

Liberation-controlled beneficiation of Moroccan andalusite ore through particle size optimization and integrated gravity–magnetic separation

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Abstract: The beneficiation efficiency of andalusite ores is strongly governed by particle size because of its effect on mineral liberation and separation selectivity. In this study, the effect of particle size on the upgrading performance of an andalusite ore from the Moroccan Sidi Bou-Othmane deposit was investigated using shaking table gravity concentration followed by dry high-intensity magnetic separation. Optical microscopy revealed a progressive increase in mineral liberation, from 61% in the 600–900 μm fraction to 92% in the 45–150 μm fraction. Although the finest fraction produced the highest Al_2O_3 grade (41.35 wt.%), metallurgical recovery remained limited (21.90%) owing to excessive entrainment of ultrafine particles during gravity separation. The 150–355 μm fraction provided the optimum balance between concentrate grade and recovery, yielding a gravity concentrate assaying 38.03 wt.% Al_2O_3 with a recovery of 78.30%. X-ray diffraction analysis confirmed significant enrichment of andalusite in the concentrate, accompanied by preferential rejection of quartz-rich gangue minerals. Subsequent dry high-intensity magnetic separation further improved concentrate quality by decreasing Fe_2O_3 content from 5.80 to 1.79 wt.% while slightly increasing Al_2O_3 content to 38.72 wt.%. SEM observations revealed angular, largely liberated andalusite grains with limited residual gangue attachment, consistent with the mineral liberation determined by optical microscopy. The reduction in Fe_2O_3 content was confirmed by XRF analysis. These findings provide quantitative insights into liberation-controlled andalusite beneficiation and establish, at laboratory scale, a low-cost pre-concentration route for low-grade andalusite ores. The shaking table stage showed statistically significant differences among the investigated particle-size fractions, while replicate trials assessed experimental reproducibility.

Keywords: andalusite beneficiation, particle size optimization, mineral liberation, gravity concentration, high-intensity magnetic separation

1. Introduction

Andalusite, kyanite, and sillimanite are polymorphs belonging to the sillimanite group of anhydrous aluminosilicate minerals (Al_2SiO_5). Although they share the same chemical composition, these minerals differ significantly in crystal structure and physicochemical behavior. Among them, andalusite is particularly valued in the refractory industry owing to its high alumina content, excellent thermal stability, low thermal expansion coefficient, and ability to be directly employed without prior calcination, thereby reducing energy consumption during refractory production (Elhani et al., 2023; Misra et al., 2026; Namiranian and Kalantar, 2014).

Natural andalusite ores rarely occur in a pure state and are commonly associated with gangue minerals such as quartz, muscovite, biotite, garnet, and iron-bearing phases. These associated minerals introduce undesirable impurities, including Fe_2O_3 , CaO , MgO , TiO_2 , and alkali oxides, which adversely affect the refractoriness, thermomechanical stability, and corrosion resistance of refractory products. Among these impurities, iron oxides are particularly detrimental because they promote liquid-phase

formation at elevated temperatures and decrease refractoriness under load. Consequently, industrial applications of andalusite require beneficiation processes capable of producing alumina-rich concentrates with controlled impurity levels, generally targeting Al_2O_3 contents above 45 wt.% and minimal iron concentrations (Namiranian and Kalantar, 2014; Niu et al., 2019).

Particle size is a critical parameter in mineral beneficiation because it directly influences mineral liberation, separation selectivity, and metallurgical recovery (Ayhan and Abakay, 2005; Xia, 2017; Zhao et al., 2013). Inadequate liberation at coarse particle sizes often results in poor separation efficiency, whereas excessive grinding may generate ultrafine particles that negatively affect gravity and magnetic separation performance. In gravity concentration processes such as shaking table separation, particle size governs particle stratification, differential settling velocity, and transport behavior across the deck surface. Beneficiation efficiency is therefore generally maximized within an optimum size range where mineral liberation and hydrodynamic separation conditions are simultaneously favorable (Yao, 1992).

Previous studies on andalusite beneficiation have primarily focused on gravity and magnetic separation techniques (Ajaka et al., 2015; Amanullah et al., 1990; Brandão and Mendes, 1998; Gogou et al., 2022; Nekipelova et al., 2023; Zhu et al., 2015). Gravity concentration has been shown to be particularly effective for coarse, well-liberated andalusite particles, whereas high-intensity magnetic separation is commonly employed to remove iron-bearing gangue minerals. Nevertheless, most published studies provide limited quantitative information regarding the relationship between particle size, mineral liberation degree, concentrate grade, and metallurgical recovery, and comparable quantitative datasets remain scarce even for related aluminosilicate systems.

In the absence of detailed particle-size-oriented investigations on andalusite ores, relevant insights may be inferred from studies conducted on mineral systems exhibiting similar density and magnetic susceptibility contrasts, including kyanite, sillimanite, quartz-feldspar systems, and heavy mineral sands (Izerdem and Ergun, 2024; Nzeh et al., 2023). These investigations consistently demonstrate that beneficiation performance is highly dependent on particle size distribution: coarse particles generally contain incompletely liberated composite grains, whereas excessively fine particles are affected by entrainment phenomena, reduced settling-velocity contrasts, and lower magnetic separation selectivity (Al-Maghrabi, 2004; Kumar et al., 2016; Raghavan et al., 2006).

The efficiency of magnetic separation is also strongly influenced by particle size and magnetic field intensity. High-intensity magnetic separators are widely used to eliminate paramagnetic iron oxides and iron-bearing silicates associated with andalusite ores. Previous investigations have shown that reducing particle size enhances magnetic separation efficiency by improving the exposure of magnetic phases. However, excessively fine particles may reduce selectivity because of particle aggregation and lower magnetic force-to-gravity ratios (Na et al., 2024; Yao, 1992). Consequently, optimization of feed particle size prior to magnetic separation is essential to achieve low iron contents while preserving high alumina recovery.

Recent studies further emphasize the importance of particle size optimization in mineral processing operations. Comprehensive reviews of gravity and magnetic separation technologies have demonstrated that separation performance is jointly controlled by particle size and operating parameters such as magnetic field intensity and hydrodynamic conditions (Nzeh and Popoola, 2024a; Nzeh et al., 2024b). Investigations on conventional gravity concentration devices, including shaking tables, spiral concentrators, and Falcon concentrators, indicate that maximum separation efficiency is generally achieved within intermediate particle size ranges, typically between 141 and 245 μm (Izerdem and Ergun, 2024; Nzeh et al., 2023). Furthermore, fine particles below approximately 500 μm are particularly susceptible to entrainment losses and reduced settling velocity contrasts, leading to lower recovery efficiency (Chaurasia et al., 2025). These observations highlight the importance of identifying an optimum processing window that balances mineral liberation and separation selectivity.

The Sidi Bou Othmane andalusite deposit in central Morocco represents a promising resource for refractory and ceramic applications. Recent studies have confirmed the ceramic potential of Moroccan andalusite through the synthesis of mullite-based ceramics and preliminary beneficiation investigations using shaking table separation (Elhani et al., 2023; Tabit et al., 2022), and the continued industrial relevance of andalusite for refractory applications has been highlighted in recent global mineral commodity assessments (U.S. Geological Survey, 2025). However, quantitative relationships between

particle size, mineral liberation degree, concentrate grade, and metallurgical recovery have not yet been comprehensively established for this specific deposit (Arib et al., 2004; Elhani et al., 2023; Tabit et al., 2022), despite the general recognition of this limitation across andalusite beneficiation studies noted above.

To address this limitation, the present study provides a systematic, particle-size-resolved investigation of the beneficiation behavior of the Sidi Bou Othmane ore, with four specific objectives: (i) to quantify mineral liberation as a function of particle size over four size fractions ranging from 45 to 900 μm ; (ii) to evaluate the performance of shaking table gravity concentration for each fraction and identify the optimum particle-size window in terms of concentrate grade and metallurgical recovery; (iii) to optimize dry high-intensity magnetic separation of the best gravity concentrate by examining the effect of drum rotation speed on iron removal efficiency; and (iv) to characterize the upgraded products by X-ray diffraction (XRD) and scanning electron microscopy (SEM) in order to assess their mineralogical enrichment. By combining these elements within a single, internally consistent dataset, this study establishes a quantitative liberation–grade–recovery relationship for the Sidi Bou Othmane deposit at laboratory scale, providing a low-cost beneficiation route applicable to similar low-grade andalusite ores.

2. Materials and methods

2.1. Raw material and sample preparation

Approximately 300 kg of run-of-mine andalusite ore was collected from the near-surface zone of the Sidi Bou-Othmane deposit (central Morocco). The bulk sample was homogenized by cone-and-quarter riffing to obtain representative sub-samples. The ore was crushed below 2 mm using a jaw crusher and subsequently ground in a ceramic ball mill to a nominal top size of ~ 1 mm to minimize iron contamination. The ground material was wet-sieved into four particle-size fractions: 600–900, 355–600, 150–355 and 45–150 μm . Approximately 10 kg of material from each fraction was used for beneficiation tests. Particles finer than 45 μm were removed by controlled desliming prior to processing to limit the adverse effects of ultrafine material on gravity separation performance.

2.2. Characterization methods

Chemical composition was determined by X-ray fluorescence (XRF) analysis. Mineralogical characterization was performed by X-ray diffraction (XRD) using $\text{CuK}\alpha$ radiation at 40 kV and 30 mA, over a 2θ range of $10\text{--}70^\circ$ with a step size of 0.02° and a counting time of 2 s per step. Phase identification was performed by comparison with reference powder diffraction files from the International Centre for Diffraction Data (ICDD Powder Diffraction File, PDF), using PDF #83-1510 for andalusite, consistent with the reference card used for the same deposit in our previous study (Elhani et al., 2023), and the widely used reference PDF #00-046-1045 for the low-quartz ($\alpha\text{-SiO}_2$) structure.

Mineral liberation and phase associations were evaluated by optical microscopy using an Olympus BH2-UMA stereoscopic and reflected-light microscope on polished grain mounts prepared from each particle-size fraction. For each fraction, the polished section was examined following a systematic raster pattern to avoid preferential field selection. A total of 20 fields of view were analyzed at a magnification of $100\times$, corresponding to the examination of approximately 500 andalusite-bearing grains per size fraction.

A transparent point-counting grid was superimposed on each reflected-light micrograph, and each andalusite grain intersected by the grid was classified according to its liberation state. A grain was considered liberated when more than 90% of its exposed cross-sectional area consisted of andalusite, whereas grains containing more than 10% of associated quartz, hematite or muscovite were classified as locked (composite). The degree of liberation was calculated as the percentage of liberated andalusite grains relative to the total number of andalusite-bearing grains counted.

Scanning electron microscopy (SEM) with secondary-electron imaging was performed directly on grains of the upgraded andalusite concentrate (150–355 μm fraction, after magnetic separation), mounted for observation without any thermal treatment, to evaluate particle morphology and residual gangue association.

2.3. Beneficiation procedures

Gravity concentration was performed using a laboratory Wilfley shaking table (fiberglass deck 45.72 cm × 1.016 m; capacity 68 kg h⁻¹). Operating parameters were optimized as follows: water flow rate 12 L/min, pulp density 40 wt.%, deck inclination 12°, vibration amplitude 15 mm, shaking speed 470 rpm. Shaking table tests were performed in five replicate trials for each particle-size fraction. Reported Al₂O₃ grade and recovery values correspond to the mean of these five replicates and the associated standard deviations are reported in Table 3.

Metallurgical recovery was calculated on a dry mass basis using the standard two-product formula:

$$R (\%) = (C \times c) / (F \times f) \times 100 \quad (1)$$

where F and C are the dry masses of the feed and concentrate, respectively, and f and c are the corresponding Al₂O₃ grades of the feed and concentrate.

The gravity concentrate from the optimal size fraction was subsequently upgraded by dry high-intensity magnetic separation at a field strength of up to 1.5 T. Drum rotation speed was varied over four levels: 400, 300, 200 and 100 rpm (denoted Mag 1 to Mag 4, respectively), while maintaining a constant blade inclination angle of 70° and an excitation current of 4.8 A, in order to evaluate the effect of particle residence time in the magnetic field on iron removal efficiency. At each drum rotation speed, three independent magnetic separation trials were performed, and each resulting product was analyzed by XRF. Reported Fe₂O₃ and Al₂O₃ contents correspond to the mean of these replicates, with standard deviations given in Table 5.

Statistical significance among particle-size fractions (Al₂O₃ grade and recovery) and among drum rotation speeds (Fe₂O₃ and Al₂O₃ content) was assessed by one-way analysis of variance (ANOVA), followed by Tukey's honestly significant difference (HSD) post-hoc test for pairwise comparisons, using a significance threshold of $\alpha = 0.05$.

3. Results and discussion

3.1. Particle size distribution and chemical characterization of the feed

The particle size distribution of the run-of-mine andalusite ore, obtained by dry sieve analysis, is presented in Fig. 1. The results indicate a median particle size (d₅₀) of approximately 250 μm and a d₈₀ value of approximately 600 μm, while particles finer than 45 μm account for 16.52 wt.% of the total mass. This relatively high proportion of fines suggests that excessive grinding may lead to increased slime generation, which can negatively affect subsequent gravity separation efficiency.

The chemical composition of the raw ore and of the four particle-size fractions is given in Table 1. The bulk ore contains 20.73 wt.% Al₂O₃, 59.85 wt.% SiO₂ and 6.21 wt.% Fe₂O₃, confirming the necessity

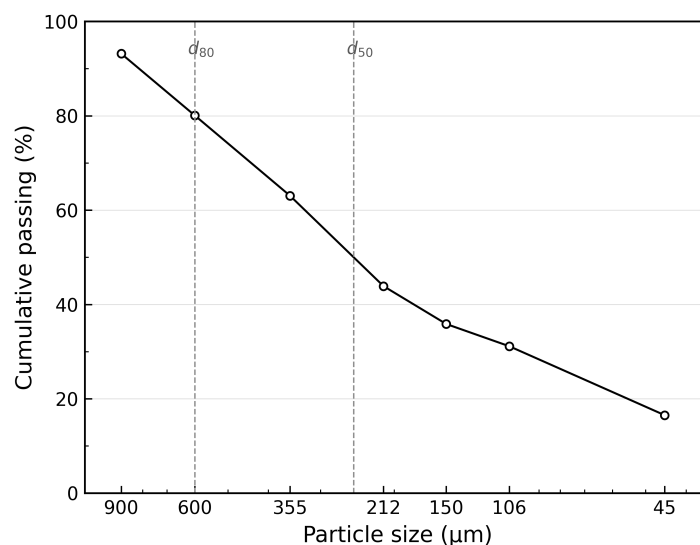


Fig. 1. Particle size distribution of the andalusite ore, based on dry sieve analysis (nominal sieve apertures: 900, 600, 355, 212, 150, 106 and 45 μm)

of beneficiation before industrial use. Across the four size fractions, Al_2O_3 content increases progressively with decreasing particle size, from 20.18 wt.% in the 600–900 μm fraction to 21.18 wt.% in the 45–150 μm fraction, while Fe_2O_3 content correspondingly decreases from 6.05 to 5.64 wt.%. This trend is consistent with the preferential liberation of iron-bearing gangue minerals from andalusite at finer particle sizes, in agreement with the liberation degrees reported in Table 2.

Table 1. Chemical composition of the andalusite ore and of the four particle-size fractions (wt.%)

Particle-size fraction	SiO_2	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	MnO	Na_2O	P_2O_5	TiO_2
Raw ore	59.85	20.73	0.53	6.21	2.73	0.99	0.16	<0.01	<0.01	1.00
600–900 μm	59.97	20.18	0.61	6.05	1.96	0.94	0.15	<0.01	<0.01	0.90
355–600 μm	59.64	20.45	0.53	6.16	1.84	0.91	0.16	<0.01	<0.01	0.91
150–355 μm	60.32	21.02	0.45	5.87	1.95	0.94	0.15	<0.01	<0.01	0.89
45–150 μm	61.13	21.18	0.39	5.64	1.70	0.92	0.14	<0.01	<0.01	0.76

3.2. Mineral liberation analysis

Microscopic examinations were carried out on the four size fractions (600–900, 355–600, 150–355 and 45–150 μm). Stereoscopic and reflected-light microscopy revealed a strong dependence of mineral liberation on particle size, as shown in Fig. 2.

For the coarsest fraction (600–900 μm), the degree of liberation of andalusite grains was low, with andalusite particles largely locked with quartz and hematite. In the 355–600 μm fraction, liberation improved slightly; however, a significant proportion of andalusite grains remained partially associated with hematite. A marked increase in liberation was observed for the 150–355 μm fraction, indicating that grinding to this size range effectively promotes mineral separation. In the finest fraction (45–150 μm), most andalusite grains were fully liberated, and iron-bearing minerals were predominantly present as free particles.

Prior to further processing, particles finer than 45 μm were removed by controlled desliming to limit the adverse effects of ultrafine material on gravity separation performance.

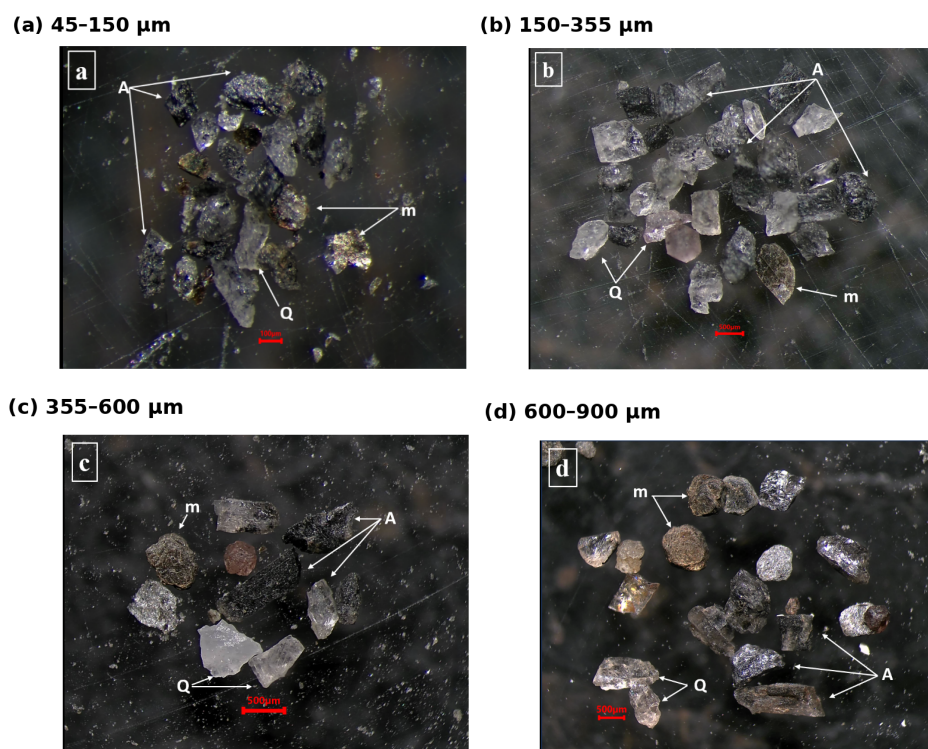


Fig. 2. Reflected-light optical micrographs of the four particle-size fractions: (a) 45–150 μm , (b) 150–355 μm (optimal fraction), (c) 355–600 μm and (d) 600–900 μm . A: andalusite; Q: quartz; M: muscovite; H: hematite. Scale bars: 200 μm

Using the point-counting procedure, the liberation degree increased progressively with decreasing particle size, from approximately 61% for the 600–900 μm fraction to 76% for the 355–600 μm fraction, 83% for the 150–355 μm fraction, and 92% for the 45–150 μm fraction (Table 2). These observations are consistent with the progressive release of andalusite from quartz and iron-bearing gangue minerals during comminution, explaining the improved beneficiation performance obtained for the 150–355 μm size fraction.

Table 2. Degree of liberation (free state) of andalusite for the four size fractions

No.	Particle-size fraction (μm)	Liberation degree (%)
1	600–900	61
2	355–600	76
3	150–355 (optimal)	83
4	45–150	92

3.3. Effect of particle size on shaking table performance

The shaking table results clearly demonstrate the strong influence of particle size on both concentrate grade and recovery of andalusite. Reported Al_2O_3 grade and recovery values (mean $\pm$ SD, $n = 5$) are summarized in Table 3. The one-way ANOVA demonstrated statistically significant differences in Al_2O_3 grade and recovery among the investigated particle-size fractions ($F(3,16) = 8333$, $p < 0.001$ and $F(3,16) = 56910$, $p < 0.001$, respectively), indicating that the observed differences among particle-size fractions were statistically significant.

Table 3. Liberation degree, Al_2O_3 grade and Al_2O_3 recovery (mean $\pm$ standard deviation, $n = 5$) for each particle-size fraction

Particle-size fraction (μm)	Liberation degree (%)	Al_2O_3 grade (wt.%), mean $\pm$ SD (n=5)	Al_2O_3 recovery (%), mean $\pm$ SD (n=5)
600–900	61	27.54 ± 0.11 a	70.80 ± 0.16 a
355–600	76	29.58 ± 0.16 b	82.52 ± 0.35 b
150–355 (optimal)	83	38.02 ± 0.15 c	78.30 ± 0.31 c
45–150	92	41.34 ± 0.21 d	21.90 ± 0.24 d

Means within a column not sharing a letter are significantly different (Tukey's HSD, $p < 0.001$)

The finest fraction (45–150 μm) yields the highest Al_2O_3 grade (41.34 ± 0.21 wt.%), consistent with its high liberation degree (92%, Table 3). However, this fraction exhibits a markedly lower recovery ($21.90 \pm 0.24\%$), which is attributed to poor stratification and excessive entrainment of fine particles (slimes) during shaking table operation. This behavior is consistent with basic gravity-separation hydrodynamics: because the terminal settling velocity of a particle scales approximately with the square of its diameter under Stokes' regime, the differential settling-velocity contrast between andalusite and lighter gangue particles decreases sharply below approximately 150 μm . Under these conditions, fine particles of both phases are increasingly transported together within the thin film flow on the deck, so that valuable andalusite fines are entrained into the tailings irrespective of their density, which explains the loss of recovery despite the high liberation degree of this fraction.

The 150–355 μm fraction presents the most balanced metallurgical performance, producing a concentrate grading 38.02 ± 0.15 wt.% Al_2O_3 with a high recovery of $78.30 \pm 0.31\%$. This size range corresponds to an optimal compromise between sufficient mineral liberation (83%, Table 3) and favorable gravity separation conditions, in which the settling-velocity contrast between andalusite and gangue remains large enough to allow effective stratification on the deck.

For the coarser fractions, a progressive decrease in Al_2O_3 grade is observed. The 355–600 μm fraction shows a relatively high recovery ($82.52 \pm 0.35\%$) but a low Al_2O_3 content ($29.58 \pm 0.16\%$), consistent with a significant proportion of locked (composite) particles at this size (liberation degree of only 76%, Table 3) and consequent gangue dilution of the concentrate. In the coarsest fraction (600–900 μm), both grade

and recovery decline further (27.54 ± 0.11 wt.% Al_2O_3 , $70.80 \pm 0.16\%$ recovery), reflecting the low liberation degree (61%, Table 3) and reduced separation selectivity of largely composite particles. Overall, these results confirm that particle size plays a critical role in andalusite beneficiation by shaking table, and identify the 150–355 μm fraction as the optimal size range for this ore, as illustrated in Fig. 3.

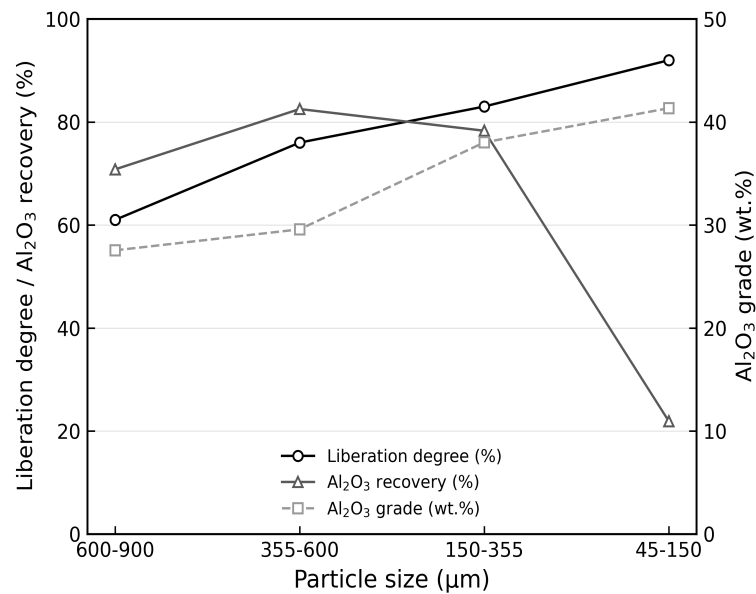


Fig. 3. Shaking table concentration results (liberation degree, Al_2O_3 grade and recovery) for each particle-size fraction (data from Table 3)

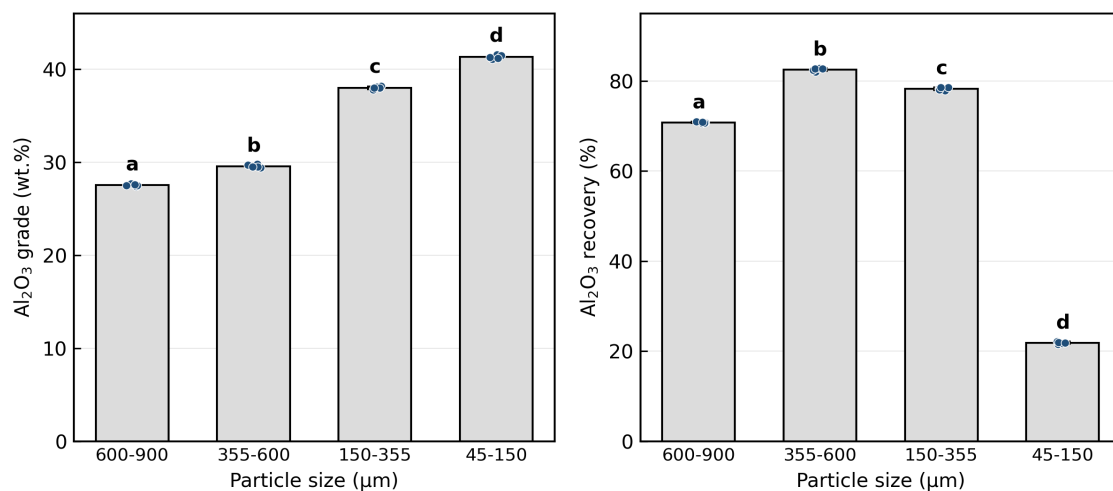


Fig. 4. Al_2O_3 grade (a) and recovery (b) by particle-size fraction (mean $\pm$ SD, $n = 5$). Different letters denote significant differences (Tukey's HSD, $p < 0.001$)

As shown by the significance analysis in Fig. 4, the Al_2O_3 grade of the shaking table concentrate obtained in the present study (38.02 wt.%) is consistent with the concentrate composition previously reported for the same deposit (38.46 wt.% Al_2O_3 at 80% recovery). This composition indicates potential relevance to refractory applications. In this context, the obtained concentrate represents an upgraded alumina-rich product that may serve as a suitable feedstock for further evaluation and upgrading toward refractory applications. This Al_2O_3 content remains below the higher alumina levels (>45 wt.%) reported for premium high-alumina refractory products (Namiranian and Kalantar, 2014; Niu et al., 2019), suggesting that additional beneficiation may be required where such compositions are targeted. Potential approaches include regrinding and reprocessing of the middlings, an additional gravity or flotation cleaning stage to further reject residual quartz and mica, or integrated gravity-flotation-

magnetic flowsheets, as reported for related aluminosilicate ores (Ajaka et al., 2015; Amanullah et al., 1990; Brandão and Mendes, 1998; Gogou et al., 2022; Nekipelova et al., 2023; Niu et al., 2019; Zhu et al., 2015). These results provide a basis for considering further process development aimed at increasing the alumina grade and improving the removal of residual quartz- and mica-bearing gangue. Fig. 5 presents a conceptual flowsheet combining the beneficiation stages investigated in this study with potential additional upgrading steps.

The chemical composition of the gravity concentrate from the 150–355 μm fraction is presented in Table 4. Al_2O_3 increased from 20.73 wt.% in the feed to 38.03 wt.%, while Fe_2O_3 was reduced to 5.80 wt.%. Residual SiO_2 (47.20 wt.%) reflects the presence of unliberated quartz, and K_2O (1.15 wt.%) indicates minor mica retention.

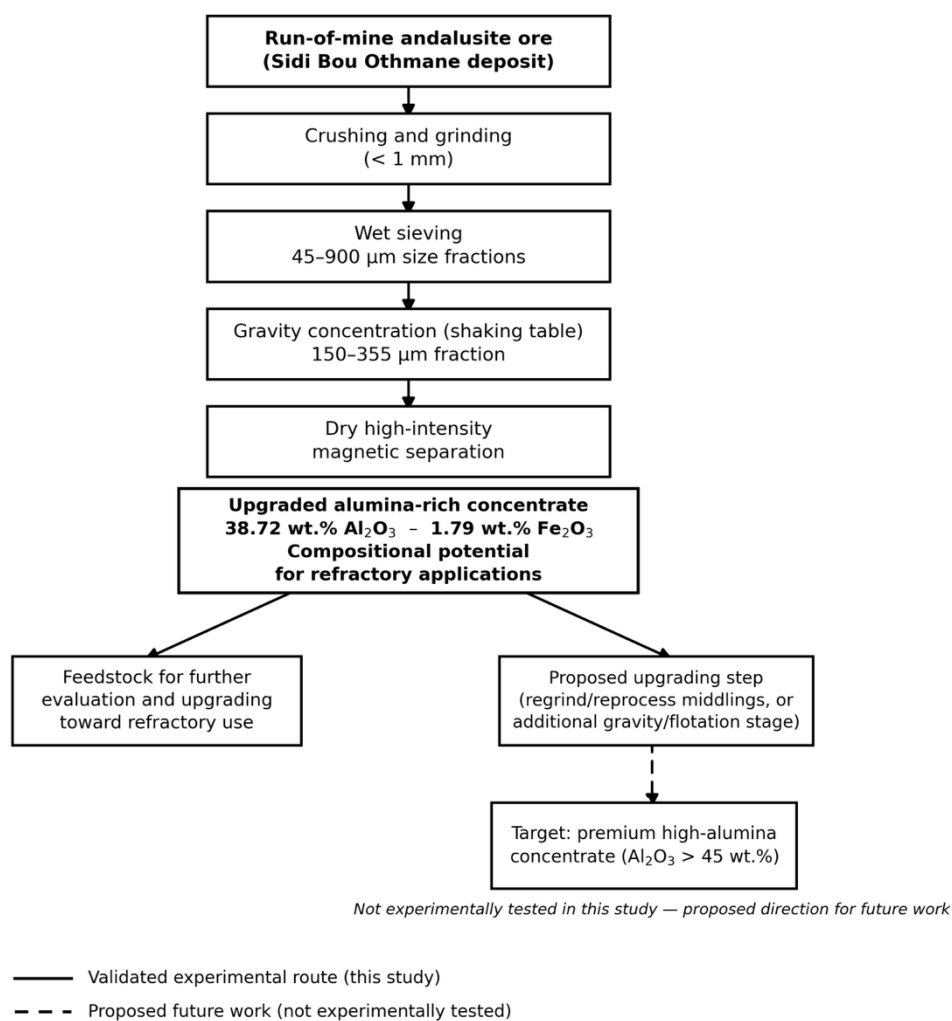


Fig. 5. Proposed beneficiation flow sheet for the Sidi Bou Othmane andalusite ore

Table 4. Chemical composition of the gravity concentrate (150–355 μm fraction)

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	TiO_2	L.O.I
47.20	38.03	5.80	0.40	0.45	1.15	0.65	1.90

XRD analysis (Fig. 6) confirms the mineralogical basis of this separation: the concentrate is dominated by strong andalusite reflections, whereas the tailings show a higher relative contribution of quartz-associated silicate gangue phases. Minor muscovite reflections (labeled m) are present in both patterns, consistent with the residual mica-rich gangue identified by optical microscopy and SEM. This mineralogical contrast validates gravity separation as an effective pre-concentration step prior to magnetic cleaning.

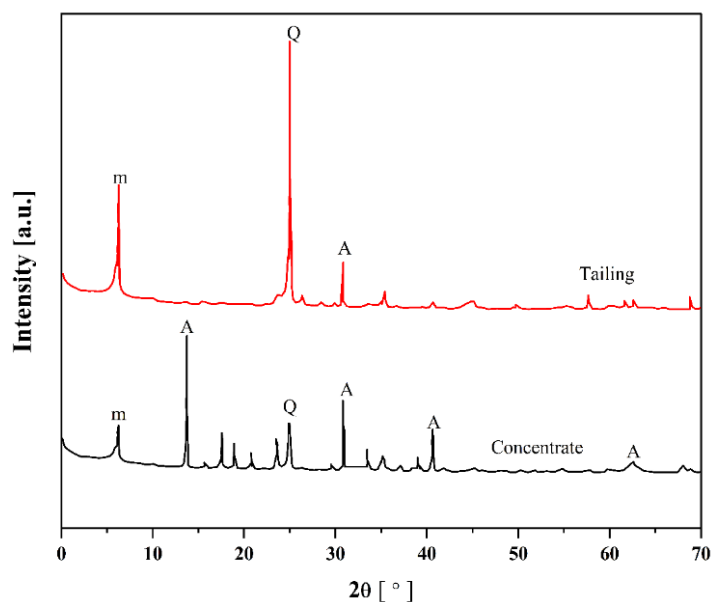


Fig. 6. XRD patterns of the gravity concentrate and the tailings from the 150–355 μm fraction: A, andalusite (PDF #83-1510); Q, quartz (PDF #00-046-1045); m, muscovite (PDF #01-082-2450)

3.4. Upgrading by high-intensity magnetic separation

The gravity concentrate obtained from the optimal 150–355 μm fraction was subjected to dry high-intensity magnetic separation to reduce iron-bearing impurities and improve alumina grade. Magnetic separation was performed at four drum rotation speeds (400, 300, 200 and 100 rpm; Mag 1 to Mag 4) under constant operating conditions, including a blade inclination angle of 70° and an electric current of 4.8 A.

The results of the magnetic separation tests, expressed as mean $\pm$ standard deviation of the three independent trials performed at each drum rotation speed, are summarized in Table 5 and Fig. 7.

Table 5. Evolution of Fe_2O_3 and Al_2O_3 content of the concentrate during dry high-intensity magnetic separation, as a function of drum rotation speed.

Test	Drum speed (rpm)	Fe_2O_3 (wt.%), mean $\pm$ SD (n=3)	Al_2O_3 (wt.%), mean $\pm$ SD (n=3)
Feed (gravity concentrate)	-	5.80 ± 0.04 a	38.03 ± 0.06 a
Mag 1	400	4.75 ± 0.04 b	38.16 ± 0.04 b
Mag 2	300	3.61 ± 0.03 c	38.31 ± 0.04 c
Mag 3	200	2.50 ± 0.04 d	38.52 ± 0.03 d
Mag 4 (final concentrate)	100	1.79 ± 0.03 e	38.72 ± 0.03 e

Means within a column not sharing a letter are significantly different (Tukey's HSD, $p < 0.001$)

The initial Fe_2O_3 content of the gravity concentrate was 5.80 ± 0.04 wt.% with an Al_2O_3 grade of 38.03 ± 0.06 wt.%. Decreasing drum rotation speed progressively enhanced iron removal, from 4.75 ± 0.04 wt.% Fe_2O_3 at 400 rpm (Mag 1) to 1.79 ± 0.03 wt.% Fe_2O_3 at 100 rpm (Mag 4), while Al_2O_3 grade increased correspondingly from 38.16 ± 0.04 to 38.72 ± 0.03 wt.%. This clear, monotonic trend of decreasing Fe_2O_3 content and increasing Al_2O_3 grade with decreasing drum rotation speed reflects the selective removal of iron-rich gangue minerals with increasing residence time of particles in the magnetic field. These results confirm that magnetic separation effectively upgrades the gravity concentrate by significantly reducing iron impurities without substantial loss of alumina-bearing phases. The one-way analysis of variance (ANOVA) confirmed that both Fe_2O_3 and Al_2O_3 contents differed significantly across the five drum-speed conditions ($F(4,10) = 7114$, $p < 0.001$ and $F(4,10) = 133$, $p < 0.001$, respectively), indicating that the observed differences among drum-speed conditions were statistically significant, as illustrated in Fig. 8.

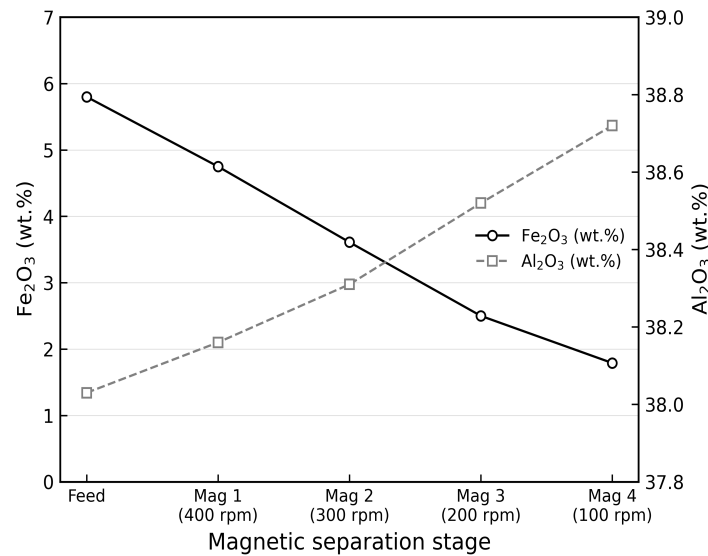


Fig. 7. Evolution of Fe₂O₃ and Al₂O₃ content during dry high-intensity magnetic upgrading of the optimum gravity concentrate (150–355 μ m)

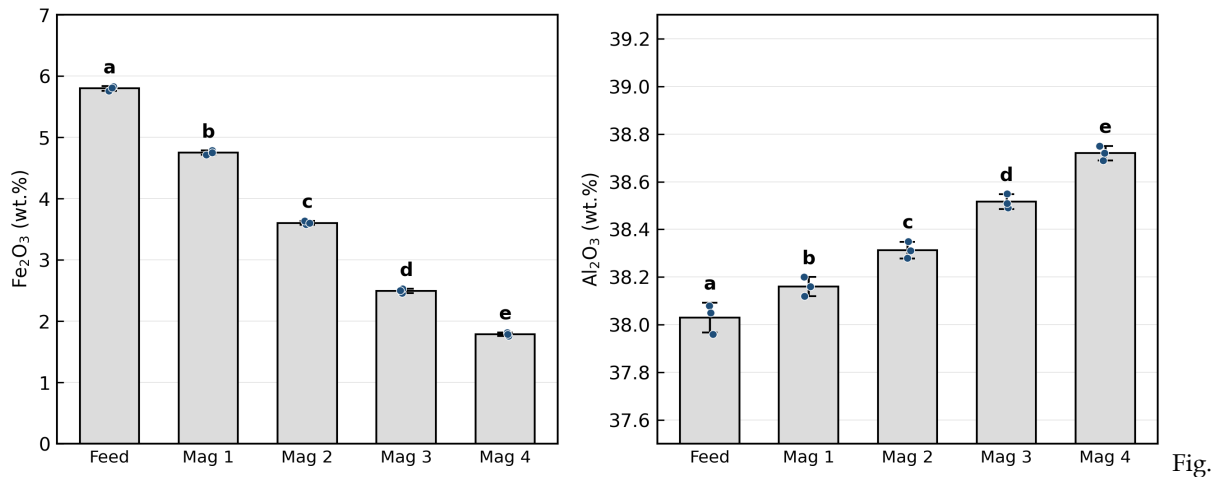


Fig. 8. Fe₂O₃ (a) and Al₂O₃ (b) content by magnetic separation stage (mean $\pm$ SD, $n = 3$). Different letters denote significant differences (Tukey's HSD, $p < 0.001$)

3.5. Microstructural characterization of the upgraded concentrate

Scanning electron microscopy (SEM) with secondary-electron imaging was performed directly on grains of the upgraded andalusite concentrate (150–355 μ m fraction, after magnetic separation). The micrographs presented in Fig. 9 therefore correspond to the raw beneficiated concentrate, examined at increasing magnification.

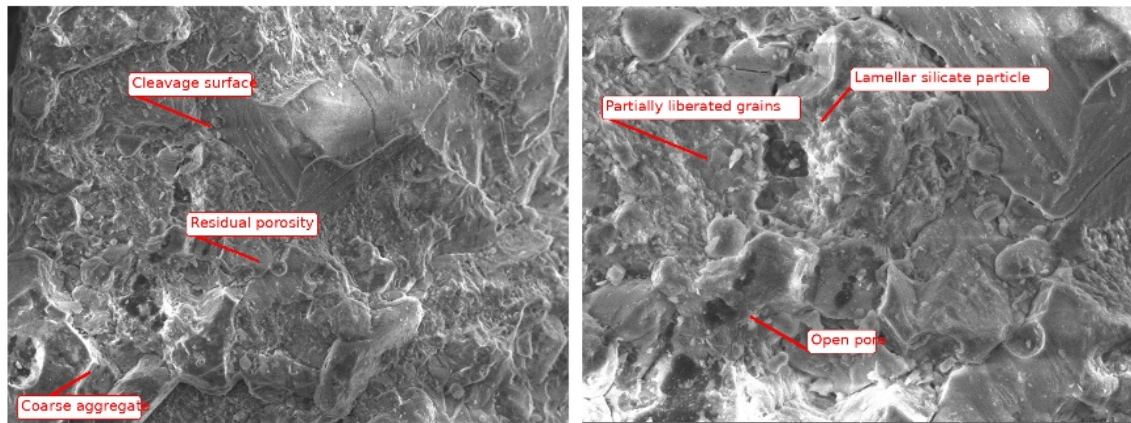
The low-magnification image (Fig. 9a) shows a heterogeneous assemblage of angular and sub-angular grains of variable size, separated by interparticle voids resulting from the packing of loose particles. Cleavage surfaces and fractured grain edges are clearly visible, reflecting the mechanical breakage of the ore during crushing and grinding, and indicating a well-liberated particle population consistent with the high liberation degree measured for this fraction (83%, Table 3). The intermediate-magnification image (Fig. 9b) reveals partially liberated grains in contact with lamellar particles, likely corresponding to residual mica-rich gangue (muscovite/biotite), consistent with the XRD results; fine attached particles and open pores remain locally distributed between grains, indicating incomplete separation of some fine gangue from andalusite surfaces despite beneficiation. This residual gangue association is consistent with the K₂O content (1.15 wt.%, Table 4) still present in the concentrate. The high-magnification image (Fig. 9c) highlights rough, irregular particle surfaces with fracture-related

features and fine particle attachments generated during grinding, reflecting the mechanical nature of the size-reduction process applied to the ore.

Overall, these SEM observations confirm the presence of angular, largely liberated andalusite grains with limited residual gangue attachment, in good agreement with the XRD and XRF results. They do not, by themselves, provide direct evidence regarding the ceramic or refractory behavior of the concentrate upon firing; assessing such behavior would require a dedicated sintering study (firing at several temperatures, densification and shrinkage measurements, refractoriness-under-load and thermal-shock testing), which is proposed here as a direction for future work.

(a) General morphology ($\times 2000$)

(b) Particle morphology ($\times 5000$)



(c) Surface texture ($\times 10000$)

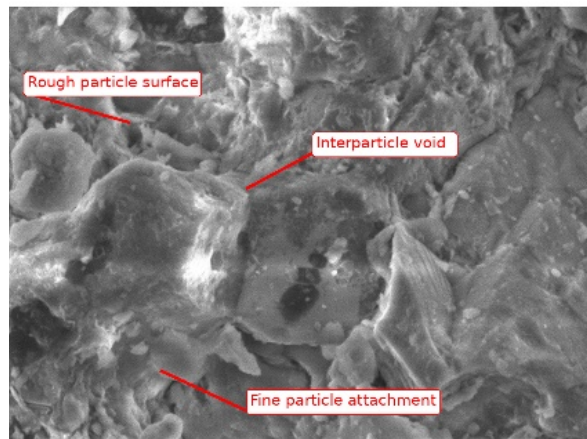


Fig. 9. SEM micrographs of the upgraded andalusite concentrate (150–355 μm fraction): (a) low magnification, (b) intermediate magnification, (c) high magnification

4. Conclusions

Particle size strongly influenced the beneficiation performance of the Sidi Bou Othmane andalusite ore by controlling mineral liberation, separation selectivity and metallurgical recovery. Liberation degree progressively increased from 61% for the 600–900 μm fraction to 92% for the 45–150 μm fraction; however, excessive fineness reduced shaking table efficiency owing to ultrafine-particle entrainment. Among the investigated fractions, the 150–355 μm size range provided the best metallurgical performance, producing a gravity concentrate containing 38.03 wt.% Al_2O_3 at 78.30% recovery. Subsequent dry high-intensity magnetic separation further upgraded the concentrate, reducing Fe_2O_3 from 5.80 to 1.79 wt.% while increasing Al_2O_3 to 38.72 wt.%. XRD analysis confirmed andalusite enrichment and selective gangue rejection, while SEM observations of the upgraded concentrate revealed angular, largely liberated andalusite grains with limited residual gangue attachment, consistent with the mineral liberation determined by optical microscopy; the corresponding reduction in Fe_2O_3 content was independently confirmed by XRF analysis. The final Al_2O_3 content of 38.72 wt.%

indicates effective alumina upgrading through the combined gravity-magnetic beneficiation route. The substantial decrease in Fe_2O_3 further demonstrates the improvement in the chemical quality of the beneficiated concentrate. Overall, the results establish the potential of the proposed beneficiation flowsheet to produce an alumina-enriched and iron-depleted andalusite concentrate. Where higher Al_2O_3 grades are required for specific refractory applications, additional upgrading stages may be considered; however, the suitability of the resulting concentrate for refractory use would require dedicated thermal, mechanical, and high-temperature performance testing.

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