited precipitation. Some areas are used as pasture, whereas others are cultivated. Native vegetation includes halophytic species such as *Tamarix* spp., *Seidlitzia* spp., *Avena* spp., *Alhagi* spp., and *Prosopis* spp. Drought and alterations in the hydrological regime have reduced vegetation cover and density (Jafari, 2020). The resulting loss of surface protection has increased soil exposure to the wind erosion. Wind erosion is severe across the region and strongly influences sediment transport and deposition, particularly in the southern plain, where saline-sodic soils, shallow groundwater, and sparse vegetation create favorable conditions for aeolian activity.

Soil sampling and analysis

Soil samples were collected from the 0–10 cm surface layer in areas susceptible to wind erosion (Fig. 1). Soil salinity was determined from the electrical conductivity (EC) of the saturated extract using an EC meter (United States Salinity Laboratory Staff, 1954). Soil pH was measured in saturated paste using a glass-electrode pH meter (PTR 79). Soil texture was determined by the hydrometer method (Gee and Bauder, 1986). Gypsum content was measured by acetone precipitation (United States Salinity Laboratory Staff, 1954). Organic carbon was determined by wet oxidation (Walkley and Black, 1934). Calcium carbonate equivalent (CCE) was determined by acid neutralization followed by base titration (Nelson, 1982). Groundwater salinity was measured by EC, and groundwater depth was recorded in boreholes using an electronic depth gauge.

Sodium concentration in the saturated extract was determined via flame photometry (CL361 model). Calcium and magnesium were quantified through EDTA titration (Jackson, 1975). The sodium adsorption ratio (SAR) was calculated accordingly: $SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$ (meq L⁻¹)^{0.5}. As for clay mineral identification, samples were air-dried, ground, and sieved through a 2-mm mesh. Clay fraction purification followed the methods of Mehara and Jackson

(1960) and Kittrick and Hope (1963). Separated clay samples were saturated with magnesium, magnesium-ethylene glycol, and potassium at 550 °C. A few drops of the treated clay suspensions were placed on glass slides and dried in a desiccator. XRD analyses were performed using a Siemens D-500 diffractometer with CuK α radiation at 40 kV and 30 mA. Clay minerals were identified based on peak analysis in different treatments (Grim, 1963). Semi-quantitative estimations of clay minerals were conducted by measuring the height and width of the first-order peaks (Johns et al., 1954). The diversity and distribution of clay minerals in each section were determined and compared. Then, clay mineral distribution maps were generated based on estimated values in GIS software. Maps of each mineral were illustrated accordingly.

RESULTS

Soil characteristics of the studied areas

Selected soil and non-soil characteristics of the studied regions are presented in Table 1.

West Karun (region 1)

West Karun exhibits moderate salinity (ECe: 16–32 dS m⁻¹) compared to the other sections, although its SAR (30–70 (meq L⁻¹)^{0.5}) remains high, indicating significant sodicity. The soil texture is predominantly silty clay to silty clay loam (SiC-SiCL), contributing to slightly lower wind erodibility (29–395 g m⁻² h⁻¹) than other regions. The water table is shallower (100–150 cm), which, combined with periodic flooding (F1) and water ponding (P2), influences soil salinity dynamics. Organic matter (OM) is very low (< 0.5%), typical of arid regions, while calcium carbonate (CCE > 40%) and gypsum (20–40 meq 100g⁻¹) are abundant. Vegetation cover remains stable (< 25% in arid season, 25–50% annually), likely due to the slightly better moisture retention from flooding (Table 1).

East Karun (region 2)

East Karun has the highest salinity (ECe: 32–100 dS m⁻¹) and gypsum content (40–60 meq 100g⁻¹) among the four

sections, reflecting its geological setting with gypsum-rich deposits. The texture (SiC-SiCL) is similar to West Karun, but wind erodibility is higher (78–993 g m⁻² h⁻¹), possibly due to the reduced flooding (F0) and deeper groundwater (> 150 cm) (Table 1). Water ponding (P1) occurs but is less frequent than in West Karun. Like other sections, organic matter is minimal (< 0.5%), and CCE exceeds 40%. Despite high salinity, vegetation cover remains comparable (< 25% in the dry season, 25–50% annually), suggesting some halophyte adaptation (Table 1).

East Hendijan (region 3)

East Hendijan shares high salinity (ECe: 32–100 dS m⁻¹) and sodicity (SAR: 30–70 (meq L⁻¹)^{0.5}) with East Karun but has a slightly coarser texture (SiC-C), influencing its moderate erodibility (80–450 g m⁻² h⁻¹). The water table is deep (> 150 cm), and unlike East Karun, it experiences no flooding (F0), though water ponding (P2) still occurs (Table 1). Gypsum content (20–40 meq 100g⁻¹) is lower than in East Karun, while CCE remains > 40%. Vegetation cover is similar to other regions (< 25% in the dry season, 25–50% annually), but the lack of flooding may contribute to the slightly lower variations in sediment yield compared to the West Karun (Table 1).

West Hendijan (region 4)

West Hendijan has the highest wind erodibility (112–914 g m⁻² h⁻¹) among the four sections, likely due to its silty clay loam texture (SiC-SiCL) combined with deep groundwater (> 150 cm) and high salinity (ECe: 32–100 dS m⁻¹) (Table 1). Unlike East Hendijan, it experiences occasional flooding (F1) and frequent water ponding (P2), which may temporarily reduce erosion but contribute to long-term salinization. Gypsum content (20–40 meq 100g⁻¹) and CCE (> 40%) are consistent with other regions, and organic matter remains negligible (< 0.5%). Despite arid conditions, vegetation cover persists (< 25% in the dry season, 25–50% annually), though wind erosion remains a dominant factor in sediment transport (Table 1).

Table 1. Selected soil and non-soil characteristics of the four studied sections

Zone	ECe (dS m ⁻¹)*	SAR (meq L ⁻¹) ^{0.5}	OM (%)	CCE (%)	Gypsum (meq 100g ⁻¹)	Texture	WT (cm)	ECwt (dS m ⁻¹)	Erodibility (g m ⁻² h ⁻¹)	Vegetation cover (Arid season)	Vegetation cover (whole year)	Water ponding	flooding
West Karun	16–32	30–70	< 0.5	40 >	20–40	SiC-SiCL	100–150	32–100	29–395	< 25	25–50	P2	F1
East Karun	32–100	30–70	< 0.5	40 >	40–60	SiC-SiCL	150 <	32–100	78–993	< 25	25–50	P1	F0
East Hendijan	32–100	30–70	< 0.5	40 >	20–40	SiC-C	150 <	32–100	80–450	< 25	25–50	P2	F0
West Hendijan	32–100	30–70	< 0.5	40 >	20–40	SiC-SiCL	150 <	32–100	112–914	< 25	25–50	P2	F1

*ECe: Electrical Conductivity of soil extract, SAR: Sodium Adsorption Ratio, OM: Organic Matter, CCE: Calcium Carbonate Equivalent, Text.: Texture (SiC: Silty Clay, SiCL: Silty Clay Loam, and C: Clay), WT: Water Table depth, ECwt: Electrical Conductivity of groundwater, Erodibility: Sediment yield at a wind velocity of 20 m s⁻¹, P1/P2: Water ponding severity (P1: Moderate and P2: Severe), and F0/F1: Flooding frequency (F0: None and F1: Occasional).

All regions exhibit highly saline soils ($16\text{--}100\text{ dS m}^{-1}$), while some are more extreme ($32\text{--}100\text{ dS m}^{-1}$). This could be due to the arid climate, poor drainage, and capillary rise of saline groundwater (Jafari, 2020). While all four sections share high sodicity, low organic matter, and calcareous soils, West Karun (1) has the lowest salinity and benefits from periodic flooding, thereby reducing erosion. The SAR indicates strong sodicity, leading to dispersion, poor structure, and reduced permeability (Qadir et al., 2007). East Karun (2) has the highest gypsum and salinity but lacks flooding, thereby leading to greater wind erosion. East Hendijan (3) has a coarser texture and no flooding, resulting in moderate erodibility. West Hendijan (4) exhibits the highest wind erodibility due to its texture and hydrological conditions, despite some flooding influence. These variations highlight how slight differences in soil properties, groundwater, and hydrology shape erosion and salinity dynamics across the region. Texture (SiC-SiCL, SiC-C) causes low permeability, exacerbating waterlogging and salinity. Shallow water table ($100\text{--}150\text{ cm}$) contributes to secondary salinization via capillary rise (Jafari, 2020). High erodibility ($29\text{--}993\text{ g m}^{-2}\text{ h}^{-1}$) was happen due to low OM and high CCE are typical of calcareous desert soils (Table 1). The extremely high sediment yield under wind erosion (20 m s^{-1}) suggests low aggregate stability, which is likely due to sodicity, low OM, and lack of vegetation (Jafari et al., 2019). Sparse vegetation ($< 25\%$) in arid conditions increases erosion risk. Water ponding (P1-P2), flooding

(F0-F1), and poor drainage leads to waterlogging, further degrading soil structure. All regions are uncultivated, possibly due to extreme salinity and sodicity, making them unsuitable for conventional agriculture (Jafari and Bazrekar, 2022).

Clay minerals of the regions

Given the large number of samples, only one representative XRD diffractogram, from sample 1226 in the eastern Karun River area, is presented (Fig. 2). The diffractogram shows reflections attributable to quartz (0.33 nm), kaolinite (0.71 nm), illite (1.00 nm), vermiculite, chlorite, palygorskite (1.05 nm), and sepiolite (1.25 nm). The kaolinite reflection disappears after heating, while the 1.00 nm vermiculite reflection is restored following potassium saturation and heating. A 1.40 nm reflection after magnesium saturation indicates the presence of 2:1 clay minerals. Ethylene glycol treatment (Mge) produces a 1.60 nm reflection, confirming smectite. Smectite was detected in most of the studied areas. A 1.05 nm reflection that remained unchanged after the applied treatments was attributed to palygorskite, whereas sepiolite was identified by its characteristic 1.21 nm reflection. Sepiolite occurred in fewer samples than palygorskite. Chlorite was detected in all samples and was unaffected by potassium saturation and heating, although its peak intensity decreased in some samples.

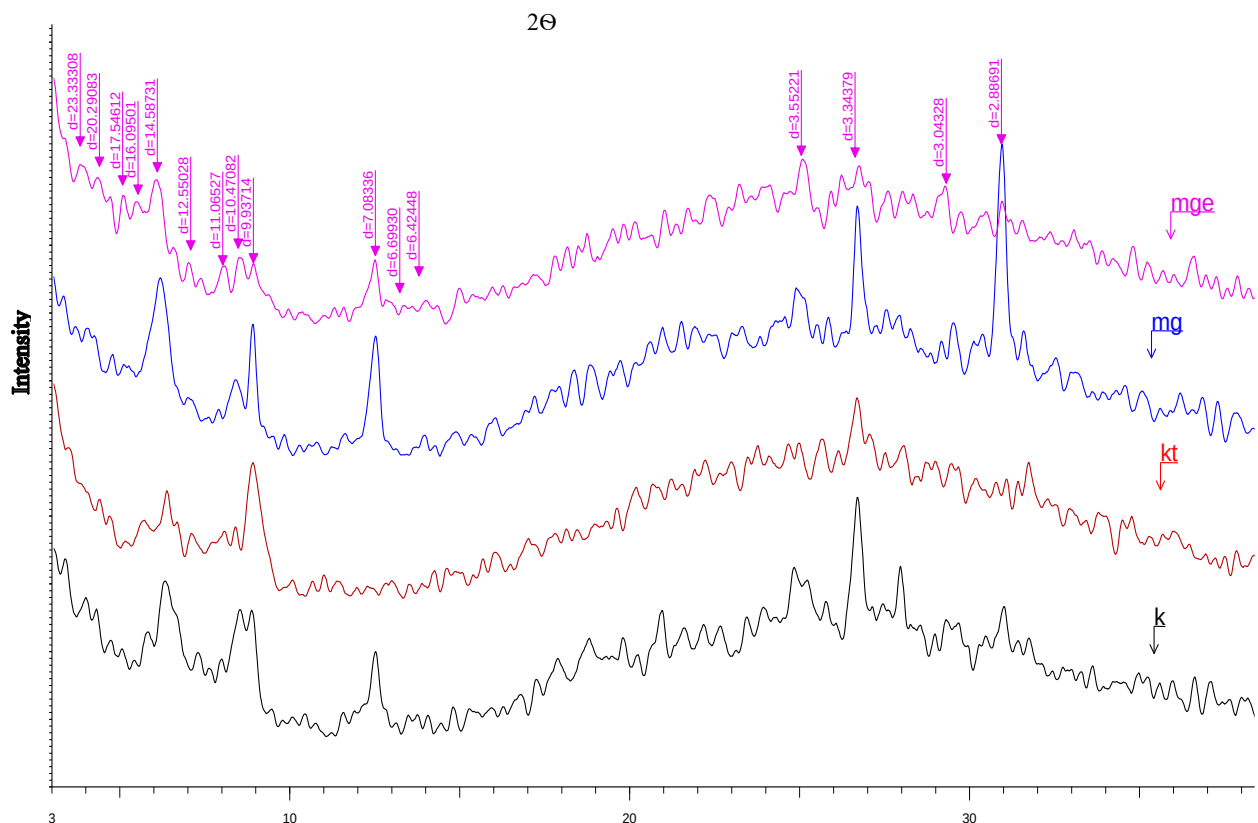


Fig. 2. X-ray diffraction (XRD) pattern for clay minerals in the eastern Karun region (Sample 1226).

The west Karun region (region 1)

Table 2 presents the semi-quantitative estimates of clay mineral abundance based on XRD peak patterns for samples from the west Karun region. The clay assemblage comprises kaolinite, illite, palygorskite, smectite, chlorite, vermiculite, and sepiolite. Kaolinite accounts for 20–30% of the clay fraction in all samples. Illite generally ranges from 10–20%, but exceeds 30% in sample 915. Palygorskite occurs at 10–

20% in most samples and reaches 20–30% in sample 18. Smectite ranges from 10–20%. Chlorite occurs at 5–10%, while vermiculite is generally less abundant, ranging from trace amounts to moderate levels. Sepiolite occurs at 5–10% in some samples, and mixed-layer illite–vermiculite occurs sporadically. Samples 20, 172, and 286 contain relatively higher proportions of smectite and vermiculite, whereas samples 510 and 515 contain less smectite and more sepiolite.

Table 2. Clay minerals assemblage and their semi-quantitative estimation in the west Karun region

Sample	Kaolinite	Illite	Illite like	Palygorskite	Sepiolite	Chlorite	Vermiculite	Smectite	Illite + Vermiculite
3	+++ ¹	++	+	++	+	++	+	+	+
18	+++	++	+	+++	+	+	+	+	ND ¹
20	+++	+++	+	++	+	+	+	++	ND
23	+++	+++	ND	++	ND	+	++	++	ND
47	+++	++	ND	++	+	+	++	++	+
50	+++	+++	+	++	ND	+	++	+	ND
52	+++	++	ND	++	+	++	++	++	ND
125	+++	++	+	++	ND	+	++	++	ND
172	+++	+++	ND	++	ND	++	++	++	-/+
232	+++	++	ND	++	ND	++	++	++	+
286	+++	++	-/+	++	ND	++	++	++	ND
350	+++	++	-/+	++	ND	-/+	++	+	+
436	+++	++	ND	++	+	++	++	+	+
507	+++	++	+	++	+	++	++	++	-/+
510	+++	++	+	+	++	+	+	++	+
513	+++	++	+	+	ND	+	++	++	+
515	+++	++	ND	++	+	+	+	+	+
580	+++	++	ND	++	ND	++	++	++	+
583	+++	++	+	+	+	+	++	++	+
648	+++	++	+	+	-/+	++	++	++	-/+
651	+++	++	ND	++	+	+	+	++	+
711	+++	+++	ND	++	ND	++	+	+	+
843	+++	++	ND	+	ND	++	++	+	+
846	+++	++	ND	++	ND	++	++	++	ND
849	+++	++	-/+	++	+	+	++	++	+
852	+++	++	+	++	+	++	++	+	+
915	+++	++++	+	++	-/+	+	+	++	ND
918	+++	++	ND	++	ND	+	++	++	+
940	+++	++	+	++	+	+	++	++	ND
943	+++	++	ND	++	+	+	++	+	-/+
1057	+++	++	ND	+	-/+	+	++	++	+
1095	+++	++	+	++	ND	++	++	+	ND
1098	+++	++	ND	++	ND	++	++	++	+
1295	+++	++	ND	++	ND	++	++	++	ND

Relative proportions of minerals are shown by – (< 3%), – /+ (3–5%), + (5–10%), ++ (10–20%), +++ (20–30%), and ND (not detectable).

The east Karun region (Region 2)

Table 3 presents the clay mineral assemblage of the east Karun region. Kaolinite accounts for 20–30% of the clay fraction in all samples. Illite generally ranges from 10–20%, exceeding 30% in sample 915. The illite-like mineral occurs at trace amounts (5–10%), with several samples showing no detectable amounts (ND). Palygorskite occurs at 10–20% in most samples, with sample 18 reaching 20–30%. Overall, palygorskite ranges from 5% to 20%. Its lowest abundance occurs in

sample 1249 from cultivated land, whereas the highest values occur in samples 600, 659, and 864 from areas supporting halophytic shrubs. Sepiolite occurs at 5–10% or is not detected in most samples and was present in 28% of all samples. Chlorite ranges from 5–10% to 10–20%, while vermiculite generally occurs at 10–20%. Smectite is consistently present at 10–20%, reaching 20–30% in a few samples. Mixed-layer illite-vermiculite occurs sporadically at trace to 5–10%, with many samples showing no detectable amounts.

Table 3. Clay minerals assemblage and their semi-quantitative estimation in the east Karun region

Sample	Kaolinite	Illite	Illite like	Palygorskite	Sepiolite	Chlorite	Vermiculite	Smectite	Illite + Vermiculite
516	+++	++	+	+	+	++	+	++	+
522	+++	++	+	++	+	+	+	++	+
584	+++	++	ND	++	+	+	+	++	+
586	+++	++	+	++	+	++	++	++	-/+
587	+++	++	-/+	++	+	+	++	++	+
595	+++	++	+	++	+	+	++	+	+
611	+++	++	ND	+++	-/+	++	++	+	+
615	+++	++	-/+	++	-/+	++	++	+	+
653	+++	++	+	++	ND	++	+	+	ND
656	+++	++	ND	++	+	++	++	+	-/+
659	+++	++	ND	+++	ND	+	++	+	+
662	+++	++	ND	++	ND	++	++	+	-/+
665	+++	++	ND	++	+	+	++	+	+
668	+++	++	ND	+++	ND	+	++	+	+
671	+++	++	ND	+++	ND	-/+	++	+	+
673	+++	+	ND	++	-/+	+	++	++	+
734	+++	++	ND	++	ND	++	+	+	+
764	+++	++	ND	++	ND	+	++	+	+
767	+++	++	ND	++	+	++	++	++	-/+
790	+++	++	ND	++	ND	+	++	+	+
853	+++	++	-/+	++	ND	+	++	+	+
855	+++	+++	ND	++	ND	++	+	+	+
861	+++	+++	ND	++	ND	++	++	+	ND
864	+++	++	+	+++	+	+	+	+	-/+
867	+++	++	+	++	ND	+	++	+	ND
870	+++	+++	ND	++	ND	+	++	++	+
894	+++	++	ND	++	ND	+	++	++	-/+
946	+++	+++	ND	+++	ND	++	+	+	-/+
948	+++	+++	ND	++	ND	++	++	+	ND
950	+++	+++	ND	++	ND	++	+	+	ND
952	+++	++	ND	++	ND	++	++	+	+
955	+++	+++	ND	++	ND	++	++	-/+	ND

Table 3. Continued

Sample	Kaolinite	Illite	Illite like	Palygorskite	Sepiolite	Chlorite	Vermiculite	Smectite	Illite + Vermiculite
958	+++	+++	+	++	ND	+	++	++	ND
960	+++	+++	ND	+++	-/+	+	++	-/+	-/+
1007	+++	+++	-/+	++	ND	+	++	+	-/+
1008	+++	++	-/+	++	ND	++	++	++	-/+
1010	+++	++	ND	++	+	-/+	+	++	+
1013	+++	++	ND	+++	ND	++	++	+	+
1016	+++	+++	ND	++	ND	++	++	+	+
1018	+++	++	+	++	+	++	++	+	-/+
1058	+++	++	-/+	++	++	++	++	++	ND
1061	+++	++	ND	+++	ND	+	++	+	+
1064	+++	++	+	++	+	++	+	++	+
1066	+++	++	+	+++	ND	+	++	++	ND
1079	+++	++	+	+	ND	++	+	++	+
1081	+++	++	ND	++	+	++	++	+	ND
1083	+++	++	ND	+++	ND	++	++	++	ND
1205	+++	++	ND	++	ND	+	++	++	+
1206	+++	++	-/+	++	-/+	++	++	++	+
1217	+++	++	+	++	+	+	++	++	+
1218	+++	++	+	++	ND	+	++	++	+
1219	+++	++	ND	++	ND	++	++	++	+
1220	+++	++	ND	+	+	+	++	++	+
1221	+++	+++	ND	+	+	+	+	++	+
1225	+++	+++	+	+	ND	++	+	++	+
1227	+++	++	+	++	ND	++	+	++	-/+
1229	+++	++	ND	+	ND	++	++	++	+
1249	+++	+++	-/+	-/+	-	++	+	++	-/+
1345	+++	++	ND	++	ND	+	+	++	+
1355	+++	++	ND	+	ND	+	++	++	+
1356	+++	++	-/+	+	ND	+	++	+++	ND
1359	+++	++	ND	++	ND	++	++	++	+
1360	+++	++	ND	++	ND	++	++	++	-/+
1374	+++	++	-/+	++	ND	+	++	++	-/+

Relative proportions of minerals are shown by – (< 3%), –/+ (3–5%), + (5–10%), ++ (10–20%), +++ (20–30%), and ND (not detectable).

The east Hendijan region (Region 3)

Table 4 presents the clay mineral assemblage of the east Hendijan region. Kaolinite is abundant in all samples, while illite occurs at moderate to high levels, with the highest abundances in samples 82 and 87. Palygorskite is present at moderate levels in most samples but is absent from sample 99. Sepiolite occurs only in trace amounts in samples 56 and 103 and is absent from the remaining samples. Smectite and vermiculite occur at minor to moderate levels, with relatively higher smectite abundances in samples 84, 87, and 99. Chlorite occurs at moderate levels and reaches its

highest abundance in sample 99. Mixed-layer illite-vermiculite occurs at trace to moderate levels in samples 56, 87, 99, and 103.

The west Hendijan region (Region 4)

Table 5 presents the clay mineral assemblage of the west Hendijan region. Kaolinite is abundant in all samples, while illite occurs at moderate to high levels. Palygorskite is also present at moderate to high levels in most samples. Vermiculite and smectite generally occur at moderate levels, although smectite is occasionally recorded at lower levels (+

to ++). Chlorite ranges from trace to moderate amounts. Mica-like minerals and sepiolite occur at trace levels or are not detected (ND) in many samples, with sepiolite restricted

to a few samples. Mixed-layer illite-vermiculite occurs mainly at trace levels, with moderate amounts recorded in a few samples (Table 5).

Table 4. Clay minerals assemblage and their semi-quantitative estimation in the east Hendijan region

Sample	Kaolinite	Illite	Illite like	Palygorskite	Sepiolite	Chlorite	Vermiculite	Smectite	Illite + Vermiculite
53	+++	++	+	++	ND	++	++	+	ND
56	+++	++	-/+	++	+	+	++	+	+
82	+++	+++	+	++	ND	+	+	+	ND
84	+++	++	+	++	ND	++	++	++	ND
87	+++	+++	ND	++	ND	++	++	++	+
99	+++	+++	ND	ND	ND	+++	+	++	++
103	+++	++	+	++	-/+	++	++	+	+
121	+++	++	ND	++	ND	++	++	+	ND

Relative proportions of minerals are shown by – (< 3%), –/+ (3–5%), + (5–10%), ++ (10–20%), +++ (20–30%), and ND (not detectable).

Table 5. Clay minerals assemblage and their semi-quantitative estimation in the west Hendijan region

Sample	Kaolinite	Illite	Mica like	Palygorskite	Sepiolite	Chlorite	Vermiculite	Smectite	Illite + Vermiculite
133	+++	++	ND	++	ND	+	++	++	ND
187	+++	++	ND	++	ND	++	++	+	-/+
193	+++	++	ND	++	ND	-/+	++	++	+
196	+++	++	-/+	++	ND	+	++	++	ND
274	+++	++	ND	+++	ND	+	++	+	+
280	+++	++	ND	+++	ND	+	++	+	ND
282	+++	++	ND	+++	ND	+++	++	+	ND
328	+++	++	ND	+++	ND	+	++	++	-/+
343	+++	++	ND	+++	ND	++	++	+	+
346	+++	++	-/+	+++	ND	++	++	+	ND
413	+++	++	+	++	+	++	+	++	ND
430	+++	+++	ND	++	-/+	+	+	++	-/+
501	+++	++	ND	++	-/+	+	++	++	+
504	+++	++	+	++	+	+	++	+	+
576	+++	++	ND	++	+	++	+	+	-/+
579	+++	++	+	++	ND	++	+	+	+
599	+++	++	+	++	ND	++	++	++	-/+
1111	+++	++	-/+	++	+	-/+	++	+	-/+
1143	+++	++	-/+	++	+	++	++	++	+
1155	+++	++	-/+	++	+	++	++	++	+
1159	+++	++	-/+	+	+	++	++	++	-/+
1162	+++	++	ND	++	+	++	++	++	+
1172	+++	++	-/+	++	+	++	++	++	-/+
1173	+++	++	-/+	++	+	++	++	++	-/+
1179	+++	++	ND	+	ND	+	++	++	+
1185	+++	++	+	++	+	+	+	+	++
1187	+++	++	-/+	++	ND	+	++	++	++
1199	+++	++	+	++	-/+	++	++	+	+
1228	+++	+++	+	+	ND	++	+	++	+
1238	+++	++	ND	++	-/+	++	++	++	-/+
1270	+++	++	ND	++	+	++	+	+	-/+
1293	+++	++	ND	++	ND	++	++	++	ND
1294	+++	++	ND	++	ND	+	++	++	+

Relative proportions of minerals are shown by – (< 3%), –/+ (3–5%), + (5–10%), ++ (10–20%), +++ (20–30%), and ND (not detectable).

DISCUSSION

Factors controlling erodibility across regions

Sediment yield varies widely across the study area ($29\text{--}993\text{ g m}^{-2}\text{ h}^{-1}$), reflecting differences in soil properties and surface conditions. High SAR promotes soil dispersion and may facilitate particle detachment by wind, while low organic matter reduces aggregate stability and increases erodibility. East Karun has the highest sediment yield ($78\text{--}993\text{ g m}^{-2}\text{ h}^{-1}$), coinciding with high SAR and low OM. In contrast, West Karun has the lowest range ($29\text{--}395\text{ g m}^{-2}\text{ h}^{-1}$), consistent with lower SAR and relatively higher OM. Flooding frequency also influences erosion conditions. Frequent flooding (F0/F1) can increase surface-water erosion, whereas reduced flooding may promote salinity and sodicity, alter groundwater conditions, and reduce vegetation cover, thereby increasing susceptibility to wind erosion. Vegetation cover is generally below 25% during the dry season and ranges from 25% to 50% annually. Halophytic species allow vegetation to persist under highly saline conditions, but extensive areas remain uncultivated (UN) because of severe salinity and sodicity, leaving the soil more exposed to wind erosion.

Origin and stability of dominant clay minerals

Kaolinite

The consistently high abundance of kaolinite across all regions cannot be attributed to its formation under the current climate. Kaolinite commonly forms under humid conditions and may be inherited from parent rocks in upstream areas. Its transport to the alluvial plains of southern Khuzestan by water-eroded sediments has been documented previously (Jafari, 2006; Chorom et al., 2009). High CCE ($>40\%$) and low OM ($<0.5\%$) may further favor kaolinite preservation by limiting dissolution. The arid climate and limited leaching, together with the clayey texture (SiC–SiCL to C), also promote kaolinite retention by restricting water movement and mineral translocation.

Illite

The higher abundance of illite in East Hendijan may reflect three factors. First, high SAR ($30\text{--}70\text{ (meq L}^{-1})^{0.5}$) and ECe ($16\text{--}100\text{ dS m}^{-1}$) indicate saline-sodic conditions that may favor illite preservation and limit its transformation to smectite or vermiculite. Second, the low OM content ($<0.5\%$) may reduce conditions conducive to mineral transformation. Third, the relatively high gypsum content ($20\text{--}60\text{ meq }100\text{ g}^{-1}$) maintains high Ca^{2+} activity, which may reduce illite dissolution. Previous studies in nearby areas have reported transformation of illite into vermiculite or mica-like minerals (Jafari et al., 2017).

Fibrous clay minerals

Palygorskite

Palygorskite is widespread across all regions, with slightly higher abundances in East Karun and West Hendijan (Fig. 3). Its preservation is favored by arid conditions and high evaporation, while neoformation may occur from smectite or through precipitation from Mg^{2+} -rich groundwater. Shallow groundwater, such as the 100–150 cm water table in West Karun, may facilitate capillary transport of Mg^{2+} to

the soil surface. High CCE ($>40\%$) may also favor palygorskite stability under these conditions (Table 6). Aeolian input provides an additional source, as palygorskite-rich wind-blown sediments have been documented in the sand dunes of Khuzestan Province (Jafari and Hassanizade, 2023; Hassanizade and Jafari, 2021). Its fine crystal size facilitates suspension and long-distance transport, contributing to its occurrence in atmospheric dust across the Middle East and Africa (Galan and Singer, 2011).

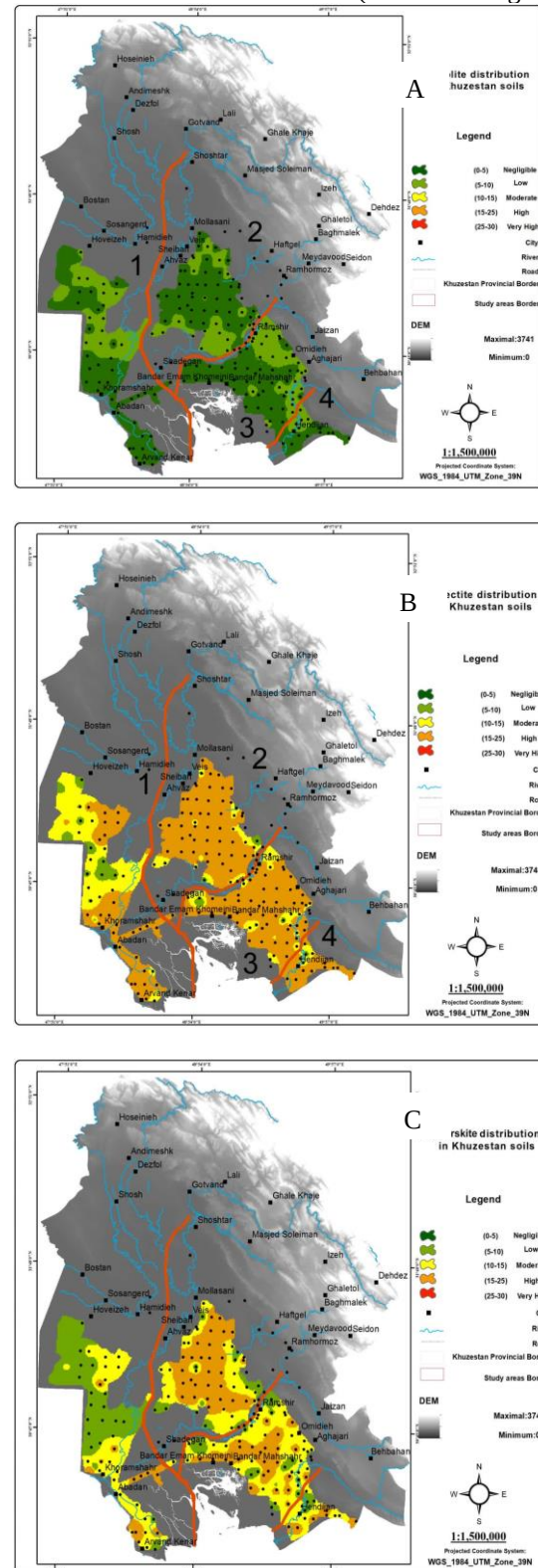


Fig. 3. Distribution of (A) sepiolite, (B) smectite, and (C) palygorskite clay minerals in different study area.

The lower palygorskite content in western Karun, near the Hoor al-Azim wetland, indicates that increased soil moisture from irrigation or waterlogging can reduce or remove palygorskite from the soil mineral assemblage. Previous studies showed its transformation into smectite under such conditions (Chorom et al., 2009; Pishgir and Jafari, 2014).

Sepiolite

Sepiolite occurs at very low abundances across all regions, with the highest frequency in West Karun (44%) and the lowest in East Hendijan (12.5%) (Fig. 3). Its formation is favored by high Mg^{2+} and Si activities under strongly evaporative conditions. Sepiolite is susceptible to leaching and is generally favored by alkaline conditions, which may explain its greater persistence in highly arid environments. The lower abundance in East Hendijan, despite its proximity to the sea, may be related to higher surface-soil moisture. Sepiolite may also be partly removed during carbonate removal in sample preparation, potentially leading to underestimation of its abundance (Singer and Galan, 2013). The occurrence of sepiolite in adjacent gypsum-rich soils (Abdoli and Jafari, 2017) further suggests that some sepiolite in the study area may be derived from aeolian deposits originating in Iraq.

Expandable and intermediate clay minerals

Smectite

Smectite is more abundant in West Karun and East Hendijan and less abundant in East Karun and West Hendijan. Its abundance may be favored by periodic wetting and drying associated with flooding, particularly in West Karun (F1). Lower gypsum content in West

Karun (20–40 meq 100 g^{-1}) may also favor smectite persistence, as gypsum can reduce clay dispersion. The low smectite abundance in East Karun, despite its high erosion rates, may indicate preferential removal of fine smectite-rich particles from the soil surface. Under saline-sodic conditions, smectite is readily dispersed, and its fine particle size and expandable structure may facilitate aeolian transport. Smectite has also been reported in wind-blown sediments entering Iran from Iraq (Hassanizade and Jafari, 2021) and in saline-sodic soils of Iraq (Albadran, 2021). In West Karun, where groundwater occurs at 1–1.5 m depth, the higher smectite abundance may reflect enhanced preservation or formation under near-surface groundwater conditions.

Vermiculite

Vermiculite is more abundant in West Karun and East Hendijan, where periodic flooding occurs. Repeated wetting and drying may promote vermiculite formation through the transformation of illite. Low OM (< 0.5%) may limit biological activity and favor vermiculite preservation. Under well-drained conditions, potassium loss from mica or illite can promote vermiculite formation (Grim, 1962). Some vermiculite may also be transported from well-drained upstream areas.

Chlorite

Chlorite is more abundant in West Hendijan, where high Mg^{2+} activity associated with saline groundwater (ECwt 32–100 dS m^{-1}) may favor its formation. Low OM and limited leaching may further enhance chlorite preservation in Khuzestan soils, particularly in the southern areas (Jafari et al., 2014).

Table 6. Final Comparison of clay minerals in different regions

Mineral	West Karun	East Karun	East Hendijan	West Hendijan
Kaolinite	High (+++)	High (+++)	High (+++)	High (+++)
Illite	Medium-High	Medium-High	Medium-High	Medium-High
Illite-like	Low-Very Low	Very Low-ND	Low-Very Low	Very Low-ND
Palygorskite	Medium-High	Medium-High	Medium	Medium-High
Sepiolite	Very Low-ND	Very Low-ND	Very Low-ND	Very Low-ND
Chlorite	Medium	Medium	Medium-High	Medium
Vermiculite	Medium-High	Medium-High	Medium-High	Medium-High
Smectite	Medium	Medium	Medium	Medium
Illite + Vermiculite	Very Low-ND	Very Low-ND	Low-Medium (few)	Very Low-ND

Mixed-layer illite-vermiculite

This mineral occurs in some West Karun and East Hendijan samples but is absent from the other regions. Its presence may represent an intermediate stage in the weathering of illite to vermiculite. Fluctuating water tables and ponding (P1–P2) create wet–dry cycles that may facilitate this transformation. Its formation is favored under well-drained conditions and may also be promoted by potassium removal through plant uptake.

Mineral inheritance versus pedogenic formation

The clay mineral assemblage of the study area can be broadly divided into two genetic groups. The first comprises minerals largely inherited from parent materials, including kaolinite, illite, and chlorite. Their widespread occurrence reflects both inheritance and relative stability under the prevailing soil conditions. The second comprises minerals whose abundance is more strongly influenced by pedogenic transformation, neoformation, or aeolian input, including smectite, palygorskite, and vermiculite. Their relative abundances vary among regions in response to local environmental conditions. Smectite may form through illite transformation in well-drained environments (Jafari et al., 2017) or through neoformation, although some smectite in southern Khuzestan soils is inherited from parent materials (Ghorban Lovineh et al., 2015). Palygorskite may likewise be inherited, neoformed under arid conditions, or introduced by aeolian transport. Limited clay-mineral transformation in the region is likely related to the extremely low precipitation and soil moisture. Conversely, moisture associated with irrigation or waterlogging may promote the removal or alteration of sensitive minerals such as sepiolite and smectite (Chorom et al., 2009).

Wind erosion as a mineral transport mechanism

Palygorskite and smectite, owing to their fine particle size and fibrous or platy structures, are readily transported by wind. Accordingly, they are among the predominant silicate minerals deposited in stabilized sand dunes in the study area (Hassanizade and Jafari, 2021). Annual aeolian sediment deposition ranges from 100 to 480 g m⁻² y⁻¹ and includes soluble salts, gypsum, carbonates, and silicate clay minerals (Hassanizade and Jafari, 2021). Studies of stabilized dunes in neighboring arid regions have shown distinct silicate-mineral distributions between surface and deeper layers, consistent with long-term aeolian deposition over more than 60 years (Hassanizadeh and Jafari, 2021). The high palygorskite abundance in East Karun may therefore reflect both aeolian input and favorable conditions for its preservation. Continued erosion and redeposition may also redistribute sepiolite and other fine-grained minerals, particularly in East Karun, where wind erosion is more intense.

Summary of regional mineralogical controls

The mineralogical differences among the four regions reflect interactions among salinity, gypsum content, flooding regime, soil moisture, and texture (Table 6). In East Karun, hypersaline and gypsum-rich conditions may favor

palygorskite preservation and accumulation. In West Karun, periodic flooding may promote smectite formation, while greater moisture availability may limit palygorskite accumulation. In East Hendijan, the relatively coarser texture is associated with higher illite abundance, whereas greater soil moisture may contribute to the lower abundance of sepiolite. In West Hendijan, high gypsum content and intense wind erosion may contribute to the relatively high chlorite abundance. Overall, the clay mineralogy reflects both inherited minerals and ongoing processes, including aeolian input, mineral transformation, and in-situ neoformation, under the prevailing arid conditions.

CONCLUSION

This study investigated clay mineralogy across four regions of the Khuzestan Plain (West Karun, East Karun, East Hendijan, and West Hendijan) in relation to wind erosion. Kaolinite (20–30%) was the most abundant clay mineral, followed by illite (10–20%) and palygorskite (10–20%). Smectite and vermiculite generally occurred at 10–20%, while chlorite ranged from 5–10% to 10–20% and was most abundant in West Hendijan. Sepiolite was the least abundant mineral (< 10% or ND), occurring most frequently in West Karun (44%) and least frequently in East Hendijan (12.5%). Mineralogical differences among the regions were associated with variations in salinity, gypsum content, flooding, soil moisture, texture, and wind erosion. East Karun had the highest palygorskite and the lowest smectite abundances, whereas West Karun had relatively higher smectite and lower palygorskite. East Hendijan was characterized by higher illite and the lowest sepiolite frequency, while West Hendijan had the highest chlorite abundance. These patterns suggest that wind erosion contributes to the redistribution of fine-grained minerals, particularly smectite and palygorskite. Annual aeolian sediment deposition of 100–480 g m⁻² y⁻¹ provides an additional source of clay minerals to surface soils. Overall, the clay assemblage reflects three principal sources and processes: (i) inheritance from parent materials, particularly kaolinite, illite, and chlorite, (ii) pedogenic transformation and neoformation, involving smectite, vermiculite, and mixed-layer clays, and (iii) aeolian addition, particularly of palygorskite, smectite, and sepiolite. The observed regional differences therefore reflect the combined influence of inherited mineralogy, local soil-forming conditions, and ongoing aeolian redistribution in this arid landscape.

High salinity (ECe 16–100 dS m⁻¹), high SAR, low OM (< 0.5%), shallow groundwater (100–150 cm), and sparse vegetation create highly erodible soil conditions. Sediment yield ranges from 29 to 993 g m⁻² h⁻¹, with the highest values recorded in East Karun. Future research should combine quantitative mineralogical analysis, provenance tracing using isotopic fingerprints, and long-term monitoring to better resolve mineral redistribution and erosion dynamics. Site-specific management and remediation strategies are also needed to reduce wind erosion in the most vulnerable areas.

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CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Conceptualization: Siroos Jafari; Methodology: Siroos Jafari; Software: Siroos Jafari and Saeed Maravani; Validation: Siroos Jafari, Saeed Maravani, and Ali Ajdari; Formal analysis: Siroos Jafari and Ali Ajdari; Investigation: Siroos Jafari and Saeed Maravani; Resources: Siroos Jafari and Saeed Maravani; Data curation: Siroos Jafari and Saeed Maravani; Writing—original draft preparation: Siroos Jafari and Saeed Maravani; Writing—review and editing: Siroos Jafari and Saeed Maravani; Visualization: Siroos Jafari and Saeed Maravani; Supervision: Siroos Jafari, Saeed Maravani, Ali Ajdari, and Mehdi Mashal; Project administration: Ali Ajdari; Funding acquisition: It had not funding.

DECLARATION OF COMPETING INTEREST

We declare that the manuscript contents are original and assign all rights for the academic use of the contents, tables, and images.

ETHICAL STATMENT

Approval was granted by the ethics committee of agricultural sciences and natural resources University of Khuzestan.

DATA AVAILABILITY

Further data can be obtained by contacting the corresponding author via email.

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