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Mineralogical and microstructural characterization of El Hadjeb dune sands (Algeria) using XRD and SEM

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Abstract

This study provides a morphological and mineralogical characterization of sands from the dunes at El Hadjeb, near Biskra, southeastern Algeria. At the transition between Saharan and steppe environments, these dunes are of growing environmental and tourism significance. Representative sand samples from three distinctly different geomorphological positions were characterized using X-ray diffraction (XRD) and scanning electron microscopy (SEM) analyses. XRD indicated quartz-dominated composition (up to 92.28 wt.%), with subordinate levels of calcite, indicating high mineralogical maturity, characteristic of well-developed aeolian systems. SEM analysis revealed sub-angular to sub-rounded grains with conchoidal fractures, micro-scarps, and pitting, typical of high-intensity mechanical weathering and long-distance transport in winds. The absence of clay coatings, gypsum phases, and biological material further confirms the arid, high-energy deposition setting. These results improve the understanding of the mineralogical maturity and textural characteristics of Saharan dune sands, which is essential for evaluating their suitability in soil rehabilitation, their integration into building materials, and their relevance to regional planning for ecotourism. The combined use of XRD and SEM illustrated how complementary geoscientific methods can provide detailed mineralogical and textural information essential for supporting sustainable management strategies in the studied region.

1. Introduction

Arid environments represent some of the toughest and least understood terrestrial environments, marked by harsh climatic conditions, scarce water resources, and distinctive geomorphologic processes (Abbasi et al., 2025; Abd El-Ghani et al., 2017; Gutiérrez, M, 2005; Nash, 2012; Zhang et al., 2023).

Within these regions, sand dunes appear as important geomorphologic elements that develop from the interactions of wind dynamics, sediment availability, and surface settings. These aeolian landforms not only record past and present climatic and geological events but also play a critical role in landscape evolution, pedogenesis, plant distribution, and human land use (Frías-Ureña et al., 2022; Zhu, 2022).

The area of Biskra, at the interface between the Saharan desert and Algeria's high plateaus in the north, presents a multifaceted and highly contrasting landscape ranging from mountains and foothills to glacis, plains, and depressions. Under these conditions, the El Hadjeb dunes, extending approximately 10 kilometers west of Biskra and up to the commune of Oumache, represent exemplary features of Saharan dune systems. These dunes exist in a geological

context defined mainly by gypsum- and calcium carbonate-rich soils that largely influence local hydrogeological settings, formative processes in the soil, and agricultural activities, particularly water management (Boumaraf et al., 2023; Kessasra and Mezerreg, 2023; Samia et al., 2023)

Despite their importance for both ecological and economic viewpoints, the microstructural and mineralogical properties of the El Hadjeb dunes have never been systematically characterized. Studies that have been performed in diverse parts of the Sahara have indicated that the dune sand composition may vary significantly, ranging from associations mainly made up of quartz to more evaporitic-rich associations that contain gypsum and halite. It is important to understand these differences because they not only affect the mechanical character of the sands but their chemical reactivity, fertility potential, and susceptibility to changes in the environment (Benaafi et al., 2020; Hachem et al., 2023; Mechri et al., 2017; Meftah and Hani, 2022; Moufti, 2013; Ramadan et al., 2022)

In addition, the El Hadjeb dunes are also becoming an essential element in the development of desert tourism and sustainable eco-tourism in the Biskra area. Consistent with Algeria's broader objectives for the diversification of the economy and improvement of natural heritage, these dunes are increasingly included in tourism itineraries that involve landscape discovery, oases visit, and agro-tourism excursions. Integrated understanding of their geoscientific characteristics can thus support improved land use planning and protection, and supply information for use in building materials, and in soil stabilization and reclamation in the environment (Akacem et al., 2020; Hadjadj et al., 2025; Mohammed and Driss, 2019; Moulay-Ali et al., 2021; Slimane and Zohra, 2024).

The present research utilizes X-ray diffraction (XRD) and scanning electron microscopy (SEM) in characterizing surface features and the mineralogical phases in dune sands from the El Hadjeb area. XRD is used in the effective identification and quantification of crystalline mineral content, and it is supplemented with high-definition descriptions of particles' morphology, texture, and microstructural characteristics from SEM, hence identifying facies that pertain to intensity of weathering, transport mechanisms, and deposition environments.

Key objectives of this research are to determine the mineralogical character of the dune sands at El Hadjeb, with particular regard for silicate and evaporitic materials, to examine the microstructural and morphological characteristics of sand grains to assess the influence of aeolian processes and aerial geological setting, and to explore regional environmental management, dynamics of the soils, and potential uses in tourism and georesource extraction applications. Overall, this research contributes to improved understanding of Saharan geomaterials and provides a scientific basis for addressing desertification, land degradation, and sustainable dune system management in semi-arid regions.

2. Materials and methods

2.1 Sampling strategy and site description

Sand samples were collected from three representative sites in the El Hadjeb dune field, as depicted in Figure 1. These were designated as PP.01, PP.02, and PP.03, strategically selected based on geomorphological position and elevation changes. PP.01 is located in the southern section of the dune system, at the edge of cultivated soil, represents a transitional zone between human-modified land and active aeolian transport. At the base of a rocky escarpment is PP.02; it represents a colluvial and aeolian active zone where the probable accumulation of sediment is influenced by slope processes and wind. PP.03, which lies farther north and at a higher altitude, represents the typical zone of a central dune crest and is relatively unimpacted by human activity but more exposed to prevailing winds. All samples were collected using sterile plastic scoops and immediately sealed in polyethylene bags to prevent contamination or moisture uptake. The exact coordinates of each sampling location were recorded using a handheld GPS device with an accuracy of ± 3 meters.

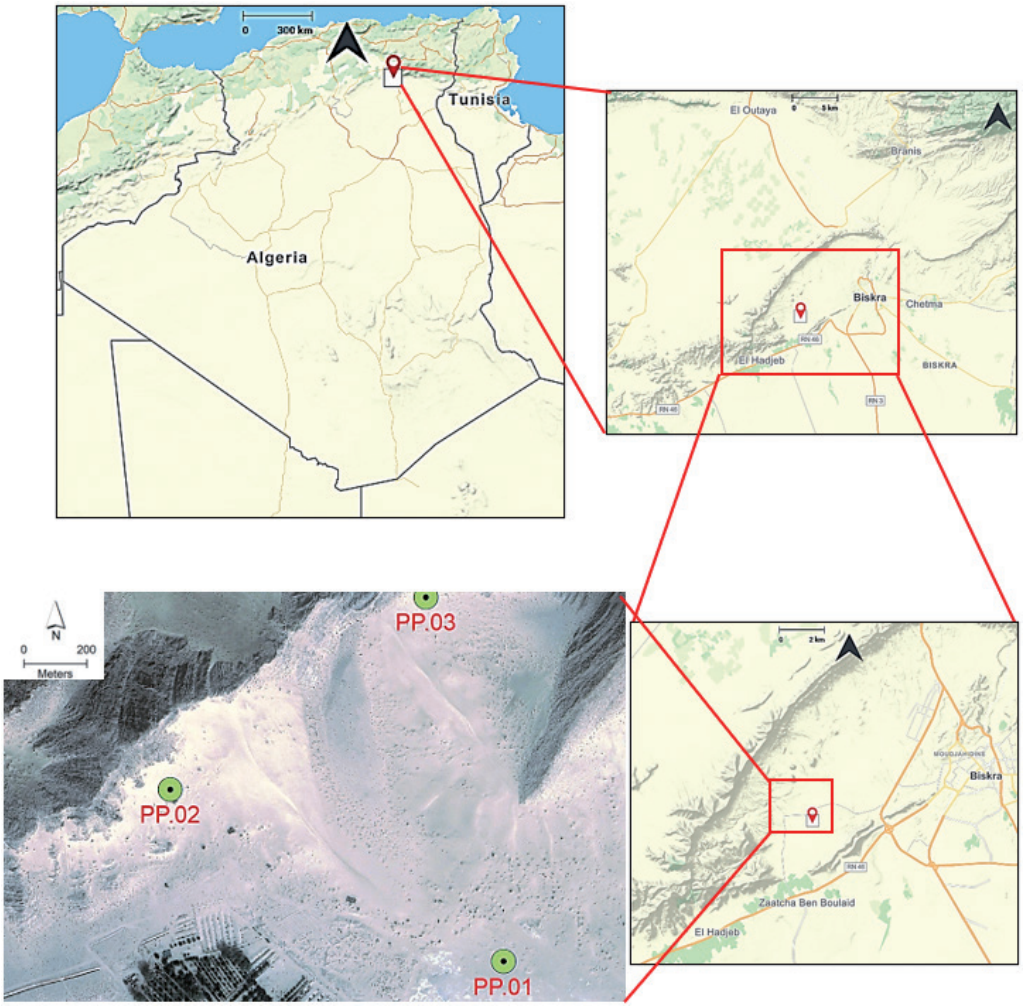

Figure 1. Location map of the El Hadjeb dune sands and sampling points (PP.01, PP.02, and PP.03). The image highlights the topographical setting and spatial distribution of dune features relative to nearby rocky outcrops and cultivated areas.

2.2 Sample preparation and analysis

Before analysis, the sands were air-dried at room temperature and, in turn, sieved in a 2 mm mesh to eliminate coarser particles and organic debris. A representative aliquot of approximately 10 g was finely powdered using an agate mortar and pestle for X-ray diffraction (XRD) analysis, while carefully transferred onto adhesive carbon stubs for Scanning Electron Microscopy (SEM) studies. Chosen grains were fixed on carbon-coated holders and sputter-coated with a thin film of either carbon or gold in preparation for enhancing surface conductivity. The XRD analysis was conducted using a Bruker D8 Advance diffractometer fitted with Cu Kα radiation (λ = 1.5406 Å), operating at 40 kV and 40 mA. Data were collected over a 2θ in the range 20° to 70°, with a step size of 0.02° and 0.5 s of counting time for each step. Phase identification was made using the X'Pert HighScore Plus software together with the ICDD PDF-2 database, and semi-quantitative analyses of the major mineral phases were supplemented using the Rietveld method when appropriate. Examination of the sands using scanning electron microscopy was made using a Thermo Fisher environmental scanning electron microscope, fitted with a secondary electron detector, and used at an accelerating voltage of 15 to 20 kV and working distance of about 10 mm. At magnifications ranging from 100× to 6000×, micrographs allowed for a detailed observation of the grain morphology, surface microtextures, and signs of weathering, in addition to the degree of rounding or abrasion. These microscopic analyses provided valuable information on mechanical history, transport dynamics, and potential diagenetic transformations that had affected the El Hadjeb dune sands.

3. Results and discussion

3.1 Mineralogical composition (XRD Analysis)

The mineralogical composition of the sand dunes from El Hadjeb was identified through the use of X-ray diffraction (Figure 2) with Rietveld refinement techniques. The mineralogical assemblage of all three samples (pp.1, pp.2, and pp.3) is dominated by crystalline quartz (SiO_2), along with a subordinate presence of calcite ($CaCO_3$). This is typical of well-sorted aeolian sands deposited in arid climates (Beddiaf et al., 2017; Meftah and Hani, 2022).

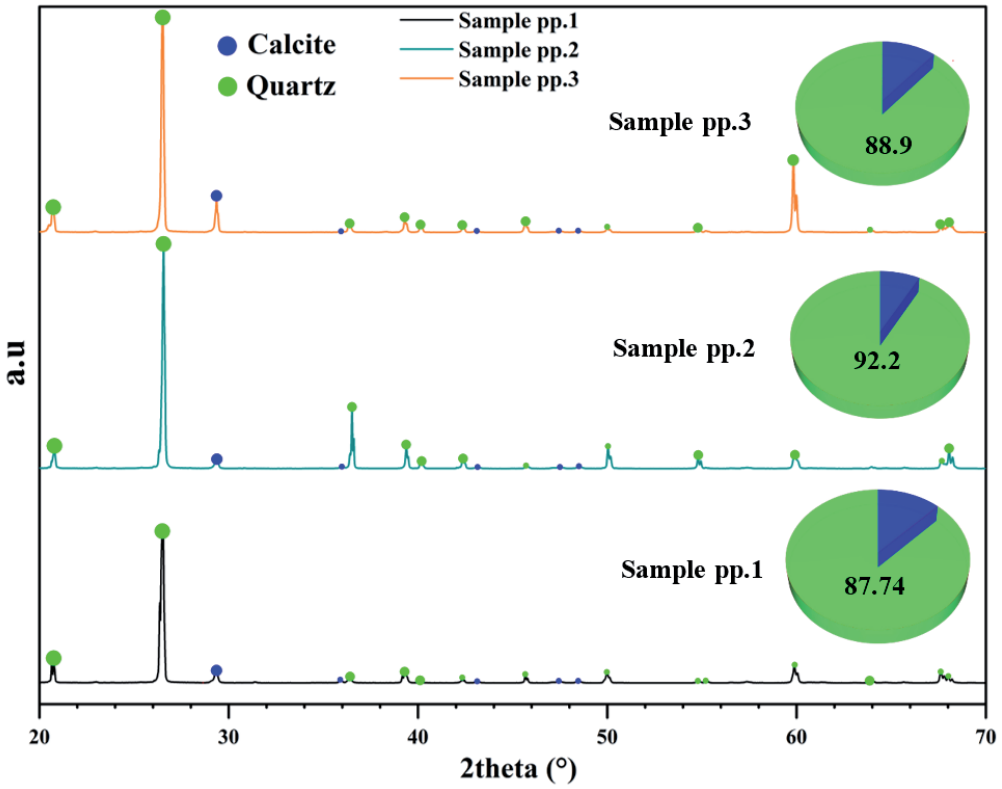

Figure 2. XRD patterns of dune sand samples (PP.1, PP.2, and PP.3) from El Hadjeb with quantitative phase distribution shown as pie charts. Green markers indicate quartz peaks, and blue markers indicate calcite peaks. Quartz dominates all samples, with PP.2 showing the highest content (92.28%).

Quartz was distinctly characterized in all samples due to its sharp and intense diffraction peaks, with the most significant reflection observed at 2θ ≈ 26.6°, which corresponds to the (101) crystallographic plane. Additional distinguishing peaks were detected at approximately 20.9°, 36.5°, 39.5°, 50.1°, and 60.0° 2θ, which further confirm the predominance of quartz (Beddiaf et al., 2015; Shah et al., 2022). The prominent intensity and narrow full width at half maximum (FWHM) of these peaks suggest that the quartz grains demonstrate a high level of crystallinity and structural organization. This implies minimal alteration and an extensive history of mechanical reworking, characteristic of detrital quartz that has undergone multiple cycles of transport and sedimentary sorting (Mahdadi et al., 2022) .

Calcite was present as a secondary mineral phase, reflected through relatively subdued reflections at about 29.4°, 39.4°, and 47.5° 2θ. Even though it was a subordinate phase, the consistent occurrence of the calcite peaks in all samples implies an episodic, if insignificant, input of carbonate material to the dune sands. Its occurrence could plausibly result from local sources, such as nearby limestone rocks, pedogenic activities involving the deposition of the carbonate, or deposition of fine, calcareous dust that is transported through regional winds (Al-Awah and Matter, 2023; Hadjadj and Chihi, 2022)

The use of quantitative analysis via the Rietveld refinement method provided a more accurate determination of the proportions of minerals. PP.2 contained the highest level of quartz, at 92.28 wt.%, followed closely by PP.3 and PP.1 at 88.9 wt.% and 87.74 wt.%, respectively. The consistently high quartz content confirms its dominance across all samples of the El Hadjeb dune sands. Lower levels of quartz in PP.1 may be due to a slightly higher level of

calcite content, and this could imply local lithological differences, variations in sediment supply, or particular micro-environment facets that accreted favor carbonates (Liu et al., 2023; Touil et al., 2023).

From a sedimentological standpoint, the elevated quartz concentration, in conjunction with the mineralogical homogeneity observed across the samples, indicates that the sands exhibit well-sorted and texturally mature characteristics (Al Buloshi and Gheith, 2022). This mineralogical maturity can be attributed to extended aeolian transport and vigorous mechanical weathering processes (Muhs, 2017). Such processes gradually remove less resilient or chemically unstable minerals, including feldspars, micas, and clay minerals, thereby resulting in a residue predominantly composed of quartz. This degree of mineralogical maturity serves as a distinctive hallmark of Saharan dune systems, where continuous wind activity functions as a natural sorting mechanism, refining the mineral composition through abrasion and selective transport (Al-Halfi and Al-Khafaji, 2022)

Limited occurrence of the calcite presents an important geochemical dimension. Its occurrence may imply occasional interactions between the aeolian system and nearby calcareous terrains, or may indicate the influx from dust plumes that originate in carbonate-bearing soils. Again, the occurrence of calcite can potentially influence surface reactivity and stabilization of dune surface pH, and thus phenomena like nutrient storage and moisture uptake (Ghadr et al., 2022)

The mineralogical composition revealed through XRD analysis illustrates both the origin and subsequent transformations of the El Hadjeb dunes. The prevalence of quartz signifies notable mechanical resilience and minimal chemical reactivity, aligning with an extensive history of physical alteration in arid climate conditions. In contrast, the lesser presence of calcite indicates nuanced interactions between aeolian processes and carbonate-rich settings, underscoring the intricate relationships among geological sources, climatic influences, and local sedimentary processes.

3.2 Morphological and Textural Features (SEM Analysis)

The SEM micrographs of the El Hadjeb dune sands (Figure 3) reveal a heterogeneous assemblage of grains exhibiting a range of shapes, surface textures, and grain-to-grain interactions, characteristic of aeolian sediments in desert environments (Kermani and Boutiba, 2023).

At low magnifications of 100× and 400×, the overall morphology of the El Hadjeb sand grains exhibits a predominance of sub-angular to sub-rounded particles, with diameters ranging from a few tens to several hundred micrometers. This extensive granulometric variation implies that the sands have experienced moderate to advanced aeolian transport, during which processes such as abrasion, impact, and grain collision have gradually worn down the sharper edges without resulting in complete rounding (Li et al., 2008; Van Hateren et al., 2020) Such intermediate morphologies are typically formed under persistent yet intermittent wind regimes, where periods of transport are interspersed with brief intervals of surface stability (Chen et al., 2022) . The generally well-sorted appearance and the low frequency of very fine particles suggest effective wind winnowing and deflation, which are characteristic of Saharan dune dynamics. These characteristics reflect the selective removal of finer dust fractions along with the preferential accumulation of quartz grains that possess high mechanical resistance.

When scanned at an intermediate magnification of about 800×, the micro-textures on the surfaces of the grains become more distinguishable. The quartz grains display conchoidal breaks, smoothly curved and polished surfaces, a high number of linear microscratches, and pits, which are all evidence of mechanical weathering enhanced by saltation. These features are a result of repeated collisions between grains during transport and frictional polishing under turbulent winds. In some instances, the quartz grains are partially coated with thin, discontinuous coats consisting of fine mineral particles or clay-sized particles adhering to grain surface through electrostatic attraction. Indeed, no complete clay films or authigenic coatings were found, implying that post-depositional alteration is restricted, with pure mechanical processes dominating (Itamiya et al., 2019; Toth III et al., 2020). Under high magnification (up to 6000×), fine-grained microsurficial detail appears. Some grains have microporosity, etch pits, and regions of localized precipitation, indicating the

potential initiation of cementation processes or initial mineral overgrowths. Localities such as these could be representative of deposits of secondary silica or carbonate, likely formed under transient moisture conditions within dune interstices, where capillary rise or evaporation concentration could for a time facilitate mineral deposition. While such features are not ubiquitous, their occurrence indicates modest diagenetic impacts superimposed on otherwise mechanically robust groundwork (De Ruiter et al., 2021; Margolis, 1968).

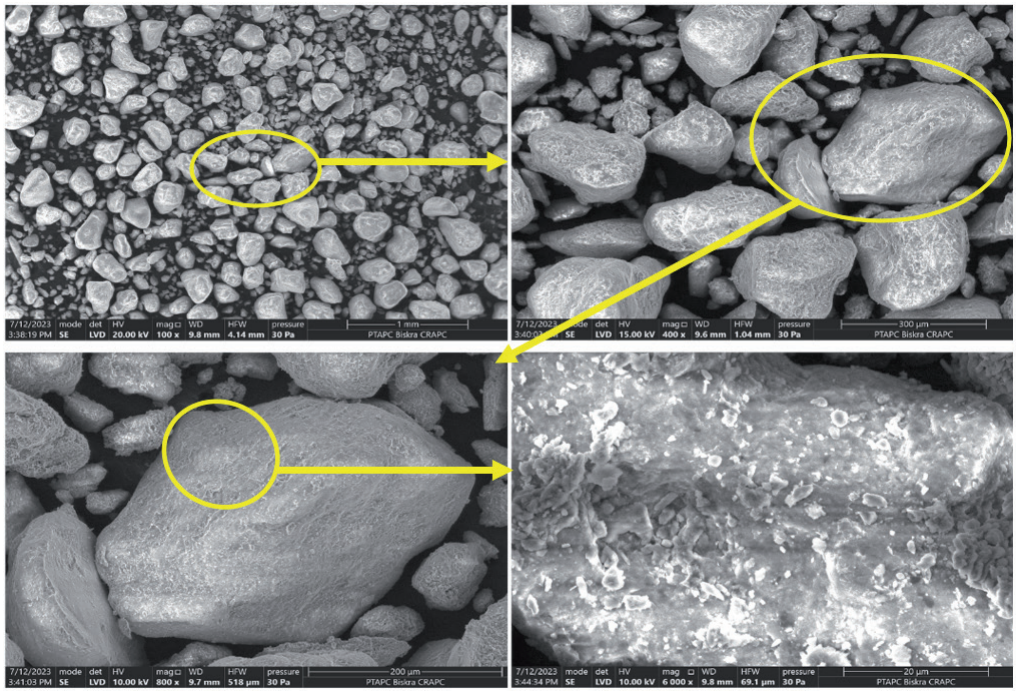

Figure 3. SEM micrographs (secondary electron, SE) of El Hadjeb dune sand sample (PP.1, PP.2, PP.3) showing grain morphology and surface microstructure

Interestingly, no biological remains in the form of diatoms, microbial filaments, or organic coatings were determined for any of the examined samples. This confirms that the depositional environment is strongly mineral-dominated and highly arid, characteristic for hyper-dry Sahara dune environments. Absence of fibrous or prismatic gypsum crystals was also established, consistent with XRD results, which showed no sulfate phases detectable, confirming lack of chemical activity of examined sands (Abdelhak et al., 2014; Glaser et al., 2023).

In combination, the SEM descriptions unequivocally confirm the interpretation of the El Hadjeb dune sands as texturally mature aeolian deposits comprised almost entirely of quartz with subordinate carbonate components. Their grain form, surface texture, and degree of sorting attest extensive exposure to transport by driving winds, high mechanical energy conditions, and little or no post-depositional chemical or biological alteration. The presence of sub-angular to sub-rounded quartz grains with conchoidal fracture textures, abrasion pits, and micro-scour marks, and the lack of clay coating and gypsum crust, reflect high textural maturity and intense mechanical sediment redistribution. The described sediment features are well known as good diagnostic criteria for mature aeolian environments (Al Buloshi and Gheith, 2022; Kermani and Boutiba, 2023; Margolis, 1968) and are indicative of high mechanical strength and low chemical activity of the sand, which are appropriate properties for their utilization in structural and geotechnical applications, as well as in other uses. Their characteristics also reveal key details concerning the aeolian processes that have operated on the El Hadjeb dune system, confirming its classification as a dynamic yet stable depositional environment within the broader Saharan sedimentary context.

4. Conclusions

The mineralogical and microstructural characterization of dune sands from El Hadjeb, Algeria, indicates that they constitute highly mature aeolian deposits dominated by well-crystallized quartz with minor calcite. Confirmation of the dominance of quartz from XRD

and sub-angular to sub-rounded grains observed by SEM with conchoidal fractures and abrasion pits support a long history of mechanical reworking under high-energy desert winds with insignificant post-depositional alterations.

These properties reflect that the El Hadjeb sands are mechanically stable, texturally mature, and chemically inert — characteristics that render them suitable for geotechnical uses, soil stabilization, and certain construction materials.

Scientifically, the results contribute to a better understanding of sediment dynamics in Saharan dune fields and provide baseline data on regional mineralogy for studies of arid geomaterials. In practice, they feed into informed decisions on the sustainable utilization of dune resources in a sustainable way within environmental management and local development initiatives.

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