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Mineralogical and Geochemical Controls on the Sustainable Beneficiation of Hydrothermal Quartz from Egyptian Eastern Desert for advanced Applications

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Abstract

The rising global demand for high-purity quartz (HPQ) in advanced technologies, such as semiconductors, photovoltaics, and optical systems, necessitates the identification and beneficiation of new high-grade quartz sources. This study presents a comprehensive investigation of the Marwit El Sweiqat quartz deposit, located in the Eastern Desert of Egypt, with a focus on its mineralogical and geochemical characteristics, impurity profiles, and beneficiation potential. The quartz body, of hydrothermal origin, exhibits favorable properties including coarse crystallinity, low structural defects, and an initial SiO₂ content averaging 99.45 wt%. Petrographic and geochemical analyses identified critical impurities such as Fe₂O₃, Al₂O₃, muscovite, feldspars, and fluid inclusions which primarily concentrated along grain boundaries and microfractures. A suite of dry high-intensity magnetic separation (DHIMS) experiments was conducted using a Rare Earth Roll separator, and the process parameters were systematically optimized through response surface methodology (RSM) and central composite rotatable design (CCRD). The optimized conditions (splitter angle of 85° and belt speed of 200 rpm) achieved removal efficiencies of up to 98.85% for Fe₂O₃ and 98.05% for Al₂O₃, reducing impurity levels to <10 ppm and <20 ppm, respectively. Final concentrates exhibited SiO₂ purities exceeding 99.95 wt%, meeting international HPQ specifications. The statistical models demonstrated strong predictive power ($R^2 > 0.90$), validating the robustness and reproducibility of the beneficiation approach. Moreover, the dry nature of the process enhances its feasibility in arid regions and offers a scalable, environmentally sustainable alternative to conventional wet processing. The results demonstrate that the Marwit El Sweiqat deposit represents a competitive HPQ source, highlighting its strategic importance for strengthening Egypt's role in the global supply chain of critical and high-technology raw materials.

Keywords: Quartz, mineralogy, deformation, beneficiation, high purity, high technical applications

1. Introduction

Quartz (SiO_2), composed of the two most abundant elements in the Earth's crust (Si and O), constitutes approximately 12.6% by weight of the lithosphere (Pan et al., 2022; Götze and Möckel, 2012). As a primary component of various igneous, metamorphic, and sedimentary rocks, quartz is one of the most widely distributed and economically important minerals (Götze et al., 2021). It appears in both crystalline and amorphous forms, with more than fifteen known polymorphs, including tridymite, cristobalite, coesite, and stishovite, each stable under specific pressure–temperature conditions (Strunz and Tennyson, 1982; Heaney et al., 1994). Among these, quartz is the most thermodynamically stable at surface conditions, and its unique chemical and physical properties (i.e., high hardness, piezoelectricity, optical transparency, chemical inertness, and thermal stability), have made it essential in a broad spectrum of modern industries, ranging from glass and ceramics to semiconductors, optics, and photovoltaics (Long et al., 2024; Moore, 2005).

Quartz can be classified both by texture and origin. Structurally, it occurs as either macrocrystalline (comprising varieties such as rock crystal, amethyst, smoky quartz, and rose quartz) or cryptocrystalline, which includes chert and agate (Upadhyay, 2025; Jovanovski et al., 2022). The genetic classification of quartz plays a critical role in determining its chemical purity, physical integrity, and industrial applicability (Müller et al., 2007; Long et al., 2024). Magmatic quartz, though volumetrically dominant, is often intergrown with feldspar and mica, limiting its value in high-purity applications. Pegmatitic quartz, formed from volatile-rich, residual magmas, yields larger and more isolated crystals with fewer inclusions. Metamorphic quartz, commonly found in quartzites and gneisses, may show high SiO_2 content but typically requires substantial processing due to deformation features and intergrowths. Sedimentary quartz, which includes detrital quartz sands and authigenic varieties in chert and silcretes, represents the main commercial source for conventional silica applications, but usually contains significant levels of iron oxides and clays (Xu et al., 2021; Melnikov, 1988; Müller et al., 2007).

Among all types, hydrothermal quartz is widely regarded as the most suitable for high-purity applications. It forms from silica-rich fluids precipitated in veins and fractures under low to moderate temperature and pressure conditions. This mode of formation promotes the exclusion of most metallic impurities and structural defects, resulting in quartz with high chemical purity, excellent crystallographic order, minimal fluid inclusions, and optical clarity (Götze and Möckel, 2012; Gao et al., 2024; Pan et al., 2022). Hydrothermal quartz typically requires significantly less beneficiation than other types and serves as the primary natural feedstock for producing high-

64 purity quartz (HPQ) used in the manufacture of semiconductors, optical fibers, solar cells, and synthetic quartz
65 crystals.

66 HPQ is a premium-grade quartz defined by extremely low concentrations of trace impurities, often <50
67 ppm total for elements such as Al, Ti, Fe, Na, and K, and must conform to strict physical and chemical standards
68 (Harben, 2002; Pan et al., 2022; Müller et al., 2007). High-purity quartz (HPQ) is a critical raw material in
69 advanced technologies due to its exceptional chemical purity and thermal stability. It is primarily used in the
70 semiconductor industry for producing crucibles essential in monocrystalline silicon growth, and in the
71 photovoltaic sector for solar-grade silicon wafers (Ma et al., 2025; Long et al., 2024). HPQ is also vital for optical
72 components, including lenses and fiber optics, as well as in high-performance ceramics and quartz glass for
73 lighting and labware (Zhang et al., 2023; Long et al., 2024). Its purity supports the manufacture of synthetic
74 quartz crystals used in frequency control devices like oscillators and resonators. With rising demand from
75 electronics, renewable energy, and telecommunications, HPQ is increasingly recognized as a strategically
76 important mineral.

77 Achieving such purity from natural quartz generally requires advanced beneficiation techniques. These
78 begin with mechanical processes such as attrition scrubbing, sieving, and magnetic separation to remove iron-
79 bearing and heavy minerals (Liu et al., 2023; Abukhadra et al., 2019; Long et al., 2024). Chemical purification
80 methods, particularly acid leaching with hydrochloric, sulfuric, hydrofluoric, and phosphoric acids, are used to
81 eliminate adhered and lattice-bound impurities (Zhang et al., 2012; Pan et al., 2022; Mustafa et al., 2011). Froth
82 flotation and high-tension separation techniques are commonly applied to separate quartz from feldspar and
83 mica, while ultrasonic and thermal treatments help to eliminate fluid inclusions and enhance leaching efficiency
84 (Goktepe et al., 2011; Farmer et al., 2000). Increasingly, optimization of beneficiation workflows is supported by
85 design of experiments (DOE) approaches, including response surface methodology (RSM) and central composite
86 rotatable design (CCRD), which allow for precise control over variables such as acid concentration, temperature,
87 and treatment time (Raghavan et al., 2006; Kincl et al., 2005).

88 In light of growing global demand for HPQ, driven by technological innovation and a shift toward
89 renewable energy, there is an increasing need to diversify and expand quartz supply chains. Traditionally, HPQ
90 has been sourced from select deposits in the United States (Spruce Pine), Norway, and Russia (Jennings et al.,
91 2024). However, these sources are approaching maturity, and new regions are being explored for viable
92 alternatives. One such region is Egyptian Eastern Desert, which forms part of the Arabian-Nubian Shield. This

geologically ancient terrane hosts more than 50 quartz deposits associated with granitic and tonalitic intrusions of Proterozoic age. These quartz bodies occur in forms including lenses, veins, and massive plugs, and are often spatially associated with pegmatites and hydrothermal vein systems (Ezzeldin, 2007; El-Ramly et al., 1967; El-Baghdady et al., 2005).

Several studies have confirmed the high chemical quality of Egyptian quartz, particularly at sites such as Wadi Warabeit, Marwit Wadi Mubarak, and Marwit Rod El-Leqah. Reported SiO_2 contents from these deposits range from 97% to over 99.5%, with relatively low concentrations of Fe_2O_3 , Al_2O_3 , and TiO_2 . Despite these advantages, exploitation remains limited due to a lack of beneficiation infrastructure, quality control certification, and alignment with international purity benchmarks. Additionally, our previous investigation involved descriptive and analysis for selected high quality sample but not representative samples for all the quartz reserves (Shahien et al., 2014). To address this gap, the present study investigates the geological, mineralogical, and geochemical characteristics of the whole quartz body of Marwit El-Sweiqat which located in Central Eastern Desert of Egypt. Special emphasis is placed on identifying the types and sources of impurities, understanding the genetic origin of the quartz (with focus on hydrothermal contributions), and evaluating the performance of magnetic separation as affordable and effective beneficiation method. The study also benchmarks the purified quartz against global HPQ standards to determine its viability for use in semiconductor, photovoltaic, and optical applications.

2. Experimental Procedures

To evaluate the quality and beneficiation potential of quartz deposits from the Eastern Desert of Egypt, comprehensive fieldwork and laboratory experiments were conducted on samples from Marwit El Sweiqat. Multiple field trips were undertaken along the Idfu–Marsa Alam road to assess the geological setting, characterize host rocks, and collect fresh representative quartz samples for analytical and beneficiation studies. The mineralogical characterization began with petrographic analysis of 25 thin sections examined under a Nikon polarized transmitted light microscope at Geology Department, Faculty of Science, Beni-Suef University-Egypt. Geochemical analysis of twelve representative samples was carried out using a PANalytical Axios Advanced XRF system to determine the major oxides at the Central Metallurgical Research & Development Institute (CMRDI) in Egypt to determine the major oxides. Analytical precision, assessed by repeated measurements of certified reference materials and duplicate samples, is better than ± 0.5 wt.% absolute for SiO_2 and generally better than ± 1 – 2% relative for the other major oxides. Typical detection limits for major oxides are on the order of 0.005–0.01 wt.%

For beneficiation testing, 30 kg of quartz from each site were crushed in stages to a final size of -0.6 mm using Denver primary and secondary jaw crushers, followed by Denver roll milling. Size classification was performed using a Retsch laboratory shaker, and the samples were divided into fractions: -0.6+0.10 mm (Ov.S.), -0.6+0.30 mm (C.S.), and -0.30+0.10 mm (F.S.), for further processing. All the previous procedures and tools were performed at the Central Metallurgical Research & Development Institute (CMRDI) in Egypt.

Magnetic separation was initially performed using a Frantz Isodynamic Separator (Model L.1) at CMRDI to fractionate minerals based on magnetic susceptibility. The quartz samples (-0.6+0.106 mm) were dried and subjected to a sequence of tests under increasing magnetic field strengths (0.1–0.6 A). Magnetic and non-magnetic fractions were microscopically examined and the magnetic field intensities were calibrated using a Gauss meter. The instrument's slope settings were fixed at 8° (side) and 12° (forward) throughout.

Subsequent high-intensity magnetic separation was carried out using a Rare Earth Roll (RER) separator (Magnaroll MR 1.125, Boxmag Rapid) at CMRDI, capable of generating fields up to 1.45 T. Ground samples were homogenized, divided into ten 100 g subsamples, and labeled based on particle size and source. A response surface methodology (RSM) and central composite rotatable design (CCRD) were employed to statistically model the effects of roll speed and splitter angle on impurity removal efficiency. The optimization targeted maximum reduction of paramagnetic contaminants, primarily Fe and Al, which were quantified using atomic absorption spectroscopy (Perkin-Elmer Analyst 200) at CMRDI.

3. Geology of Marwit El Sweiqat quartz body

The Eastern Desert of Egypt forms the north-western sector of the Arabian-Nubian Shield, representing a fragment of the East African Orogen that was assembled by Neoproterozoic (~850–550 Ma) arc–collision events (Gamaleldien et al., 2026). At a regional scale the Eastern Desert comprises ophiolites, metavolcanics and metasediments of volcanic-arc affinity, gneissic-core complexes and post-collision granites and molasse sediments; these units record the accretion and collision of terranes along ophiolite-decorated sutures followed by deformation along major shear zones (Sami et al., 2024). These rocks are exposed in three terranes within the Eastern Desert, Northern, Central and Southern, and is flanked locally by younger Phanerozoic sedimentary cover (Fig. 1A).

The Central Eastern Desert (CED) is dominated by greenschist-facies ophiolitic rocks and island-arc metavolcano-sedimentary sequences and is interspersed with Cryogenian I-type and Ediacaran A-type granites that were emplaced both syn- and post-tectonically (El-Awady et al., 2024). It hosts some of Egyptian most

prospective mineral districts, where hydrothermal fluid circulation along shear zones has generated pure quartz veins, pegmatites, quartz-vein–hosted gold, volcanic-hosted massive sulphides and banded-iron formations (Hamimi et al., 2024).

The El Sweiqat area is located within the CED of Egypt at the coordinates 25°21'N latitude and 34°13'E longitude. The area is predominantly composed of granitic plutons, basaltic flows, and various metamorphic rock units (Fig. 1B). These different geologic units are indicative of a complex tectono-magmatic history, reflective of the Arabian-Nubian Shield evolution (Sami et al., 2023). Significantly, the area hosts a large quartz body whose dimensions were calculated by the Dam Company to be approximately 90 meters wide, 50 meters high, and 350 meters long. This corresponds to an estimated geological resource of about 4,173,750 tons (Ezzeldin, 2007), highlighting the economic potential of the deposit, particularly for high-purity silica applications in glass, electronics, and solar industries.

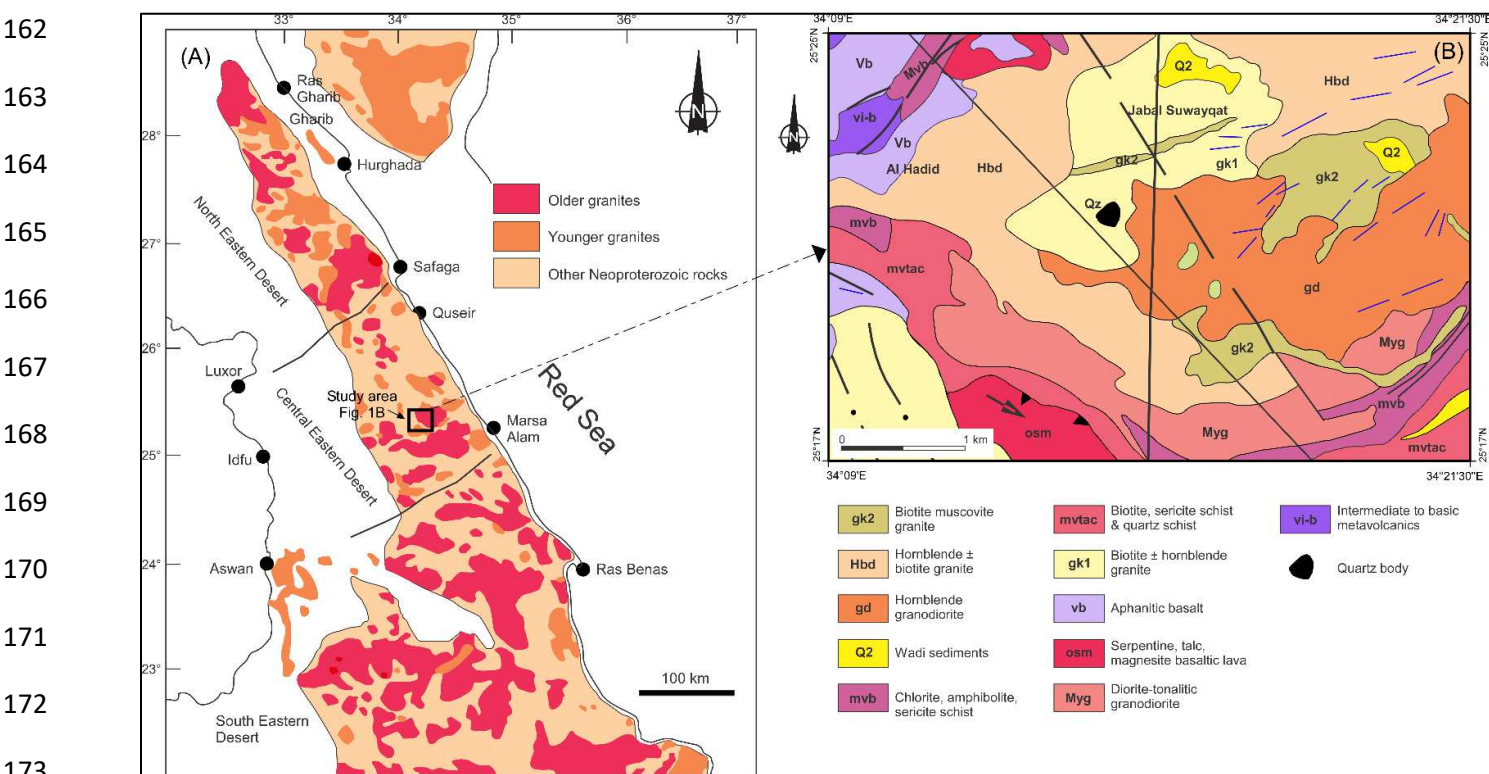


Fig.1. A) Geological map of the Eastern Desert of Egypt with the distribution of older and younger granites and other Neoproterozoic magmatic rocks (modified after Sami et al. 2024). B) Geologic map of Marwit El Sweiqat quartz deposit, Idfu-Mars Alam Road, Central Eastern Desert, Egypt (Modified after EG SMA, 1992)

Field observations indicate a lack of pegmatitic intrusions within the granitic intrusion, which is somewhat unusual and may imply a unique magmatic or cooling history. The quartz vein, referred to locally as Marwit El Sweiqat, is a prominent hydrothermal feature that intrudes and caps the granitic host (Fig. 2A). These veins appear in various morphologies, from major veins to fine veinlets, filling fracture networks across both granite

182 phases (Fig. 2B). The vein exhibits sharp intrusive contacts and is dominantly composed of milky white, intensely
183 fractured quartz, a feature that enhances its mineability. Under microscopic examination, the quartz displays
184 parallel fracture sets, some of which are stained reddish due to iron oxide impregnation, a common indicator of
185 fluid pathways and secondary alteration (Fig. 2C). The quartz body contains impurities in varying compositions
186 and amounts, including small inclusions of granitic rock, sulfide minerals, and mica aggregates (Fig. 2D). Of
187 particular geological significance is the presence of recrystallized quartz grains formed through a boundary
188 migration mechanism, signifying post-depositional thermal overprinting and the mobilization of silica (Fig. 2E).
189 Hydrothermal alteration associated with the emplacement of the quartz veins has partially affected the
190 surrounding granitic rocks. This alteration is evident both in the field and under the microscope, with clear signs
191 of metasomatic changes driven by ascending silica-rich fluids (Fig. 2F). Such observations reinforce the genetic
192 model of the quartz vein as a product of late-stage hydrothermal activity linked to regional magmatic processes.

193 The granitic host rocks in the area are divided into two distinct magmatic phases: an older (syn-collisional
194 I-type; 650-720 Ma) and a younger (late -to post-collisional A-type; 550-610 Ma) granitic rocks (Sami et al.,
195 2018). The older granites are moderately to highly weathered and manifest as medium-sized outcrops,
196 representing remnants of larger, now-exhumed granitic masses. Petrographically, the older granite is mainly
197 composed of plagioclase (48–49%), quartz (41–42%), mica (8–11%), and sparse alkali feldspar (Fig. 2G). Based
198 on modal mineralogical compositions, and in accordance with the International Union of Geological Sciences
199 (IUGS) classification, it is best categorized as tonalite. In contrast, the younger granitic phase is represented by
200 more homogenous pink granite that intrudes the older granite with well-defined contacts (Fig. 2H). This younger
201 granite is texturally massive and typically lacks structural features except near fault zones. It is rich in alkali
202 feldspar and mica, suggesting a more evolved magma source or a differentiated melt. Petrographic analysis
203 reveals that it comprises plagioclase (37–40%), quartz (30–32%), K-feldspar (27–29%), and minor mica (0–2%)
204 (Fig. 2I), which classifies it as typical granite. Evidence of post-emplacement deformation is prevalent. The older
205 granite units have been dissected by faults trending N-S and NW-SE (Fig. 1B), indicative of regional tectonic
206 stress regimes likely associated with Pan-African orogenic events. Microscopically, deformation features such
207 as micro-faults within plagioclase, evident through offset twinning lamellae, are observed (Fig. 2J). Additionally,
208 microstructural features like bent, kinked, and micro-folded feldspar, quartz, and biotite crystals provide further
209 evidence of dynamic recrystallization and tectonic overprinting (Abu Sharib and Abukhadra, 2021) (Figs. 2K and
210 L).

This two-phase granitic framework is beneficiation-relevant because feldspars and micas represent the dominant Al-bearing contaminants, while Fe-bearing alteration products and accessory phases may be spatially concentrated near contacts and structural discontinuities, increasing the likelihood of their incorporation into the quartz vein system. Also, the reported deformation history is important because it promotes brittle fracturing and microcrack generation enhances permeability for late fluids and increases the density of grain boundaries and defect network factors that (i) localize impurities along fractures and intergranular zones and (ii) facilitate impurity liberation during grinding and subsequent magnetic separation.

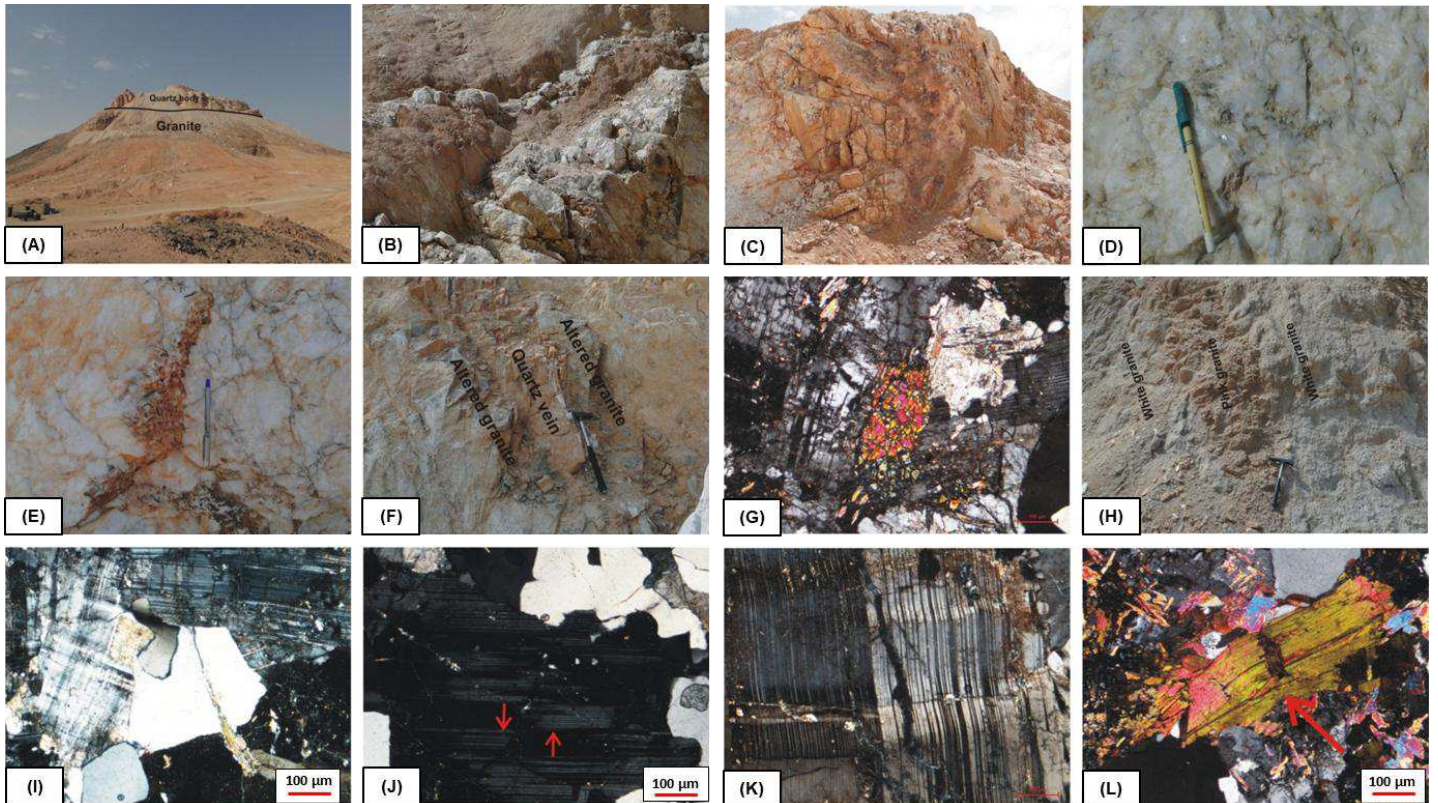


Fig. 2. Field and microscopic photos show: (A) general view shows quartz body capping the granite pluton, looking to NE, (B) parallel dike swarms cut across the pink granitic host, (C) intensively highly fractured quartz, notice the reddish color due to iron staining, (D) mica pockets inside quartz fragments, (E) field photo shows cavity filling younger generation of quartz through the main quartz body, (F) alteration zone along the contact between the quartz vein and the granitic host, (G) the main mineral components of older granite (C.N), (H) pink granite cut across older phase of white granite with sharp contact, (I) microcline, plagioclase and muscovite as mineral components of pink granite (C.N), (J) micro-fault through plagioclase, notice the displacement of twin lamellae (C.N), (K) kinked or micro-folded plagioclase crystals, and (L) well developed Kinking structure in muscovite (C.N).

4. Results and Discussion

4.1. Petrographic characterization of the samples

4.1.1. Quartz deformation

The quartz from the Marwit El Sweiqat deposit is predominantly composed of coarse quartz crystals, ranging in size from approximately 100 to 1600 μm (Fig. 3A). Due to the coarse granularity, the delineation of

individual grain shapes and boundaries is often challenging. Nevertheless, evidence of deformation-related features is abundant. Some quartz crystals, particularly those occupying micro-veins within the host quartz, demonstrate polygonization textures (Fig. 3B), indicative of recovery processes during dynamic recrystallization. Irregular and serrated grain boundaries are commonly observed between larger crystals, which are diagnostic of bulging recrystallization mechanisms (Stipp et al., 2002). This type of recrystallization reflects differential stress conditions and high dislocation densities, which cause certain quartz grains to bulge into neighboring grains (Fig. 3C), potentially forming new, smaller recrystallized crystals (Fig. 3D). These microstructures suggest that the quartz has undergone significant tectonic stress, which contributes to internal microfracturing and the development of dislocation networks, critical factors influencing the quartz physical and chemical reactivity. Optical examination reveals that many large quartz crystals display patchy or undulose extinction under crossed polars (Figs. 3E and F), both of which are characteristic features associated with low-grade metamorphic conditions, typically within the 300–400°C range (Passchier and Trouw, 1996). These features not only reflect a history of ductile deformation but are also directly linked to high dislocation densities, which have important implications for the mineral's reactivity. According to Hans-Rudolf et al. (2008), quartz grains showing undulatory extinction are significantly more reactive, which enhances their behavior in industrial processes such as acid leaching or high-temperature treatment.

Subgrain boundaries are also observed in several crystals (Fig. 3G). These boundaries, which subdivide larger grains into smaller subgrains (25–150 µm), result from dislocation glide and dynamic recrystallization. The subgrains often exhibit slightly varied crystallographic orientations, forming features consistent with secondary twinning (Fig. 3H). This microstructural arrangement increases the internal surface area and enhances the mineral's susceptibility to further recrystallization or alteration, a critical factor during physical beneficiation processes such as crushing, grinding, or magnetic separation. Deformation bands, which appear as isolated or sequential planar features (Figs. 3I and J), are common in the quartz. These bands represent intracrystalline strain and are a direct result of dislocation creep (Passchier and Trouw, 1996). Together with undulose extinction and subgrain development, they indicate substantial internal strain heterogeneity and a high degree of crystal lattice distortion. Such internal defects significantly enhance the reactivity of quartz, especially during processes that rely on surface interactions, such as chemical purification or thermal treatment in industrial applications. Micro-veinlets, generally aligned parallel to each other due to shearing stress, are another important feature within the quartz fabric. These veinlets cut through larger quartz crystals and are frequently infilled with fine-

grained quartz (Fig. 3K) or cryptocrystalline silica (Fig. 3L). These secondary silica phases often differ in optical properties and formation history from the main quartz matrix, reflecting multiple stages of hydrothermal fluid activity. They are occasionally accompanied by accessory minerals such as iron oxides and muscovite, which may influence the final purity of the quartz and require removal during beneficiation. In some sections, ribbon textures, elongated subgrain structures aligned parallel to the stretching direction, are noted (Fig. 3M). These textures are attributed to prolonged tectonic deformation involving extensive dislocation glide but limited diffusion or recovery, a process that imparts a high degree of internal strain. Additionally, kinked quartz crystals (Fig. 3N) are observed, further affirming a deformational history under directed stress.

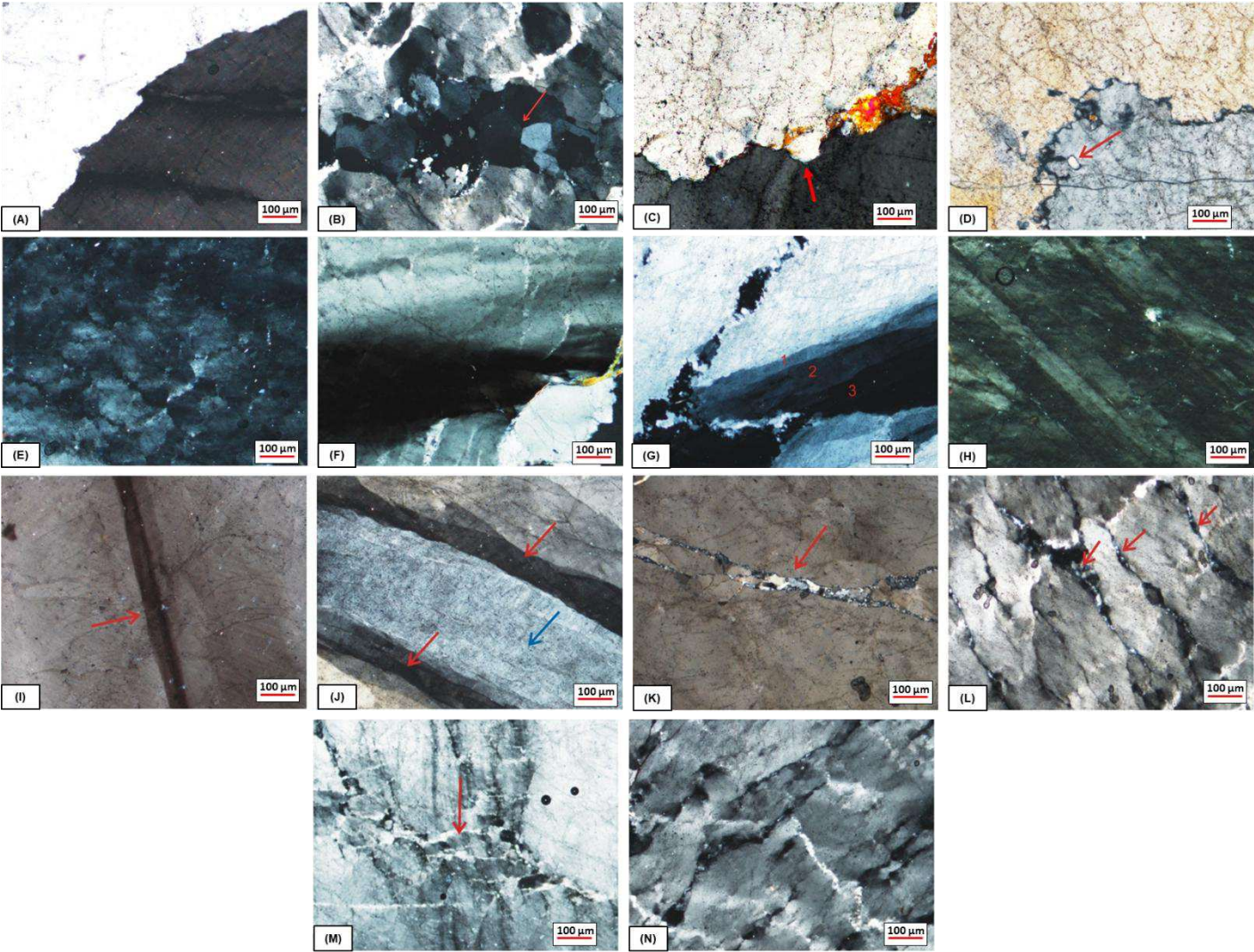


Fig.3. Photomicrographs (XPL) show: (A) general view to quartz crystals, (B) small quartz crystal with polygonal contact, (C) bulging grain boundary between quartz crystals, (D) independent small quartz crystal formed by bulging recrystallization, (E) patchy extinction of quartz, (F) undulatory extinction of quartz, (G) sub-grains in coarse large quartz crystals, (H) parallel sub-grains boundaries forming secondary twinning, (I) deformation band in quartz crystal, (J) series of deformation bands in quartz crystals, (K) parallel micro-veinlets due to shearing filled by fine quartz crystals, (L) micro-veinlet filled with cryptocrystalline silica, (M) ribbon texture, and (N) kinked quartz.

From an industrial perspective, these deformation features have significant implications. The high density of lattice defects, grain boundary irregularities, and internal substructures contribute to increased chemical reactivity, particularly important in applications requiring high-purity silica, such as semiconductor manufacturing, photovoltaic cells, and specialty glass. Moreover, during physical beneficiation, such structural complexities facilitate mechanical breakage along pre-existing planes of weakness, enhancing efficiency in comminution and reducing energy consumption during processing.

4.1.2. Types and nature of impurities

Impurities present in natural quartz can be broadly categorized into intracrystalline and intercrystalline types, based on their occurrence within or between quartz crystals. Intracrystalline impurities are those embedded within the crystal lattice and include: (i) lattice-bound trace elements also referred to as structural impurities; (ii) submicron- to nanoscale inclusions; and (iii) mineral and fluid micro-inclusions. In contrast, intercrystalline impurities occur along grain boundaries and fractures, often manifesting as mineral coatings or microcrystalline phases (Götze & Möckel, 2012). The quartz samples from Marwit El Sweiqat contain a range of mineralogical impurities, broadly categorized into solid inclusions, silicate melt inclusions, and fluid inclusions (Table 1). These impurities not only affect the purity and value of quartz for industrial applications but also influence its behavior during beneficiation and chemical treatment processes.

4.1.2.1. Solid impurities:

Among the solid inclusions observed, iron oxides constitute the most prevalent contaminants, followed sequentially by muscovite mica, plagioclase, altered potassic feldspars, zircon and rutile. The iron oxides exhibit distinct textural features: they appear as microfracture fillings within quartz crystals, with individual inclusions typically measuring 5–10 μm in diameter (Figs. 4A and B); they also form accumulations along grain boundaries that may reach up to approximately 20 μm in size (Figs. 4C and D); and they occur as fine-grained inclusions enclosed within coarser quartz grains, with dimensions ranging between 15 and 100 μm (Figs. 4E and F).

These iron oxide inclusions pose a significant issue for high-purity quartz applications, especially in industries such as electronics, optics, and solar energy, where iron is considered a major deleterious element. Their presence reduces whiteness, increases impurity levels, and can complicate acid leaching and purification processes. However, their occurrence in microfractures and at grain boundaries suggests that targeted physical beneficiation methods, such as magnetic separation or flotation, could effectively reduce their concentrations.

Impurities	Occurrences	Size
Iron oxide	Fracture filling	5 to 10 μm
	Enclosed within quartz	15 to 100 μm
	Concentrate along grain boundaries	20 μm
Muscovite	Fracture filling	~5 to 10 μm
	Enclosed within quartz	~50 to ~500 μm
	Concentrate along grain boundaries	~10 to 40 μm
Plagioclase	Enclosed within quartz	150 to 500 μm
Microcline	Enclosed within quartz	200 to 600 μm
Zircon	Enclosed within quartz	~5 μm
Rutile	Enclosed within quartz	1 μm diameter and 5 μm length
Fluid inclusions	Along fractures and grain boundaries	< 5 μm
Silicate melt inclusions	Enclosed within quartz	< 5 μm

334

335 Mica, primarily in the form of muscovite, appears either as free particles (50–500 μm) (Fig. 4G), as infill
336 within microfractures (5–10 μm) (Fig. 4H), or as fine coatings along quartz grain boundaries (10–40 μm) (Fig.
337 4I). These muscovite crystals can occur individually or as aggregates (Fig. 4J). Field and petrographic
338 observations suggest that the muscovite is largely secondary, resulting from hydrothermal alteration of biotite
339 during the migration of silica-rich fluids. This transformation is evident in the gradual increase of muscovite
340 content near the contact zones between the quartz veins and granitic host rocks. Additionally, some muscovite
341 has formed through the alteration of plagioclase feldspar (Fig. 4K), and in several cases, crystals exhibit kinking,
342 implying that they were subjected to the same tectonic deformation as the host granite (Fig. 4L). From an
343 industrial standpoint, mica negatively affects quartz purity and reactivity. It contributes to the coloration and
344 impacts the surface chemistry of the quartz, reducing its suitability for high-purity applications. Its sheet-like
345 structure can also interfere with comminution and sizing during beneficiation, leading to product variability unless
346 efficiently removed.

347 Plagioclase feldspar, although less common, is identifiable by its characteristic lamellar twinning and
348 occurs as grains between 150 and 500 μm (Figs. 4M and N). These feldspars often show signs of alteration due
349 to hydrothermal processes associated with quartz emplacement. This alteration may lead to the formation of
350 sericite and clay minerals, which affect the reactivity and beneficiation behavior of the quartz. Potassic feldspars,
351 particularly microcline, are present as minute anhedral crystals (200–600 μm), exhibiting distinctive cross-
352 hatched twinning (Fig. 4O). Microcline is the predominant K-feldspar phase in the surrounding granite and
353 commonly appears in samples closer to the granite–quartz contact zone, gradually decreasing towards the
354 quartz vein core. This spatial pattern suggests either mechanical inclusion of granitic rafts or chemical

mobilization and deposition by silica-rich hydrothermal fluids. These feldspars reduce quartz purity and must be eliminated through advanced beneficiation techniques, including flotation and acid leaching.

Zircon occurs as sharply bounded, euhedral crystals roughly 5 μm in size (Fig. 4P). Though present in minor quantities, zircon is resistant to most beneficiation processes and contributes trace elements, such as Zr and Hf that may affect the chemical specification of quartz in sensitive applications. Rutile, detected as elongated crystals (up to 5 μm long and $\sim 1 \mu\text{m}$ in diameter) (Fig. 5), is another accessory phase. Its presence is of particular concern in optical and electronic quartz products, where titanium levels must be tightly controlled.

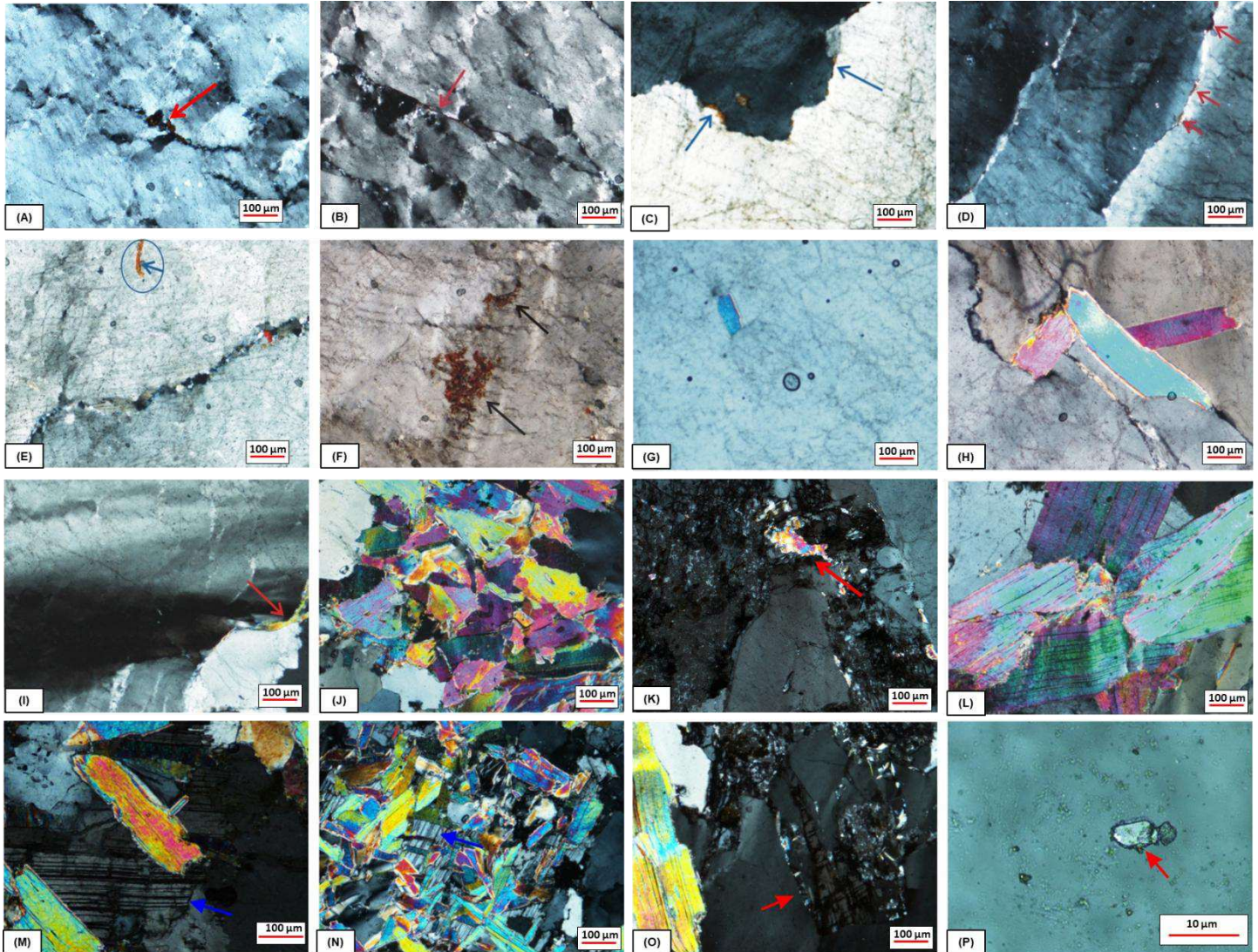


Fig.4. Microscopic photos show: (A and B) iron oxide filling micro-fractures within quartz crystals (XPL), (C and D) iron oxide concentrates along grain boundaries (XPL), (E and F) iron oxide impurities occluded by quartz (PPL), (G) muscovite crystal occluded by quartz, (H) muscovite filling microfracture within quartz, (I) muscovite impurities concentrate along grain boundaries between quartz crystals, (J) muscovite pocket within quartz, (K) rosette muscovite concentrate in altered feldspars, (L) kinked muscovite, (M and N) pocket aggregates of plagioclase and muscovite crystals enclosed within quartz grains, (O) altered potash feldspars, and (P) well developed zircon crystal in quartz crystal.

4.1.2.2. Silicate melt and fluid inclusions:

Silicate melt inclusions are seen as disseminated microcrystalline silica ($\leq 5 \mu\text{m}$), often in clustered forms within the quartz matrix (Figs. 5A and B). These inclusions represent remnants of trapped magmatic melt and are important indicators of the quartz's genesis. Their amorphous or fine-grained nature complicates beneficiation and can introduce microtextural heterogeneity that affects chemical leaching efficiency. Silicate melt inclusions are relatively rare but notable. These inclusions, which typically range from 1 to 300 μm in size, represent trapped droplets of silicate melt during quartz crystallization and may exist in glassy or crystalline forms (Götze et al., 2021; Leeder et al., 1987; Frezzotti, 2001; Webster, 2006). They provide valuable information on the melt conditions at the time of quartz formation and typically contain major elements such as Si, Al, Fe, Ca, Na, K, P, B, and F. However, their presence also compromises the chemical purity of quartz and can contribute to metallic contamination in downstream processes.

Fluid inclusions are abundant and typically $< 5 \mu\text{m}$ in size. They impart a dusty or cloudy appearance to the quartz (Fig. 5C). These inclusions are frequently aligned along planes or trails, often following grain boundaries or fractures, which suggests they are secondary in origin (Fig. 5D). Other inclusions are randomly oriented within quartz crystals and exist as three-phase (liquid, gas, and solid) inclusions (Fig. 5E), two-phase (liquid and gas) (Fig. 5F), or single-phase (liquid) (Fig. 5H). These multiphase inclusions are significant because they provide insights into the pressure–temperature–fluid evolution during quartz crystallization. Fluid inclusions may be either primary, trapped during the initial crystallization, or secondary, formed later due to recrystallization or tectonic deformation (Roedder, 1984). These inclusions are typically located along fractures and grain boundaries and frequently contain dissolved ionic species such as Na^+ , K^+ , Ca^{2+} , Mg^{2+} , Fe^{2+} , Cl^- , HS^- , HCO_3^- , and SO_4^{2-} (Hosaka & Taki, 1981; Robb, 2004). Their impact is significant, as they introduce unwanted trace elements into quartz and lower its value for ultra-pure applications like semiconductors, optical fibers, and solar cells.

Differentiating between structural, solid, and liquid inclusions is essential for assessing the quality of quartz as an industrial raw material. The HPQ required for advanced applications, demands extremely low levels of structural impurities, which are the most resistant to removal. In contrast, solid and fluid inclusions, though potentially abundant, can often be reduced through appropriate beneficiation techniques, such as comminution, flotation, or magnetic separation. However, if these inclusions are particularly fine or occur in large quantities, their removal becomes increasingly complex and cost-intensive (Blankenburg et al., 1994; Götze, 1997; Müller

et al., 2005). In the case of the quartz samples examined, the dominant impurities were identified as mineral, fluid, and silicate melt inclusions. These contaminants are primarily concentrated along grain boundaries and fracture planes. This distribution pattern is advantageous from a processing standpoint, as comminution techniques can liberate these impurities effectively. Additionally, many of these inclusions exhibit paramagnetic behavior, allowing for their selective removal via magnetic separation. This enhances the quality of the quartz concentrate and makes it more suitable for high-end industrial applications where impurity thresholds are tightly controlled.

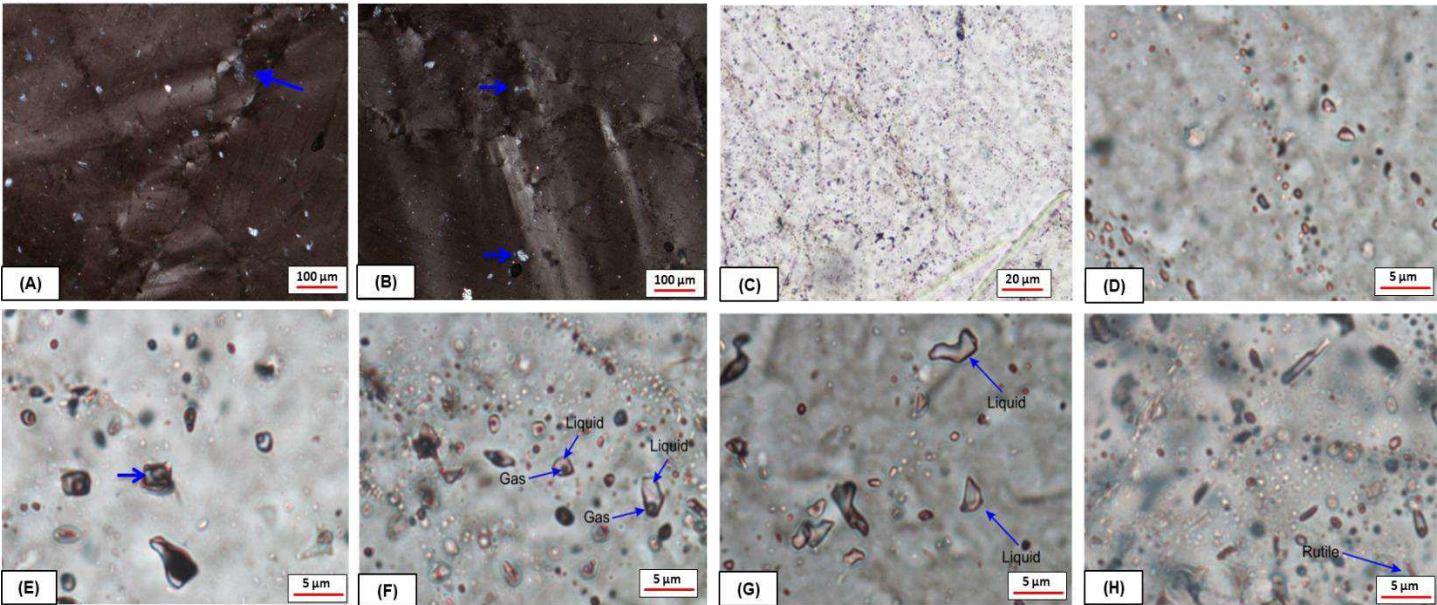


Fig.5. Microscopic photos (P.P.L) show: (A and B) micro crystallites silicate melt within quartz, (C) fluid inclusions distributed through quartz crystals, (D) parallel orientations of the fluids, (E) fluid inclusion composed of three phases (solid, liquid and gas), notice crystal in cube form may be halite (black arrow), (F) fluid inclusion composed of two phases (liquid and gas), (G) fluid inclusion of only liquid phase, and (H) rutile crystals.

4. 2. Geochemistry of Marwit El Sweiqat quartz sample

The major elements composition of the Marwit El Sweiqat quartz samples is summarized in Table 2. These samples are characterized by a high average SiO_2 content of 99.447%, indicating relatively pure quartz. However, the associated impurity content averages 0.55% (equivalent to 5523 ppm), which occurs as both trace elements and oxide inclusions. While this composition satisfies the requirements for many standard industrial applications, it falls short of the stringent purity standards required for high-tech uses such as solar-grade silicon and optical glass (Götze et al., 2021; Harben, 2002).

The predominant impurities detected include Fe_2O_3 (avg. = 0.104 wt.%), Al_2O_3 (avg. = 0.088 wt.%), CaO (avg. = 0.083 wt.%), K_2O (avg. = 0.048% wt.%), and MgO (avg. = 0.037 wt.%) (Table 2). Lesser concentrations of Na_2O (avg. = 0.032 wt.%), Cl (avg. = 0.031%), SO_3 (avg. = 0.029 wt.%), and Cr_2O_3 (0.025 wt.%) are also

present. Trace levels of TiO_2 , MnO_2 , and P_2O_5 are recorded at <0.008 wt.%, <0.012 wt.%, and <0.020 wt.% respectively. From an industrial perspective, these impurities are critical. For applications demanding ultra-high purity quartz, such as in semiconductors, photovoltaic cells, and fused silica glass, the levels of Fe, Al, Ca, Mg, and alkali elements must be significantly lower than those found in the raw Marwit El Sweiqat quartz. As such, while this quartz is suitable for traditional uses (e.g., construction materials, ceramics, and basic glass production), it requires substantial refinement to be viable for advanced technologies.

Table 2. Complete chemical analysis of Marwit Rod El Leqah Quartz samples, (wt %)

Component	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	Average
Na₂O	0.063	0.055	0.021	0.024	0.017	0.014	0.032
K₂O	0.103	0.097	0.022	0.037	0.019	0.010	0.048
CaO	0.186	0.163	0.046	0.044	0.036	0.027	0.083
MgO	0.072	0.067	0.020	0.032	0.020	0.012	0.037
Al₂O₃	0.185	0.179	0.075	0.052	0.021	0.020	0.088
Fe₂O₃	0.127	0.131	0.137	0.111	0.065	0.057	0.1046
TiO₂	0.024	0.021	0.004	0.002	<0.001	<0.001	<0.008
P₂O₅	0.052	0.044	0.007	0.016	<0.001	<0.001	0.020
SO₃	0.068	0.062	0.027	0.018	0.002	0.001	0.029
Cl	0.064	0.061	0.022	0.021	0.010	0.008	0.031
Cr₂O₃	0.071	0.048	0.019	0.012	0.003	<0.001	0.025
MnO₂	0.033	0.027	0.011	<0.001	<0.001	<0.001	0.012
SiO₂	98.804	98.923	99.544	99.613	99.782	99.845	99.447

The majority of Fe content is associated with finely disseminated iron oxides, sulfide inclusions, and muscovite. Muscovite, formed through the hydrothermal alteration of biotite, often contains iron and represents a significant contributor to total Fe impurities. The presence of Al_2O_3 is linked primarily to the occurrence of plagioclase, muscovite, microcline, and to a lesser extent, silicate melt inclusions. Structural substitutions and defects in the quartz lattice also contribute to alumina enrichment, which negatively impacts quartz's chemical purity and reactivity in precision applications.

CaO and MgO, although present in minor quantities, exceed the tolerable limits for high-end applications like solar-grade silicon and optical components. These elements are primarily sourced from plagioclase (Ca, Na), muscovite (Mg, K), and other secondary alteration minerals. In muscovite, Mg is often substituted within octahedral sites, inherited from the parent biotite phase. The physical beneficiation of quartz, particularly through grinding and flotation, may not effectively remove these chemically bound elements, which necessitates advanced purification steps such as acid leaching and thermal treatment. K_2O , averaging 0.048%, is mainly attributed to microcline and muscovite inclusions, both of which are common in samples near the granitic contact

zones. Na₂O originates primarily from plagioclase, while CaO and MgO contributions are further enhanced by fluid inclusions and melt inclusions. These inclusions not only transport elements into the quartz matrix but also create microscopic defects that can affect quartz performance during high-temperature processing.

The average TiO₂ content, although within acceptable limits for many high-tech uses, remains above the threshold for the ultra-pure silicon sector. Titanium is introduced primarily via submicron rutile inclusions and possibly through structural incorporation in the quartz lattice. Phosphorus, occurring as P₂O₅, is likely introduced through silicate melt inclusions and possibly through structural defects that facilitate elemental substitution. Manganese, appearing as MnO₂, is similarly associated with structural impurities that result from lattice dislocation or crystal imperfections formed during crystallization and tectonic stress.

Chromium, found as Cr₂O₃, is believed to substitute for Si within the quartz framework under certain conditions, further impacting the quartz's optical and electrical behavior. The high SO₃ levels are largely due to sulfide inclusions, while Cl enrichment is directly linked to fluid inclusions trapped during quartz formation. Both Cl and SO₃ represent volatile components that can significantly influence quartz reactivity during high-temperature processes and affect the final product's stability.

The geochemical profile of the Marwit El Sweiqat quartz demonstrates that, while the raw material is relatively pure compared to common quartz deposits, it does not meet the stringent purity thresholds required for advanced technological applications. The elevated levels of Fe, Al, and alkalis, necessitate rigorous purification to enhance suitability for high-value industries.

4.3. Frantz isodynamic tester results

The outcomes of magnetic separation conducted using the Frantz isodynamic separators are summarized in Table 3. The results indicate a distinct separation behavior of quartz-associated minerals based on their magnetic susceptibilities. Strongly magnetic phases, particularly iron oxides and ferruginous quartz grains, were effectively extracted as magnetic fractions at low magnetic field intensities, notably at 0.10 amperes. This early separation indicates a high magnetic response characteristic of minerals such as magnetite and maghemite, which contain significant proportions of ferrous (Fe²⁺) and ferric (Fe³⁺) iron, known for their strong magnetism.

As the magnetic field intensity was gradually increased, additional mineral phases with lower magnetic susceptibilities began to separate. This progressive behavior is particularly significant in understanding the oxidation state variability within iron oxide inclusions. The separation pattern suggests a systematic

503 transformation of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}), leading to the formation of hematite and other
504 intermediate iron oxides with varied $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratios. This redox variation directly affects the magnetic behavior
505 of these phases and explains their differential separation at increasing magnetic intensities. Similar observations
506 have been documented by Tokumitsu and Nasu (2001), who attributed such behavior to the heterogeneity in the
507 oxidation states and associated structural changes in iron-bearing minerals.

508 Furthermore, the separation process revealed that muscovite, a common phyllosilicate mineral found as
509 an impurity in quartz, began to separate distinctly within a magnetic field intensity range between 0.4 A (7,500
510 Gauss) and 0.6 A (12,300 Gauss), as indicated in Table 3. This behavior is closely related to the crystal chemistry
511 and structural characteristics of muscovite. Rochette (1987) emphasized that the magnetic susceptibility of
512 muscovite is not uniform, but rather dependent on its chemical composition, particularly the type and abundance
513 of substituting cations. While the ideal chemical formula for muscovite is $\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH},\text{F})_2$, the mineral
514 structure can accommodate substitutions of Fe^{2+} , Fe^{3+} , Mn^{2+} , or Cr^{5+} for Al and other cations (Götze et al., 2021;
515 Deer et al., 1992). These substitutions influence the overall magnetic properties of muscovite, making certain
516 grains more susceptible to magnetic separation than others.

517 The implications of these findings are notable from both mineralogical and industrial perspectives. First,
518 the ability to selectively remove iron-bearing impurities at low magnetic intensities provides a valuable
519 beneficiation strategy to upgrade quartz purity. This is particularly crucial for industries such as photovoltaics,
520 electronics, and high-purity glass manufacturing, where iron contamination must be reduced to parts per million
521 (ppm) levels. Additionally, the effective separation of muscovite at defined magnetic ranges allows for a more
522 precise targeting of phyllosilicate removal, which is essential for improving the chemical and physical
523 characteristics of quartz during further processing.

524 **Table.3.** The paramagnetic impurities separated from El Sweiqat quartz using Frantz isodynamic separator at different magnetic intensities

Test No.	Ampere, A	Gauss, G	Main magnetic separated products
1	0.10	3200	Iron oxides, strongly ferruginous quartz particles, strongly iron staining quartz and muscovite particles (Fig.6A-C).
2	0.20	4700	Mild ferruginous quartz particles, mild iron staining quartz and muscovite particles, (Fig.6D-F).
3	0.0	6700	Quartz and mica grains with mild iron staining and ferruginous materials, Fig.3.27.
4	0.40	7500	Pure muscovite particles (Fig.5G-I).
5	0.5	10000	Pure muscovite particles and quartz with muscovite inclusions (Fig.5J-L).
6	0.6	12300	Fine particles of muscovite, and quartz grains with less iron staining (Fig.5J-L).

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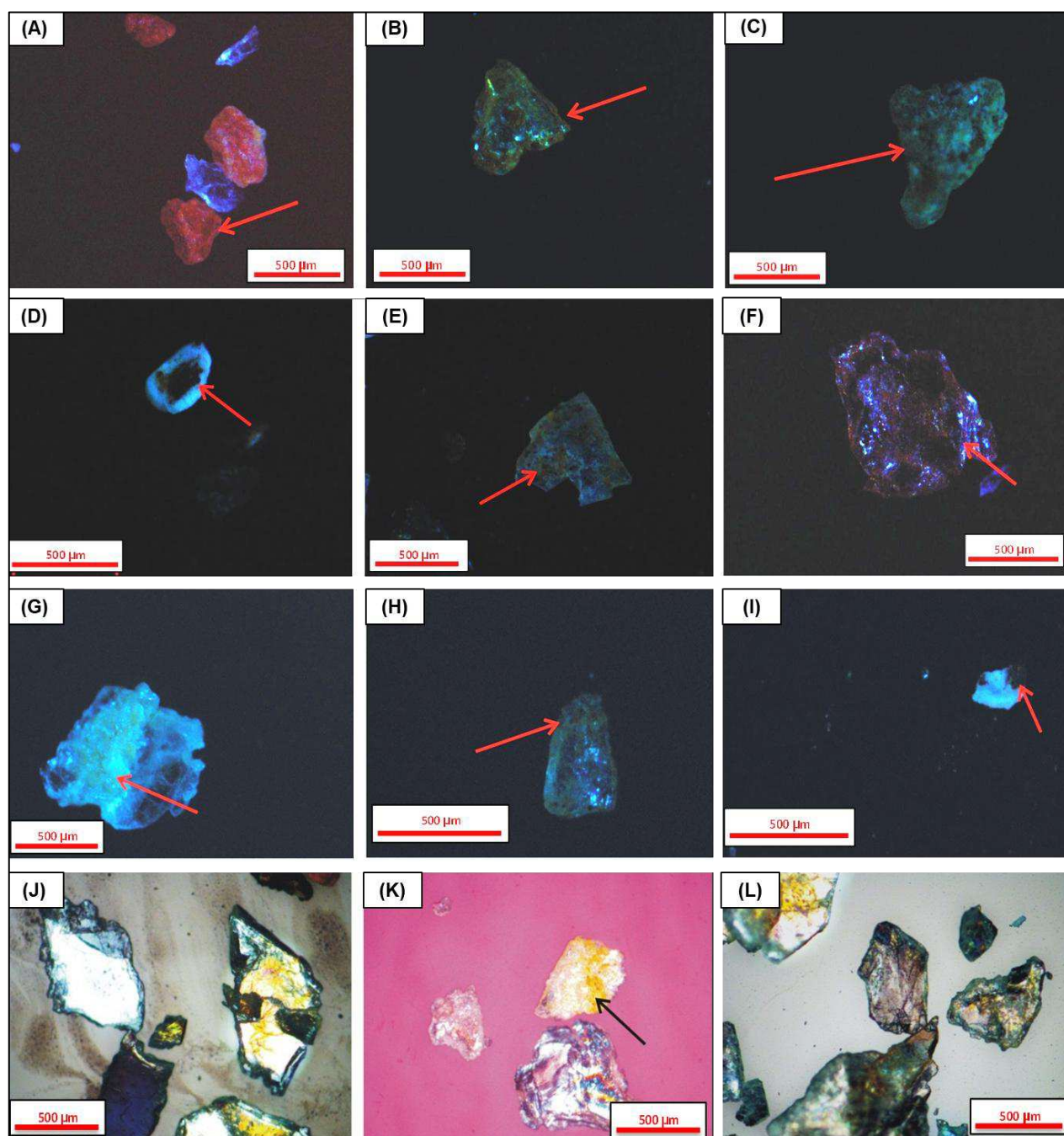


Fig.6. The paramagnetic impurities separated from El Sweiqat quartz using Frantz isodynamic separator at different magnetic intensities including (A) iron oxide, (B) iron staining muscovite grain, (C) ferruginous quartz particle, (D) iron staining quartz, (E) iron staining muscovite grain, (F) ferruginous quartz particle, (G) slightly iron staining muscovite, (H and I) slightly iron staining quartz grains, (J and K) Pure muscovite grain (black arrow in image B pointed to slightly iron staining muscovite), and (L) pure muscovite

4.4. Dry high intensity magnetic separation of Marwit El Sweiqat quartz sample

The outcomes of the dry high-intensity magnetic separation (DHIMS) experiments conducted on quartz samples from the Marwit El Sweiqat area are presented in Table S1, which details Fe_2O_3 and Al_2O_3 contents for both unclassified and classified feed fractions. The experimental design parameters and their corresponding coded and actual values are summarized in Table S2. Table 4 provides a comprehensive summary of the

experimental runs designed using the Central Composite Rotatable Design (CCRD), highlighting the key process variables and their influence on several response parameters, including Fe_2O_3 and Al_2O_3 contents, their respective removal efficiencies, and the weight recovery of the purified quartz concentrate.

Table 4. The Results of the experimental runs designed according to the CCRD of Marwit El Sweiqat quartz sample

Run No.	Splitter Angle (degree)	Belt Speed (rpm)	Response 1 Conc. Wt., %	Response 2 Fe_2O_3 %	Response 3 Fe_2O_3 Red., %	Response 4 Al_2O_3 %	Response 5 Al_2O_3 Red., %
Overall sample, -0.6+0.1 mm, (Ov.S.)							
1	85°	250	69.40	0.0047	95.43	0.0105	87.97
2	90°	200	90.31	0.0020	98.01	0.0019	97.82
3	95°	200	94.61	0.0024	97.58	0.0087	90.00
4	85°	225	67.30	0.0044	95.72	0.006	93.14
5	95°	250	95.32	0.006	94.17	0.0117	86.62
6	90°	250	91.34	0.0056	94.56	0.0115	86.85
7	95°	225	94.63	0.0054	94.75	0.0088	89.92
8	90°	225	91.22	0.0053	94.85	0.0031	96.40
9	85°	200	64.01	0.0013	98.73	0.0017	98.05
10	90°	225	91.22	0.0053	94.85	0.0031	96.40
-0.6 +0.3 mm coarse fraction (C.S.)							
1	85°	250	93.15	0.004	96.19	0.0057	93.37
2	90°	200	96.44	0.0016	98.47	0.0024	97.2
3	95°	200	96.63	0.0017	98.38	0.0029	96.63
4	85°	225	92.86	0.0020	98.09	0.0025	97.09
5	95°	250	96.84	0.0053	94.95	0.009	89.53
6	90°	250	96.70	0.0043	95.9	0.0076	91.16
7	95°	225	96.81	0.0021	98.00	0.0038	95.58
8	90°	225	96.62	0.003	97.14	0.0026	96.98
9	85°	200	92.75	0.0012	98.85	0.0019	97.79
10	90°	225	96.62	0.0021	97.14	0.0026	96.98
-0.3 +0.1 mm fine fraction (F.S.)							
1	85°	250	66.23	0.0058	94.36	0.0268	69.79
2	90°	200	86.59	0.0029	97.18	0.0339	61.9
3	95°	200	89.88	0.0049	95.24	0.0311	65.05
4	85°	225	64.41	0.0027	97.37	0.0262	70.56
5	95°	250	92.29	0.0112	89.12	0.0133	84.95
6	90°	250	90.23	0.0067	93.49	0.0160	82.00
7	95°	225	91.42	0.0054	94.75	0.0173	80.53
8	90°	225	89.79	0.0037	96.4	0.0191	78.53
9	85°	200	62.12	0.0023	97.76	0.044	50.56
10	90°	225	89.79	0.0037	96.4	0.0191	78.53

The data indicate a clear relationship between processing parameters and beneficiation efficiency. In particular, increasing the roll speed and splitter angle significantly improved the weight recovery of the quartz concentrate across all size fractions, overall (-0.6+0.1 mm), coarse (-0.6+0.3 mm), and fine (-0.3+0.1 mm), as shown in Table 4. The maximum recovery was achieved from the coarse fraction (Test No. 5 C.S.), reaching 96.84%, demonstrating the effective liberation and separation of impurities in coarser materials. In contrast, the finest fraction (Test No. 9 F.S.) yielded the lowest recovery rate at 62.12%, which is attributed to the higher surface area and more complex impurity entrapment in finer particles.

Under optimized operating conditions, splitter angle of 85° and roll speed of 200 rpm, exceptional separation efficiency was achieved for both the overall feed and the coarse fraction (Test Nos. 9 Ov.S. and 9

C.S., respectively). In these cases, the Fe_2O_3 content in the quartz concentrate was reduced to as low as 0.0013% and 0.0012%, corresponding to removal efficiencies of 98.73% and 98.85%, respectively. Similarly, Al_2O_3 contents were reduced to 0.0017% and 0.0019%, with corresponding removal rates of 98.05% and 97.79%. Under these optimized settings, the clean quartz product achieved recoveries of 64.01% for the overall sample and 92.75% for the coarse fraction (Table 4), indicating that coarse particles are more amenable to efficient impurity removal via magnetic separation. In the case of the fine fraction (-0.3+0.1 mm), optimal removal of Fe_2O_3 was achieved under the same conditions (85°, 200 rpm), while optimal Al_2O_3 removal required a higher splitter angle of 95° and a faster roll speed of 250 rpm (Table 4, Tests 9 F.S. and 5 F.S.). Under these respective conditions, Fe_2O_3 and Al_2O_3 concentrations were reduced to 0.0023% and 0.0125%, achieving removal efficiencies of 97.76% and 85.95%. The clean quartz recovery for these settings was 62.12% and 92.29%, respectively.

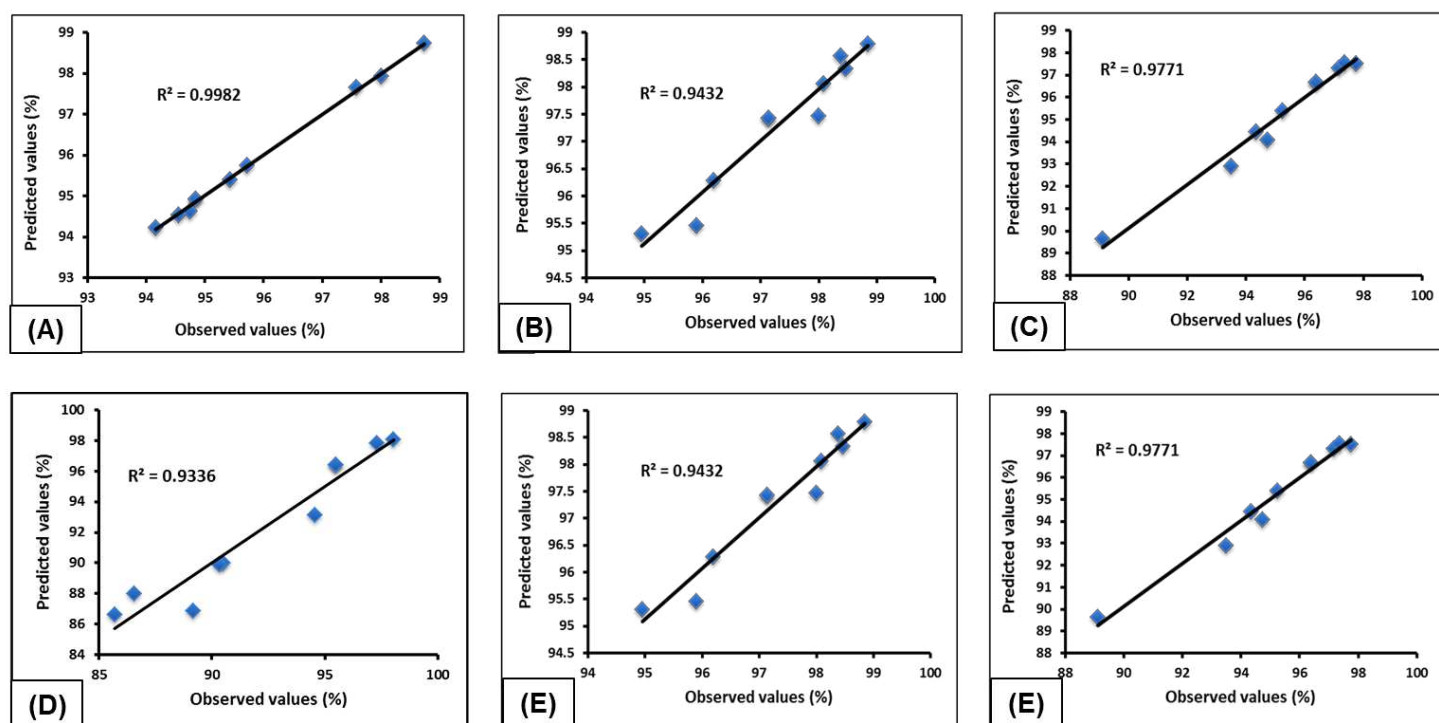


Fig.7. The correlation between the actual and predicted values by the model for the reduction of the Fe_2O_3 content ((A) Overall sample, (B) coarse fraction, and (C) fine fraction) and Al_2O_3 content ((D) Overall sample, (E) coarse fraction, and (F) fine fraction)

The statistical validation of the experimental design, as presented in the analysis of variance (ANOVA) results in Table S3, confirms the robustness of the developed model. All "Model F-values" were found to be highly significant across all tested samples, with corresponding probabilities (p-values) well below the 0.05 threshold, specifically, 0.01%, 0.01%, and 1.79% for the Ov.S. sample; 0.01%, 1.32%, and 0.04% for the C.S. sample; and 0.01%, 0.22%, and 0.03% for the F.S. sample. The absence of pure error in the dataset further

emphasizes the reproducibility and precision of the experimental methodology. Table S4 summarizes the statistically significant model terms for each of the response variables, indicating the relative influence of each process parameter and their interactions. Additionally, a strong correlation between experimental and predicted values is evidenced in Table S4, supported by the high coefficients of determination (R^2). All R^2 values exceeded 0.90, demonstrating that the quadratic polynomial models adequately captured the relationships between operating variables and performance metrics. This is further visualized in Figure 7, which confirms the model's predictive accuracy.

4.4.1. Interaction effects of operating parameters on Fe_2O_3 and Al_2O_3 removal efficiencies

3.4.1.1. Influence of splitter angle at varying belt speeds on Fe_2O_3 and Al_2O_3 reduction

The effect of the interaction between splitter angle and belt speed on the removal efficiencies of Fe_2O_3 and Al_2O_3 from Marwit El Sweiqat quartz samples is illustrated in Figure 8. The analysis focuses on three size fractions: the overall unclassified sample (Ov.S., -0.6+0.1 mm), the coarse fraction (C.S., -0.6+0.3 mm), and the fine fraction (F.S., -0.3+0.1 mm). The splitter angle was varied from 84° to 96° , and belt speeds were tested at two levels: 200 rpm and 250 rpm.

The results demonstrate a clear trend in the interaction effects. For all sample types, Fe_2O_3 removal efficiencies were maximized at a splitter angle of 85° and a lower belt speed of 200 rpm, achieving removal rates of 98.75%, 98.85%, and 97.76% for the Ov.S., C.S., and F.S. samples, respectively (Fig. 8A, B, and C). This suggests that lower belt speeds enhance the residence time of particles in the magnetic field, allowing more effective capture of iron-bearing phases, particularly those with higher magnetic susceptibility such as hematite and magnetite. When the belt speed increased to 250 rpm, Fe_2O_3 removal efficiencies declined to 95.43%, 96.19%, and 94.36% for the same fractions (Fig. 8), indicating that higher transport velocities reduce particle-magnetic field interaction time, particularly impacting finer or weakly magnetic inclusions. A similar interaction trend was observed for Al_2O_3 removal in the Ov.S. and C.S. samples. At the optimal setting of 85° splitter angle and 200 rpm, alumina removal reached ~98% in both fractions (Fig. 8). These high removal values highlight the efficiency of DHIMS in targeting alumina-bearing impurities such as muscovite, altered feldspars, and clay minerals, especially when they occur as liberated grains or are weakly bonded along grain boundaries. However, at the same splitter angle but higher belt speed (250 rpm), Al_2O_3 removal dropped to 87.9% and 93.37% in the Ov.S. and C.S. fractions, respectively (Fig. 8), confirming the adverse impact of reduced particle-field contact time.

Interestingly, the fine fraction (-0.3+0.1 mm) displayed a divergent behavior in terms of Al_2O_3 removal. In contrast to the coarser fractions, Al_2O_3 reduction in this finer material increased with both higher splitter angles and belt speeds. At 200 rpm and a splitter angle of 95° , the Al_2O_3 removal reached 65% (Fig. 8), and when the belt speed increased to 250 rpm under the same angle, the removal efficiency rose significantly to 85% (Fig. 8). This pattern is attributed to the distinct flow dynamics of fine particles, which are more responsive to enhanced magnetic gradients generated by steeper splitter angles and faster belt movement. Finer impurities such as cryptocrystalline muscovite and submicron clay particles are more likely to be influenced by these intensified conditions, leading to improved separation.

The differential responses of various size fractions to splitter angle and belt speed underscore the importance of tailoring processing conditions to the specific physical and mineralogical characteristics of the feed material. In particular, coarser fractions benefit from lower belt speeds and moderate splitter angles, which favor the effective separation of larger, strongly magnetic inclusions. In contrast, finer fractions require a more aggressive separation regime, combining high splitter angles and belt speeds to facilitate the removal of finely disseminated, weakly magnetic alumina phases. From an industrial perspective, these operational insights are highly significant. The successful reduction of Fe_2O_3 and Al_2O_3 content to sub-ppm levels under optimized conditions supports the potential of Marwit El Sweiqat quartz as a feedstock for high-purity quartz (HPQ) applications. Moreover, understanding the parameter interactions enables the design of more energy-efficient and cost-effective beneficiation strategies that maximize yield while ensuring purity.

3.4.1.2. Influence of belt speed at varying splitter angle levels on Fe_2O_3 and Al_2O_3 reduction efficiencies

The interaction between belt speed and splitter angle during dry high-intensity magnetic separation (DHIMS) plays a pivotal role in determining the removal efficiency of Fe_2O_3 and Al_2O_3 impurities from Marwit El Sweiqat quartz samples. The effects of varying belt speeds (200–250 rpm) under low (85°) and high (95°) splitter angle settings are illustrated in Figure 3.32 for three particle size fractions: the overall unclassified sample (-0.6+0.1 mm), the coarse fraction (-0.6+0.3 mm), and the fine fraction (-0.3+0.1 mm). Across all samples, the general trend reveals that impurity removal efficiency is consistently higher at lower belt speeds (200 rpm), particularly when combined with the lower splitter angle of 85° . For both the overall and coarse fractions, maximum Fe_2O_3 and Al_2O_3 reductions were recorded under these conditions, reaching approximately 99% and 98%, respectively (Fig. 8). This indicates that slower belt speeds promote prolonged interaction time between

particles and the magnetic field, thereby enhancing the separation of iron- and alumina-bearing impurities such as magnetite, hematite, muscovite, and altered feldspars.

When the belt speed remained at 200 rpm but the splitter angle was increased to 95°, the removal efficiencies declined. Fe₂O₃ reduction decreased to 97.5% for the overall sample and 98.3% for the coarse fraction, while Al₂O₃ reduction dropped more noticeably to 90% and 96%, respectively (Fig. 8). These results suggest that at higher splitter angles, the magnetic field gradient becomes more concentrated, potentially affecting the trajectory of particles and limiting the capture of weakly magnetic phases, especially those residing along grain boundaries or within finer inclusions. In contrast, the fine fraction (-0.3+0.1 mm) exhibited a more complex and somewhat inverse behavior. For Fe₂O₃ removal, the highest reduction (~97.75%) was again observed at the lower splitter angle of 85° and lower belt speed of 200 rpm (Fig. 8). However, as the splitter angle increased to 95°, the Fe₂O₃ removal declined to approximately 95% (Fig. 8), reinforcing the observation that fine particles require delicate control of flow and field interaction to prevent loss due to over-deflection or insufficient magnetic residence time.

In terms of Al₂O₃ reduction from the fine fraction, the behavior differed significantly. An irreversible relationship was observed between belt speed and Al₂O₃ removal, where the efficiency increased with higher belt speeds, particularly at higher splitter angles. At a lower splitter angle of 85°, Al₂O₃ reduction peaked at ~70% when belt speeds exceeded 240 rpm. This efficiency further improved to ~85% at the higher splitter angle of 95°, under similar high-speed conditions (Fig. 8). This suggests that in finer material, alumina-bearing minerals, typically in the form of finely disseminated muscovite or clay, respond better to more aggressive mechanical separation settings. Elevated belt speeds may facilitate the movement of these light and weakly magnetic particles into magnetic capture zones, especially when the splitter angle provides sufficient directional resolution.

The interaction effects of belt speed and splitter angle are further visualized in the 3D response surface plots shown in Figure 8. These surfaces highlight the non-linear and sample-specific nature of process optimization, emphasizing the need to tailor separation parameters based on both particle size and mineralogical composition. The results also affirm that coarser quartz fractions respond best to low belt speeds and moderate splitter angles, where gravity and inertia complement magnetic separation. Conversely, finer fractions demand higher dynamic energy inputs, via faster belt speeds and steeper splitter angles, to effectively target the ultrafine, weakly magnetic inclusions.

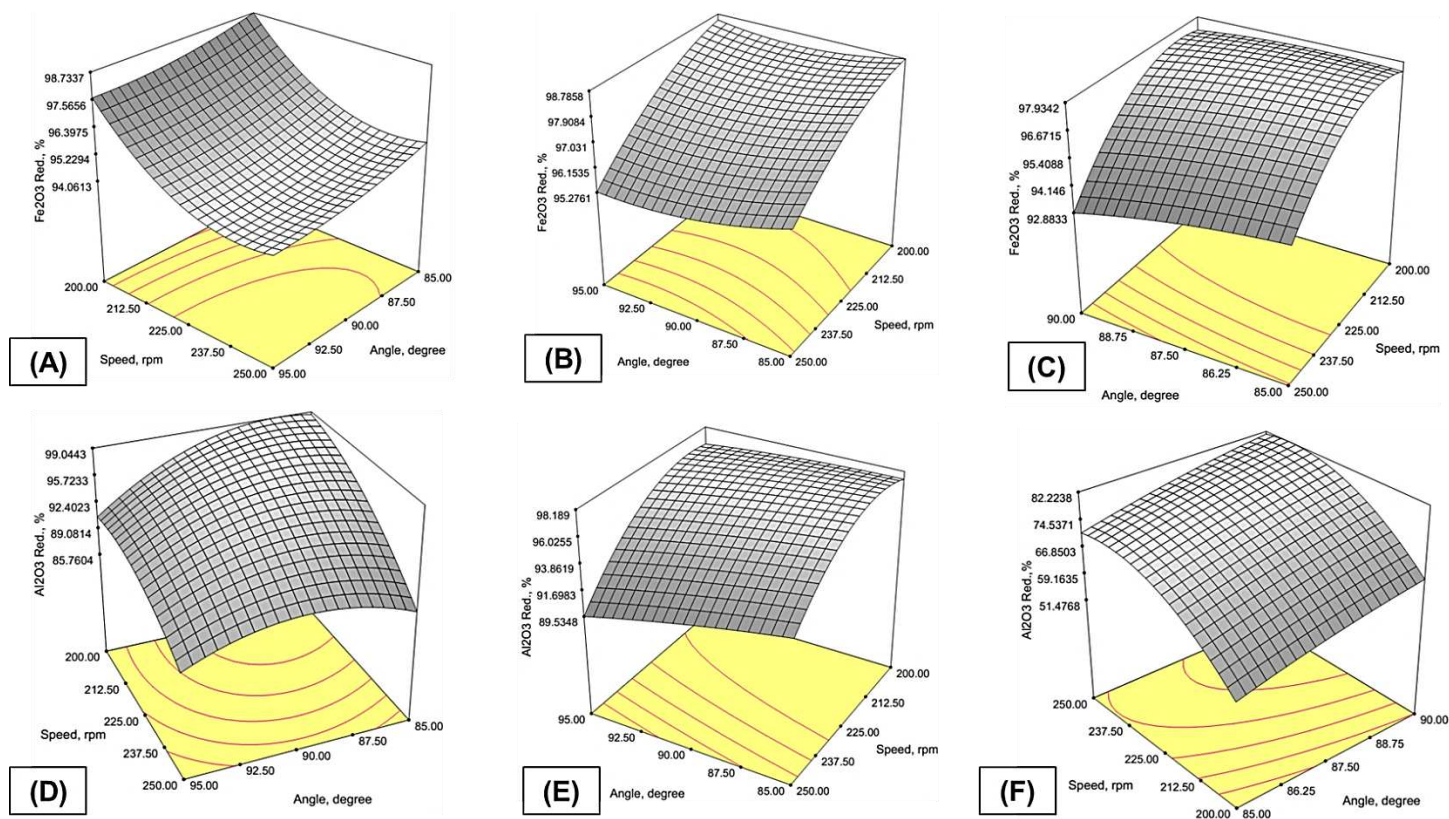


Fig. 8. the 3D curves for the interaction effect between the main influencing parameters during the reduction of the Fe_2O_3 content ((A) Overall sample, (B) coarse fraction, and (C) fine fraction) and Al_2O_3 content ((D) Overall sample, (E) coarse fraction, and (F) fine fraction).

3.4.2. Optimization, classification, and potential applications

The optimization of the dry high-intensity magnetic separation process for Marwit El Sweiqat quartz was conducted using a structured experimental design, with the optimization constraints and solutions presented in Tables S5 and 5, respectively. The goal was to determine the most efficient operating parameters for the Magnaroll separator to maximize the removal of Fe_2O_3 and Al_2O_3 , two of the most critical impurities affecting quartz quality in high-purity applications. The predicted optimal conditions derived through numerical modeling and quadratic programming were found to closely align with the best-performing experimental results. Specifically, a splitter angle of 85° and a belt speed of 200 rpm were identified as the most effective settings for the overall unclassified sample ($-0.6+0.1$ mm, Ov.S.) and the coarse fraction ($-0.6+0.3$ mm, C.S.). These conditions consistently yielded high removal efficiencies for both Fe_2O_3 and Al_2O_3 during the physical separation process.

Further refinement using a quadratic response surface methodology revealed that the alumina removal efficiency could be increased to 99% for the Ov.S. and 98.1% for the C.S. fraction by slightly adjusting the splitter angles to 86.9° and 85.15° , respectively, and fine-tuning the belt speeds to 200.7 rpm and 217.27 rpm. These

optimized settings highlight the sensitivity of the separation process to small variations in operating parameters and underscore the importance of precise control in industrial-scale beneficiation.

For the fine fraction (-0.3+0.1 mm, F.S.), the model identified slightly different optimal parameters due to the unique flow dynamics and impurity distribution in finer particles. The best results for simultaneous removal of both Fe₂O₃ and Al₂O₃ were predicted at a splitter angle of 89.92° and a belt speed of 226.28 rpm. However, when the objective was to maximize Fe₂O₃ removal specifically, the model suggested an ideal splitter angle of 85.59° and a belt speed of 212.6 rpm, which would improve iron removal efficiency from the experimentally obtained 97.76% to a slightly higher 97.93%.

Table 5. Optimization solutions of Marwit Sweiqat ground quartz sample

The unclassified sample, (OV.S.)								
Soln. No.	Angle	Speed	Wt., %	Fe ₂ O ₃ %	Fe ₂ O ₃ Red., %	Al ₂ O ₃ %	Al ₂ O ₃ Red., %	Desirability
1	90.28	200	90.72	0.0021	97.89	0.0022	97.48	0.854
2	90.18	200	90.49	0.002	97.90	0.0021	97.53	0.854
3	85.02	200	64.2	0.0013	98.73	0.0016	98.12	0.998
4	86.91	201.81	67.23	Not detected	Max.	0.0009	99.00	1.0
5	86.91	200.71	67.12	Not detected	Max.	0.0009	99.00	1.0
6	87.52	200.06	68.73	Not detected	Max.	0.0009	99.00	1.0
The -0.6+0.3 mm coarse fraction, (C.S.)								
1	91.28	202.24	96.89	0.00179	98.29	0.0022	97.33	0.932
2	85.00	202.65	92.74	0.0013	98.75	0.0018	97.802	0.988
3	85.00	205.25	92.76	0.00121	98.839	0.0017	97.96	0.983
4	85.00	200.00	92.73	0.00120	98.855	Not detected	Max.	0.984
5	85.00	200.27	92.73	0.0012	98.853	Not detected	Max.	0.983
6	85.15	217.27	92.84	Not detected	Max.	0.0016	98.10	1.0
7	85.98	207.54	92.77	Not detected	Max.	0.0017	98.02	1.0
8	87	213.33	92.82	Not detected	Max.	0.00172	98.002	1.0
9	86.66	208.49	92.79	Not detected	Max.	0.00172	97.991	1.0
The -0.3+0.1 mm fine fraction, (F.S.)								
1	90	227.47	89.83	0.0036	96.41	0.0179	79.82	0.873
2	89.92	226.28	89.80	0.0035	96.58	0.0184	79.3	0.848
3	89.95	226.21	89.80	0.00355	96.55	0.0184	79.32	0.848
4	87.15	209.74	71.56	0.0021	97.88	Not detected	Max.	1.0
5	85.59	212.6	64.13	0.00213	97.93	Not detected	Max.	1.0
6	85.51	213.68	64.11	0.00213	97.925	Not detected	Max.	1.0
7	85.20	217.66	64.17	0.0022	97.85	Not detected	Max.	1.0
8	95	250.00	92.26	Not detected	Max.	0.0133	85.02	1.0

Notably, the optimal condition for Al₂O₃ removal in the fine fraction remained unchanged from the experimental finding, reinforcing its robustness. This condition was achieved at a splitter angle of 95° and a belt speed of 250 rpm, suggesting that these parameters are particularly effective in targeting alumina-bearing impurities such as fine-grained muscovite and altered feldspars, which typically exhibit low magnetic susceptibility but can be efficiently separated at higher energy inputs.

The final chemical composition of the purified quartz products obtained under the optimized DHIMS conditions is summarized in Table 6. Overall, the treated concentrates show a pronounced reduction in the principal deleterious oxides (especially Fe₂O₃ and Al₂O₃), with a concurrent increase in SiO₂ to values approaching ultra-high purity. These results confirm the strong beneficiation potential of the Marwit El Sweiqat

quartz and provide a quantitative basis for benchmarking its quality against commonly used quartz purity standards and the requirements of different end-use sectors.

From the standpoint of purity classification, the upgraded products can be evaluated against both international and national benchmarking schemes. According to the industrial purity ranges widely used in the quartz market (Harben, 2002), the concentrates produced from the overall and coarse fractions (Ov.S. and C.S.) fall within the high-purity quartz (HPQ) field because they exhibit $\text{SiO}_2 \approx 99.91\text{--}99.98$ wt.% with extremely low levels of Fe_2O_3 and Al_2O_3 . This interpretation is supported by the obtained impurity levels, where Fe_2O_3 and Al_2O_3 were reduced to ≤ 0.003 wt.% and ≤ 0.002 wt.% in the Ov.S. products, and to below detection/near-trace levels in the coarse fraction (C.S., Test 9). In parallel, when assessed against the national benchmarks reported in [25], the products clearly transition from the “pure quartz” grade (99.0–99.5 wt.% SiO_2) to the “HPQ” grade (>99.9 wt.% SiO_2), emphasizing the technological significance of the achieved upgrading. Importantly, this upgrade is achieved via a physical, dry, and scalable route, which is a central strength of the present study.

A detailed inspection of Table 6 further highlights the impurity-control behavior across size fractions. The coarse fraction concentrate (C.S., Test 9) exhibits the highest chemical quality ($\text{SiO}_2(\text{exp.}) = 99.975$ wt.%), with most major impurity oxides (Na_2O , K_2O , MgO , Al_2O_3 , Fe_2O_3 , TiO_2 , MnO_2) at <0.001 wt.% or near trace levels. This behavior is consistent with more efficient liberation of impurity-bearing phases at coarser sizes and their improved capture by magnetic separation. The overall concentrate under the optimized condition (Ov.S., Test 9) similarly shows very high purity ($\text{SiO}_2(\text{exp.}) = 99.937$ wt.%), with Fe_2O_3 below detection and Al_2O_3 at 0.001 wt.%, confirming that the optimized parameter set effectively targets Fe/Al-bearing phases (iron oxides, mica, altered feldspar products) identified petrographically as concentrated along fractures and grain boundaries. In contrast, the fine fraction (F.S., Test 7) retains a comparatively higher Al_2O_3 level (0.020 wt.%) and lower SiO_2 (99.854 wt.%), which indicates that ultrafine alumina-bearing impurities (e.g., fine muscovite/sericite and altered feldspar/clay domains) are more difficult to completely separate under the same operating regime, likely due to their intimate association with the quartz surface and the different flow dynamics of fine particles. This fraction-specific behavior provides a practical processing implication: the coarse and overall fractions represent the most suitable feed streams for direct HPQ production by DHIMS, whereas the finest fraction may require either stricter magnetic conditions or an additional downstream purification step (e.g., selective flotation or controlled leaching) if the target market demands the lowest possible Al and alkali contents.

With respect to expected applications, the chemical specifications achieved indicate that the upgraded quartz, particularly the Ov.S. (Test 9) and C.S. (Test 9) products, can satisfy the requirements of several high-value sectors where iron and alumina are the most critical performance-limiting contaminants. The very low Fe_2O_3 and TiO_2 values are especially favorable for high-grade silica glass, optical components, and photovoltaic-related silica uses, where coloration and light transmission are strongly affected by transition metals. The strong suppression of alkalis (Na_2O and K_2O at ≤ 0.002 wt.% in the optimized products, and < 0.001 wt.% in the coarse fraction) is also advantageous for specialty glass and high-temperature silica applications, where alkalis can alter viscosity, thermal stability, and corrosion behavior. Furthermore, the overall chemical upgrading supports use in silicon metal and SiC-related industries, as well as other advanced silica-based products, consistent with the application mapping discussed in the manuscript.

Finally, based on the presented analysis, several recommendations can be made to guide future studies and industrial translation:

1. Fraction-based processing strategy: Prioritize the coarse and overall fractions as the main production streams for HPQ, because they show the highest SiO_2 (up to 99.975 wt.%) and the lowest $\text{Fe}_2\text{O}_3/\text{Al}_2\text{O}_3$ burdens under optimized DHIMS conditions.
2. Targeted treatment of fines: The fine fraction exhibits residual Al_2O_3 enrichment; therefore, it should be treated via a dedicated circuit (e.g., adjusted DHIMS settings, staged separation, or complementary purification such as flotation and/or mild acid leaching) depending on the end-use specification.
3. Trace-element certification for semiconductor-grade claims: While the achieved major-oxide chemistry demonstrates clear HPQ potential, final qualification for semiconductor and optical-grade markets should include ultra-trace determination (e.g., Li, B, P, Ti, and other trace contaminants) using high-sensitivity methods (ICP-MS / GD-MS / SIMS) as a logical next step for certification.
4. Process scaling and sustainability assessment: Given the strong performance of the dry route, pilot-scale validation and a basic techno-economic/environmental assessment would strengthen industrial feasibility, especially for deployment in water-scarce regions such as the Eastern Desert.

Collectively, the results in Table 6 demonstrate that optimized dry magnetic beneficiation can upgrade Marwit El Sweiqat quartz from a high-quality industrial starting material (~ 99.45 wt.% SiO_2 in the raw state) to HPQ-grade concentrates (> 99.93 – 99.97 wt.% SiO_2) with very low Fe- and Al-bearing impurities, thereby meeting

both international and local purity classifications and supporting several advanced silica-based applications, while also providing a clear roadmap for further certification and process refinement (Ezzeldin, 2007).

Table 6. Complete chemical analysis of the final concentrates

Component	Marwit El Sweiqat			
	Ov.S. (Test 2)	Ov.S. (Test 9)	C.S. (Test 9)	F.S.7 (Test 7)
Na ₂ O	0.007	0.002	< 0.001	0.012
K ₂ O	< 0.001	< 0.001	< 0.001	0.005
CaO	0.015	0.010	0.001	0.016
MgO	0.001	< 0.001	< 0.001	0.004
Al ₂ O ₃	0.002	0.001	< 0.001	0.020
Fe ₂ O ₃	0.003	< 0.001	< 0.001	0.005
TiO ₂	0.001	< 0.001	< 0.001	< 0.001
P ₂ O ₅	0.012	0.010	0.011	0.016
SO ₃	0.014	0.012	0.001	0.019
Cl	0.010	0.010	0.001	0.018
Cr ₂ O ₃	0.001	0.001	< 0.001	0.004
MnO ₂	< 0.001	< 0.001	< 0.001	0.011
Total	0.068	< 0.051	< 0.022	0.131
SiO ₂ (Calc.)	99.913	> 99.936	> 99.963	99.854
SiO ₂ (Exp.)	99.912	99.937	99.975	99.854
Wt., %	90.31	64.01	92.75	91.42

Conclusions

This study presents an integrated geological, mineralogical, and beneficiation assessment of the Marwit El Sweiqat hydrothermal quartz deposit in Central Eastern Desert of Egypt, with the aim of evaluating its potential as a viable source of HPQ for advanced industrial applications. The deposit is characterized by a large, structurally controlled quartz vein with favorable geological and petrographic features, including coarse crystallinity, low primary inclusions, and hydrothermal textures that facilitate impurity liberation.

Petrographic and geochemical investigations revealed that the principal impurities, Fe₂O₃, Al₂O₃, muscovite, feldspars, and fluid inclusions, are primarily concentrated along grain boundaries, fractures, and alteration zones. These characteristics render the quartz amenable to physical beneficiation techniques. DHIMS, RSM and CCRD, proved highly effective in impurity reduction. Under optimal conditions (splitter angle of 85°, belt speed of 200 rpm), Fe₂O₃ and Al₂O₃ levels were reduced to sub-10 ppm and sub-20 ppm concentrations, respectively. Final SiO₂ contents exceeded 99.95 wt%, aligning with international HPQ standards for use in semiconductors, photovoltaic cells, and optical devices.

The statistical models exhibited high predictive accuracy ($R^2 > 0.90$), confirming the reliability of the optimization approach. Furthermore, the dry processing route offers a water-efficient, scalable, and environmentally sustainable solution, particularly advantageous for arid regions such as the Eastern Desert. Collectively, the results underscore the technical and economic viability of the Marwit El Sweiqat deposit as a competitive source of HPQ. The study not only contributes to the diversification of the global HPQ supply chain

but also enhances Egyptian strategic potential in the production of critical raw materials for emerging technologies.

Declarations:

Competing interest: The authors declare that they have no known competing or conflicting interests

Data availability: The data will be available based on reasonable request.

AI tools: AI tools were used during manuscript preparation for language editing and refinement of schematic figures under the authors' supervision, who reviewed all outputs and take full responsibility for the final content

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