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The effect of collectors on the flotation of diaspore ore and importance in modelling

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Abstract: The removal of calcium-bearing gangue minerals from diasporic bauxite is essential for improving feed quality for the Bayer process. In this study, the effects of particle size, collector type, and surface electrokinetic properties on the reverse flotation of calcium-bearing minerals from low-grade diasporic bauxite were investigated. A diasporic bauxite ore from the Morçukur deposit in Seydişehir, Türkiye, was characterized by Mineral Liberation Analysis (MLA), and zeta potential measurements were performed over a wide pH range for different particle-size fractions and collector conditions. Reverse flotation experiments were conducted using sodium oleate (NaOl) and sodium lauryl sulfate (SLS) at different collector dosages and particle sizes. The results showed that particle size strongly influenced mineral liberation, surface charge, collector adsorption, and flotation selectivity. Zeta potential measurements indicated more favorable electrokinetic conditions for reverse flotation at acidic pH values, particularly at pH ≤ 7. Among the investigated particle-size fractions, the −75+53 µm fraction exhibited the most favorable flotation response, indicating improved liberation of calcium-bearing minerals. Under the experimental conditions, SLS showed superior flotation selectivity and promoted the removal of calcium-bearing minerals, whereas NaOl provided a better statistical fit in the nonlinear regression analysis. The NaOl model yielded an R^2 of 0.95 and an RMSE of 5.35, compared with R^2 = 0.89 and RMSE = 9.23 for SLS. Conversely, SLS produced a lower MAE (2.22) than NaOl (3.88), indicating smaller average prediction errors. The results demonstrate that electrokinetic characterization combined with particle-size optimization and collector selection can improve the selective removal of calcium-bearing gangue minerals from diasporic bauxite. The findings also highlight the importance of distinguishing between flotation performance and statistical model performance when evaluating collector effectiveness.

Keywords: aluminum, diaspore, calcium, flotation, zeta potential, collector, modeling

1. Introduction

Flotation is one of the most widely employed mineral beneficiation techniques, relying on differences in the physicochemical properties of mineral surfaces to achieve selective separation. Among the factors governing flotation efficiency, the electrical characteristics of mineral surfaces play a crucial role because they directly influence the adsorption behavior of collectors and other flotation reagents. In this context, zeta potential has become a fundamental parameter for investigating the electrokinetic properties of mineral particles. It is defined as the electrical potential at the slipping plane within the electrical double layer surrounding a particle suspended in a liquid medium and serves as an important indicator of surface charge characteristics (Somasundaran, 1975).

Determining zeta potential provides valuable information on mineral surface charge, isoelectric point (IEP), reagent adsorption mechanisms, and the influence of dissolved ionic species on interfacial phenomena. Consequently, zeta potential measurements are frequently integrated with complementary analytical techniques such as micro-flotation experiments, Fourier Transform Infrared Spectroscopy (FTIR), and X-ray Photoelectron Spectroscopy (XPS) to obtain a comprehensive understanding of flotation mechanisms and mineral–reagent interactions (Fuerstenau, 2005).

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Beyond surface chemistry investigations, zeta potential strongly affects the stability of mineral suspensions. The magnitude of surface charge determines the degree of electrostatic repulsion between particles, influencing dispersion, aggregation, and flocculation. These interactions can significantly affect bubble-particle attachment efficiency and, consequently, flotation performance.

Diaspore [AlO(OH)] constitutes one of the principal aluminum-bearing minerals in diasporic bauxite deposits. In natural bauxite ores, diaspore commonly occurs with clay minerals such as kaolinite, illite, chlorite, and pyrophyllite, along with various calcium-bearing gangue minerals. The successful flotation separation of diaspore from these associated minerals therefore requires a detailed understanding of their surface chemical and electrokinetic properties (Gibson et al., 2017).

Previous electrokinetic investigations have revealed considerable differences in the surface behavior of diaspore and its accompanying gangue minerals. Reported studies indicate that the isoelectric point of diaspore generally falls within the pH range of 6–7. Variations in pH alter the surface charge characteristics of mineral particles, thereby influencing reagent adsorption and flotation selectivity. Understanding these surface charge modifications is essential for optimizing flotation conditions and improving mineral separation efficiency (Yu et al., 2016; Deng et al., 2015; Jiang et al., 2010).

Removing calcium-bearing minerals from bauxite ores is a critical step in alumina production because calcium impurities adversely affect downstream processing, particularly in the Bayer process. In flotation systems designed to selectively remove calcite and dolomite from diasporic bauxite, zeta potential measurements provide direct evidence of collector adsorption and surface charge modification. However, zeta potential is not controlled solely by solution chemistry and pH; particle size, specific surface area, and collector type also influence it significantly. Therefore, evaluating the combined effects of these parameters is essential for understanding flotation selectivity in complex mineral systems.

Particle size strongly influences the electrokinetic behavior of mineral particles. As particle size decreases, specific surface area increases substantially, resulting in more active surface area and enhanced surface reactivity. Fine particles typically exhibit higher surface charge densities due to the increased presence of unsatisfied surface bonds and reactive sites. Consequently, larger absolute zeta potential values are often observed for finer particle fractions. This enhanced surface charge may promote collector adsorption and strengthen electrostatic interactions during flotation. Nevertheless, excessively fine particles frequently display colloidal characteristics and extensive hydration layers, which can hinder bubble-particle attachment and reduce flotation selectivity. In contrast, intermediate particle size fractions often provide more favorable conditions for selective separation due to a balanced combination of surface charge effects and bubble-particle interaction efficiency. Therefore, evaluating zeta potential as a function of particle size can provide valuable information for determining the optimum flotation size range for diaspore–calcite separation (Massola et al., 2009).

A comprehensive understanding of mineral surface chemistry is indispensable for the successful flotation beneficiation of diasporic bauxite ores. Numerous studies have demonstrated that zeta potential measurements are highly effective in characterizing mineral surface charge, identifying isoelectric points, evaluating reagent adsorption behavior, and assessing the influence of dissolved ions. Consequently, electrokinetic analyses have become an essential component of flotation research involving both diaspore and calcium-bearing minerals (Starov, 2010).

In this study, zeta potential measurements were performed on mineral samples of different particle size fractions to determine suitable flotation conditions for the removal of calcium-bearing minerals that negatively affect the Bayer process. Furthermore, the adsorption behavior of various collector reagents, including NaOl, sodium lauryl sulphate (SLS), sodium dodecyl sulphate (SDS), dodecylamine hydrochloride (DAH), and isodecyloxypropylamine (Lilaflot® 811 M), were investigated through electrokinetic measurements. The results provide valuable information on the flotation behavior of calcium-bearing minerals and contribute to developing more effective beneficiation strategies for diasporic bauxite ores. Based on the data obtained, flotation studies for NaOl and SLS were carried out for different particle sizes. Five collectors were initially evaluated through adsorption experiments to study their interactions with mineral surfaces. A preliminary flotation experiment was conducted for all collectors, and the two most suitable collectors were selected to compare the properties of the resulting products; experiments were then continued with these two collectors. The use of these two

collectors enabled a comparative evaluation of fatty acid-type and sulphate-type anionic collectors, while also allowing for the systematic investigation of the effects of collector dosage and particle size within a manageable experimental matrix. In this context, a model was developed using the nonlinear regression method for both collector types, and the results are presented comparatively.

2. Materials and methods

Low-grade diasporic bauxite ore obtained from the Morçukur deposit located in the Seydişehir (Konya/Türkiye) district and operated by ETİ Aluminum Inc. was utilized as the experimental material in this study. Following sample preparation, the ore was subjected to size classification using ASTM E11 standard sieves to produce six distinct particle size fractions: −212+106 µm, −106+75 µm, -75+53 µm, −53+38 µm, and −53 µm.

Detailed mineralogical characterization of each size fraction was conducted using Mineral Liberation Analysis (MLA). MLA is an advanced automated process mineralogy technique that combines scanning electron microscopy (SEM), backscattered electron (BSE) imaging, and energy-dispersive X-ray spectroscopy (EDS) to provide comprehensive mineralogical information (Gürsoy et al., 2026). This integrated methodology enables rapid, statistically reliable determination of mineral composition, particle size distribution, liberation degree, mineral associations, and textural characteristics in complex ore systems. The application of MLA facilitates a thorough understanding of the mineralogical behavior of the bauxite ore across different particle size ranges and provides essential information for evaluating beneficiation performance and optimizing subsequent flotation processes. described.

Table 1. MLA analytical data for brecciated bauxite ore from the Morçukur deposit across specified particle size fractions

Particle size (µm)	Bohmite AlO(OH) %	Diaspore AlO(OH) %	Gibbsite $Al(OH)_3$ %	Kaolinite $Al_2Si_2O_5(OH)_4$ %	Tridymite SiO_2 %	Quartz SiO_2 %	Hematite Fe_2O_3 %	Goethite FeO(OH) %	Rutile TiO_2 %	Anatase TiO_2 %	Calcite $CaCO_3$ %
-212+106	5.17	15.63	1.53	1.67	0.57	0.34	5.89	1.24	0.17	0.41	58.05
-106+75	4.71	21.43	0.58	2.85	0.64	0.21	7.64	1.27	0.32	0.45	51.68
-75+53	1.50	12.16	1.78	2.38	1.56	0.44	10.37	1.36	0.23	0.79	67.32
-53+38	2.39	16.46	1.67	2.87	0.94	0.07	8.47	0.76	0.34	0.42	56.93
-38	4.17	13.53	1.10	2.09	0.85	0.35	7.74	1.27	0.17	0.56	58.30

The mineralogical composition presented in Table 1 indicates that the investigated diasporic bauxite is characterized by a complex assemblage of aluminum-, silica-, calcium-, iron-, and titanium-bearing minerals. Although calcite is present in relatively high proportions and represents an important target for reverse flotation, silica-bearing minerals are of particular importance with respect to Bayer-process suitability. Quartz, tridymite, and kaolinite were identified in all investigated size fractions, although their relative proportions varied with particle size. These minerals constitute the principal sources of SiO_2 in the ore and may adversely affect the Bayer process, particularly when silica is present in reactive forms.

The Fe- and Ti-bearing minerals identified by MLA, mainly hematite, goethite, rutile, and anatase, should also be considered as undesirable mineral constituents from the perspective of bauxite quality. Their presence contributes to the overall impurity assemblage and may influence the chemical composition and processing behavior of the bauxite. Therefore, evaluation of the ore quality should not be based solely on the abundance of calcium-bearing minerals but should consider the combined distribution of Si-, Fe-, Ti-, and Ca-bearing phases.

The Al_2O_3/SiO_2 ratio, commonly referred to as the silica modulus, is an important parameter for assessing the suitability of bauxite as Bayer-process feed. Higher silica modulus values generally indicate a more favorable feed quality, whereas increasing silica content increases the potential for alkali consumption and associated processing problems. Accordingly, the removal of silica-bearing gangue minerals is an important objective of bauxite beneficiation. In the present study, the flotation

experiments were therefore evaluated not only in terms of CaO removal but also in terms of changes in Al_2O_3 and SiO_2 contents and the resulting silica modulus.

Calcite deserves particular attention because of its relatively high abundance in the investigated ore. The high calcite content indicates that carbonate-bearing gangue constitutes a major component of the studied material. From a flotation perspective, this provides a strong basis for targeting calcite removal through reverse flotation. However, the present mineralogical data alone do not provide sufficient evidence to establish whether the elevated calcite content is specifically associated with a karstic trap or the peripheral part of the deposit. Such a geological interpretation would require deposit-scale geological and spatial information. Therefore, in the present study, the high calcite abundance is interpreted primarily in terms of its implications for beneficiation and Bayer-process feed quality.

2.1. Methods

Zeta potential is defined as the electrical potential generated by the surface charge of a particle and the surrounding counter-ions constituting the electrical double layer (EDL). The determination of zeta potential provides valuable information regarding particle–particle interactions, including dispersion, aggregation, and flocculation mechanisms, which are essential for understanding the stability and behavior of colloidal systems. Consequently, zeta potential measurements are widely employed in numerous scientific and industrial fields, including mineral processing, pharmaceuticals, food technology, and environmental engineering.

The magnitude of zeta potential indicates the stability of colloidal suspensions. Particles exhibiting high positive or negative zeta potential values experience strong electrostatic repulsive forces, thereby promoting suspension stability and preventing aggregation. In contrast, when the zeta potential approaches zero, the electrostatic repulsion between particles decreases significantly, allowing attractive forces to dominate and increasing the likelihood of particle agglomeration. In general, colloidal systems are considered stable when zeta potential values exceed approximately ±30 mV. In contrast, values between -30 mV and +30 mV are commonly associated with reduced suspension stability and an increased tendency toward coagulation and flocculation (Somasundaran, 1975).

Zeta potential is typically determined by measuring the movement of charged particles under the influence of an externally applied electric field. The velocity of the particles is quantified as electrophoretic mobility, which constitutes the fundamental parameter used in zeta potential determination. Modern zeta potential measurements are commonly performed using Electrophoretic Light Scattering (ELS) or Laser Doppler Electrophoresis (LDE) techniques. These methods enable accurate determination of electrophoretic mobility, which is subsequently converted into zeta potential values (mV) through the application of the Smoluchowski or Henry equations, depending on the characteristics of the suspension system (Delgado et al., 2007; ASTM E2865-12, 2022).

Within the scope of the present study, zeta potential measurements were carried out using a Malvern Panalytical Zetasizer Ultra instrument (Fig. 1). Measurements were performed for each sample over a wide pH range encompassing both acidic and alkaline conditions in order to evaluate the variation of surface charge characteristics as a function of pH. Pure water was used as the solution for zeta potential measurements. The tests were repeated three times, and the averages were taken.

Fig. 1. Malvern Panalytical Zetasizer Ultra instrument utilized for zeta potential measurements

3. Results and discussion

In bauxite flotation systems, anionic collectors, particularly fatty acids and oleate-based reagents, are widely utilized to promote the selective recovery of alumina-bearing minerals. Although alumina minerals generally exhibit slightly negative surface charges under alkaline conditions (pH 9–10), collector adsorption can still occur effectively. This behavior indicates that the adsorption process is governed not only by electrostatic interactions but also by specific chemical adsorption mechanisms. The occurrence of collector adsorption can be verified through zeta potential measurements, which reveal alterations in surface charge characteristics following reagent addition (Fuerstenau, 2005; Laitinen et al., 2016; Gungoren et al., 2020).

Depressants commonly employed in the flotation of aluminum-bearing ores include starch, sodium silicate, and carboxymethyl cellulose (CMC). These reagents selectively adsorb onto gangue mineral surfaces, shifting their zeta potential toward more negative values and consequently suppressing collector adsorption. As a result, flotation selectivity between valuable alumina minerals and gangue phases is significantly enhanced. Given that bauxite ores are typically characterized by fine particle sizes and substantial clay mineral content, zeta potential represents a critical parameter influencing particle dispersion and flocculation behavior. Appropriate control of pH and reagent dosages can effectively reduce slime coating phenomena, thereby improving flotation performance (Yu et al., 2016).

The isoelectric points (IEPs) of bauxite-associated alumina minerals are generally reported within the pH range of 8–9, whereas gangue minerals commonly possess lower IEP values. Consequently, zeta potential plays a fundamental role in regulating collector adsorption behavior, determining optimal flotation pH conditions, assessing depressant effectiveness, and ultimately controlling flotation selectivity (Deng et al., 2015; Jiang et al., 2010).

As part of the present study, pH-dependent zeta potential measurements were initially conducted for Circulation Fluidized Bed (CFB) alumina (Al_2O_3), aluminum hydroxide [$Al(OH)_3$], and red mud samples collected from the processing plant. Fig. 2 presents the corresponding results.

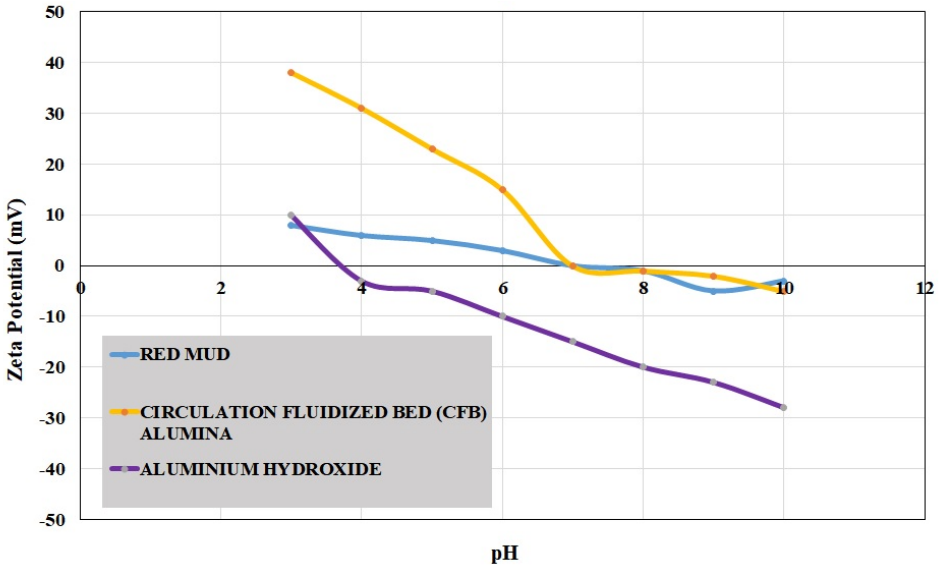

Fig. 2. Zeta potential measurements at different pH values for circulation fluidized bed (CFB) alumina, moist hydrate-alumina, and red mud

Zeta potential and point of zero charge (PZC) measurements conducted on alumina samples revealed significant differences between Circulation Fluidized Bed (CFB) alumina and aluminum hydroxide. The distinct zero-charge points observed for these two aluminum-bearing materials indicate differences in their surface charge characteristics as a function of pH (Hao et al., 2011). Considering the surface charge behavior under both positive and negative charge regimes, hydrated alumina was considered a more representative material for aluminum flotation investigations, as it more closely reflects the physico-chemical surface properties of alumina minerals present in the ore (Gao et al., 2024).

Previous studies on the flotation of aluminum-bearing minerals have demonstrated that acidic pH conditions are generally more favorable for selective separation. Under acidic pH conditions, the surface charge density of aluminum minerals remains relatively moderate, facilitating depressant adsorption onto alumina surfaces while enhancing the effectiveness of collectors directed toward calcium- and silica-bearing gangue minerals (Yu-hua et al., 2008; Li et al., 2010). Consequently, improved selectivity between valuable aluminum minerals and associated gangue phases can be achieved.

Within the framework of the present study, zeta potential measurements were performed on different particle-size fractions to determine their respective points of zero charge, taking into account the mineral liberation characteristics of the ore. Fig. 3 presents the resulting zeta potential profiles for the investigated size fractions.

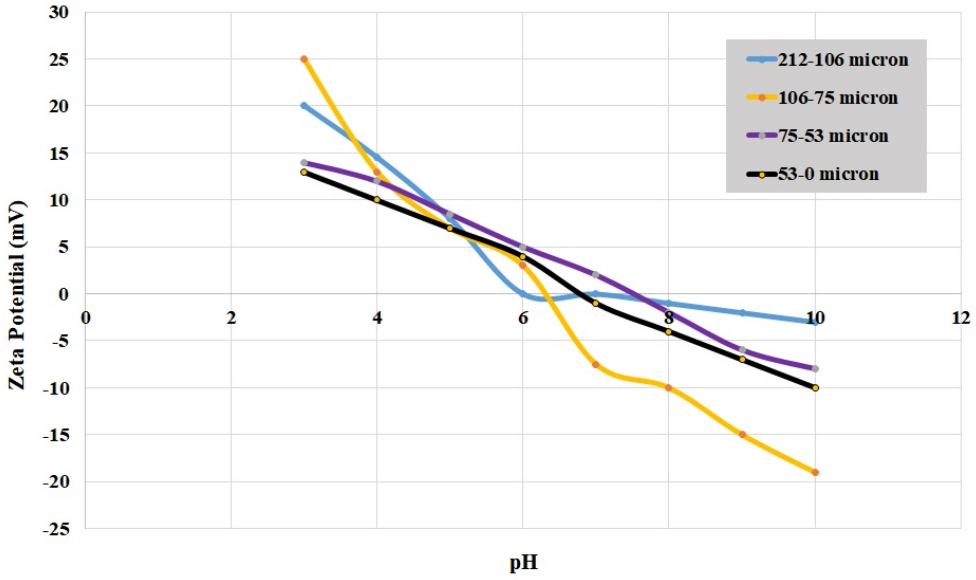

Fig. 3. Zeta potential measurements of the ore at different pH values for the different sieve size fractions

The zeta potential measurements showed that all investigated particle size fractions exhibited more favorable surface charge characteristics for flotation under acidic conditions, particularly at pH 7 and below. These findings suggest that acidic pH conditions provide a suitable electrochemical environment for the selective separation of minerals and are therefore advantageous for the application of reverse flotation in bauxite beneficiation (Hai-pu et al., 2010; Yuhua et al., 2003). In reverse flotation systems, where gangue minerals are selectively floated while alumina-bearing minerals are depressed, maintaining the pulp under acidic conditions is generally considered essential for achieving effective separation and improved flotation selectivity (Sleppy, 2002).

To evaluate the influence of collector type on mineral surface properties and flotation behavior, zeta potential measurements were subsequently conducted using different collectors at a fixed particle size fraction. Fig. 4 presents the corresponding results.

In flotation research, the isoelectric point (IEP), often used interchangeably with the pH at which the zeta potential becomes zero, is frequently reported in place of the zero point of charge (ZPC or pHpzc). Although these concepts are closely related, they are not identical. The ZPC refers to the pH at which the net surface charge of a mineral is zero, whereas the IEP is defined as the negative logarithm of the concentration of potential-determining ions at which the zeta potential of the mineral becomes zero (Somasundaran, 1975; Fuerstenau, 2005).

Efficient flotation requires mineral particles to remain sufficiently dispersed within the pulp. This dispersion behavior is governed primarily by the zeta potential of the particles and the thickness of the electrical double layer (EDL) surrounding their surfaces. Particles exhibiting high absolute zeta potential values possess thicker EDLs, resulting in stronger electrostatic repulsion and improved dispersion stability. Conversely, as the zeta potential decreases, the EDL becomes progressively compressed, reducing the repulsive forces between particles (Honggang, 2022; Yu-Ren et al., 2010; Longhua et al., 2014).

When the zeta potential approaches approximately ±30 mV, the stability of the suspension begins to decline due to compression of the electrical double layer. As the pulp pH approaches the ZPC, attractive London–van der Waals forces increasingly dominate interparticle interactions, allowing particles to move closer together. At zeta potential values below approximately ±10 mV, the electrical double layer may collapse almost completely, promoting particle aggregation and coagulation, which can significantly impair flotation performance (Hu et al., 2003; Zhao et al., 2003).

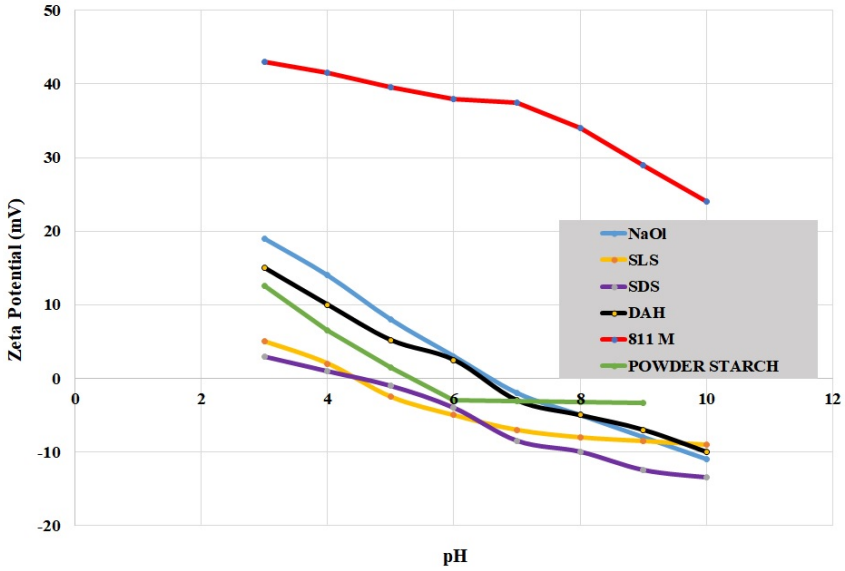

Fig. 4. Zeta potential measurements at different pH values for the different collectors in the -100+75 µm size fraction

Diasporic bauxite ores are generally characterized by low Al/Si mass ratios, and extensive comminution is often required to liberate valuable aluminum-bearing minerals from associated gangue phases prior to flotation. Although diaspore is naturally hydrophilic, previous studies have shown that liberated diaspore particles can attach to air bubbles over a broad particle-size range, from coarse particles of approximately 297 µm to ultrafine particles smaller than 37 µm (Massola et al., 2009). However, complex mineralogical associations within aluminosilicate-rich ores make adequate liberation and selective recovery difficult. In particular, the fine particle fraction generated during grinding commonly contains clay minerals, predominantly kaolinite, which adversely affects flotation performance (Jiang et al., 2010; Xia et al., 2009).

In oxide mineral flotation systems, collector adsorption is strongly influenced by the electrical double layer developed on mineral surfaces. Consequently, the surface charge characteristics of diaspore and its associated gangue minerals, particularly their isoelectric points, represent critical parameters governing flotation selectivity and process efficiency (Laitinen et al., 2016). The surface charge of diaspore is controlled by protonation and deprotonation reactions involving surface hydroxyl groups, resulting in the formation of hydroxylated surface species in aqueous environments (Hao et al., 2011).

Previous investigations have reported that the IEP of diaspore in deionized water, in the absence of flotation reagents, generally ranges between pH 5 and 7.5, which is considerably higher than that of associated aluminosilicate minerals (Yu et al., 2016; Deng et al., 2015; Jiang et al., 2010). Variations in the reported IEP values have been attributed primarily to differences in silicate impurity content (Hu et al., 2003; Yu-lin et al., 2011). Further demonstrated that the presence of 5×10^{-4} mol/dm^3 Ca^{2+}, Mg^{2+}, and Na^+ ions shifted the IEP of diaspore from pH 7.2 to approximately 4.5, 8.0, and 6.8, respectively. Kaolinite, illite, and pyrophyllite possess similar surface chemical characteristics and typically exhibit low IEP values, generally below pH 4, resulting in negatively charged surfaces across a wide pH range. The relatively high IEP of diaspore reflects the abundance of Al–O surface sites compared with the Si–O-dominated surfaces of aluminosilicate gangue minerals (Jiang et al., 2010). Furthermore, a negative correlation has been reported between IEP and SiO_2 content, whereas a positive correlation exists

between IEP and Al_2O_3 content in diaspore flotation systems (Hu et al., 2003; Yao et al., 2019; Franks and Meagher, 2003).

The surface charge of diaspore and most associated minerals is positive at pH values below the IEP and negative at pH values above the IEP (Feng et al., 2009; Deng et al., 2015; Yu-hua et al., 2008; Li et al., 2010; Laitinen et al., 2016; Hai-pu et al., 2010; Yuhua et al., 2003; Zhao et al., 2003). Since the IEP is highly sensitive to pH and solution chemistry, the addition of flotation reagents can significantly alter surface charge behavior and shift the IEP. Interactions between ionic flotation reagents and surface species on diaspore are often mediated through hydrogen bonding and specific adsorption mechanisms (Xia et al., 2009). Numerous studies have shown that anionic collectors can substantially reduce the IEP of diaspore, often to values below pH 4, whereas the corresponding shift for kaolinite is relatively minor. In contrast, cationic collectors generally shift the surface charge toward more positive values, producing a particularly pronounced effect on kaolinite, for which IEP values exceeding pH 8 have been reported (Yuhua et al., 2003; Zhao et al., 2003; Wu et al., 2022).

Among all reagents investigated, 811M exhibited a distinctly different behavior. The zeta potential remained highly positive throughout the investigated pH range (+43 to approximately +24 mV), and no isoelectric point (IEP) was observed between pH 3 and 10. This behavior indicates that 811M strongly modifies the mineral surface and maintains a positively charged electrical double layer over a broad pH range. Such behavior suggests either strong specific adsorption or the formation of a positively charged adsorbed layer on the mineral surface. From a flotation perspective, this collector would not be expected to promote adsorption of anionic species but may enhance interactions with negatively charged minerals.

Based on the literature and the experimental results obtained in the present study, the zeta-potential measurements demonstrate that the investigated collectors substantially modified the electrokinetic properties of the mineral suspension. The magnitude and direction of the changes depended strongly on the collector type. In the presence of the anionic collectors NaOL, SLS, and SDS, the zeta potential progressively shifted toward more negative values as the pH increased, with the curves crossing the zero-potential region at different pH values. DAH and starch also produced pronounced changes in the surface charge, although their effects differed in magnitude and pH dependence. In contrast, 811 M maintained a positive zeta potential throughout the investigated pH range, indicating a fundamentally different interaction with the mineral surface. These results demonstrate that collector addition modifies the interfacial charge environment and, consequently, the electrokinetic behavior of the mineral particles. The pronounced negative shift observed in the presence of NaOL indicates a substantial modification of the surface charge, which is consistent with the adsorption of anionic oleate species onto positively charged surface sites. However, zeta-potential changes alone cannot be considered definitive evidence of the amount or mechanism of collector adsorption. Therefore, the electrokinetic results were interpreted together with the adsorption and flotation data to evaluate the collector–mineral interactions and their implications for flotation selectivity (Fuerstenau, 2005; Laitinen et al., 2016). Among the investigated anionic collectors, NaOl and SLS produced one of the most pronounced shifts in zeta potential, changing the surface from a positively charged state at acidic pH to a negatively charged state at alkaline pH.

3.1. Flotation studies

Feed particle size is one of the most critical parameters influencing flotation performance, as it directly affects mineral liberation, reagent adsorption, and bubble-particle interactions. In the present study, reverse flotation experiments were conducted on diasporic bauxite ore classified into three particle-size fractions (−212+106 μm, −106+75 μm, and −75+53 μm) to investigate the effects of particle size, collector type and dosage, depressant dosage, and pulp pH on flotation performance. Particular emphasis was placed on selectively removing carbonate-bearing minerals and improving concentrate quality, especially with respect to the silica modulus value.

The primary objective was to identify the optimum flotation conditions for the beneficiation of diasporic bauxite through reverse flotation. Accordingly, a comprehensive experimental program was designed to determine the most effective collector type and dosage, as well as the optimum pH conditions required for the selective separation of gangue minerals. These investigations aimed to

establish the fundamental flotation parameters needed to produce a concentrate that meets the silica modulus requirements of the Bayer process while reducing the content of undesirable carbonate minerals (Gürsoy et al., 2026).

The experimental work further investigated the effectiveness of two anionic collectors, sodium oleate (NaOl) and sodium lauryl sulfate (SLS), for the flotation separation of carbonate- and silicate-bearing gangue minerals from diasporic bauxite. The effects of collector type on the chemical composition and quality of the flotation products were evaluated based on changes in Al_2O_3, CaO, and SiO_2 grades. Particular emphasis was placed on determining whether the silica modulus of the bauxite concentrate could be increased above 7, a value commonly targeted for suitable Bayer-process feed. The removal of carbonate-bearing minerals was also considered a critical objective because their presence may increase caustic soda consumption and adversely affect Bayer-process operation (Gürsoy et al., 2026). Five collectors were initially evaluated in the adsorption experiments to investigate collector–mineral interactions systematically. Based on the adsorption and zeta potential results, NaOl and SDS were selected for the subsequent flotation experiments because they exhibited pronounced interactions with the mineral surface and represented different anionic collector chemistries. This selection allowed the flotation responses of a fatty-acid-based collector (NaOl) and a sulfate-based collector (SDS) to be compared while maintaining a manageable experimental matrix. By comparing NaOl and SLS, both anionic collectors with different functional groups and surface-interaction characteristics, this study aimed to elucidate the role of collector chemistry in controlling flotation selectivity and concentrate quality in diasporic bauxite.

Depressants constitute another important group of flotation reagents and play a crucial role in achieving selective mineral separation. In the reverse flotation of diasporic bauxite, the objective is to promote the flotation of carbonate and silicate gangue minerals while suppressing the flotation of valuable bauxite minerals. Therefore, the selection of an appropriate depressant is essential for maximizing flotation selectivity and concentrating quality. Previous studies have demonstrated that various depressants can be employed in bauxite flotation systems, with starch being one of the most widely used and effective reagents for depressing aluminum-bearing minerals (Gürsoy et al., 2026). Based on these findings, starch was selected as the depressant reagent in the present flotation experiments. All flotation tests were carried out using a conventional laboratory-scale flotation machine. Fig. 5 illustrates the experimental setup used throughout the study.

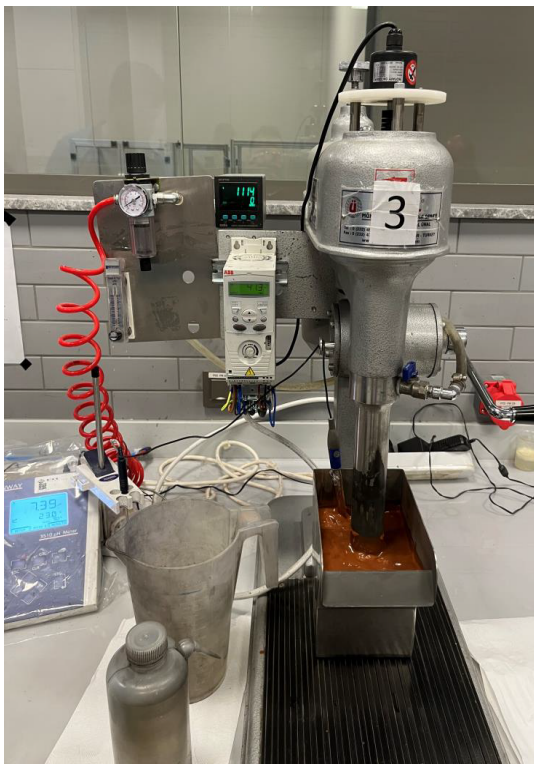

Fig. 5. Mechanical flotation machine used in flotation experiments

3.2. Flotation studies using NaOl

In flotation studies conducted with different particle sizes, the experimental conditions were designed by standardizing all conditions except the collector type (Table 2). The results of flotation experiments conducted with different particle sizes and different collector amounts are given in Figs. 6-8.

Table 2. Flotation experimental conditions with NaOl collector type included

Material	Diaspore
Depressant – Starch	1500 g/Mg
Collector	NaOl (g/Mg)
Frothing Agent – MIBC	35 g/Mg
pH Regulator-H_3PO_4	5.5 pH
Solid Ratio	30 %
Airflow Rate	2 dm^3
Temperature	23.5 °C
Mixing Speed	800 rpm
Flotation Cell Volume	2.2 dm^3

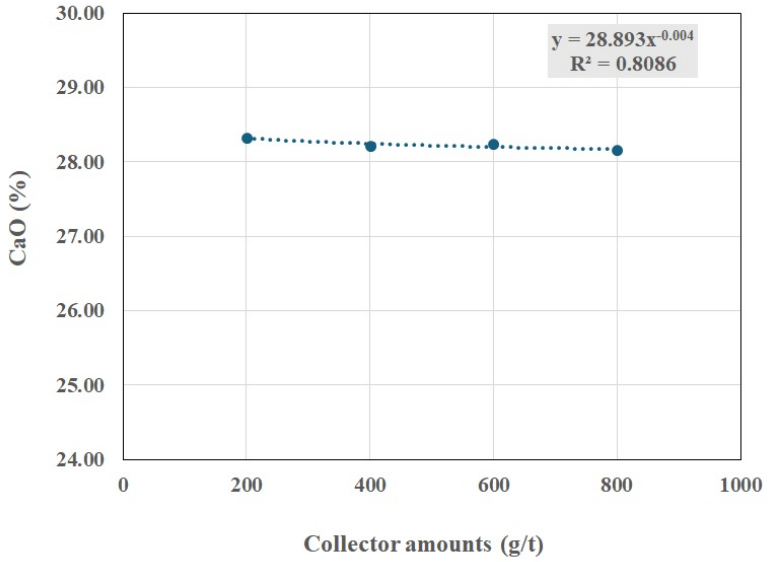

Fig. 6. CaO % results obtained in aluminum concentrate (cell) during flotation with NaOl at -212+106 µm

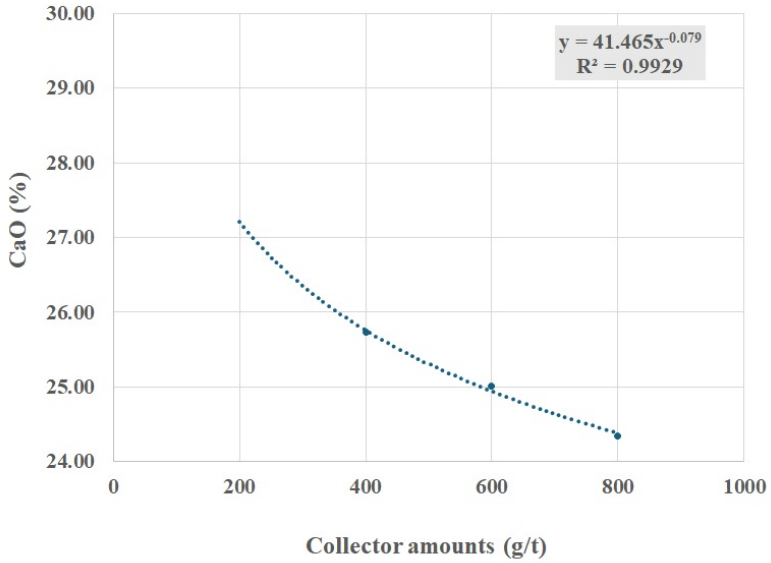

Fig. 7. CaO % results obtained in aluminum concentrate (cell) during flotation with NaOl at -106+75 µm

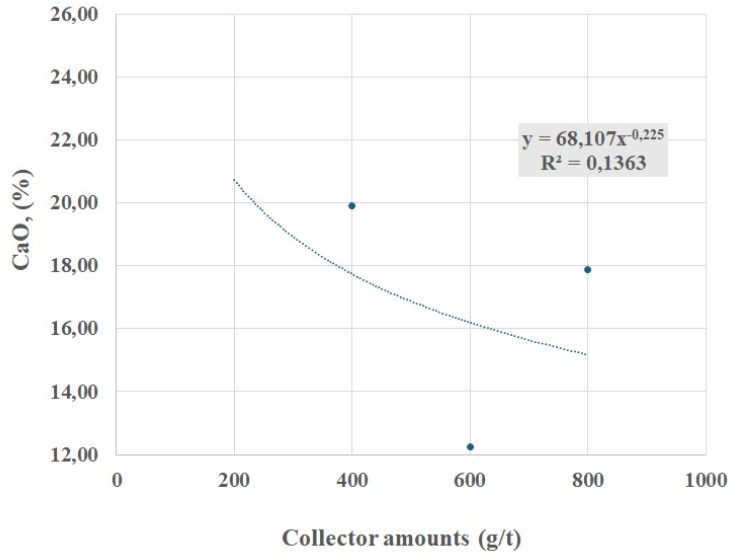

Fig. 8. CaO % results obtained in aluminum concentrate (cell) during flotation with NaOl at -75+53 µm

The choice of NaOl as a collector type can be explained as follows: When CaO comes into contact with water, it very quickly transforms into $Ca(OH)_2$ (calcium hydroxide, slaked lime) and is practically always found in this form in the flotation medium. Sodium oleate (NaOl) is an anionic fatty acid salt collector and works very well in calcium-containing salt-type minerals (Gürsoy et al., 2026). The mechanism works as follows:

- Oleate ions ($R\text{-}COO^-$) react with Ca^{2+} ions on the mineral surface.
- A Ca-oleate complex/salt is formed ($Ca(RCOO)_2$).
- Because this salt is hydrophobic (repellent), it adheres to the mineral air bubble and rises to the surface (flotation occurs).

However, in calcium flotation with NaOl it is generally preferred that the pH of the medium be basic. The main reason for this preference is that it increases the stability of NaOl. However, the natural suppression of aluminum minerals in flotation and the greater stability of starch as a suppressant in an acidic environment led to the pH of the medium being acidic.

It is important to distinguish calcite from calcium oxide (CaO), since CaO is not the primary mineralogical phase identified in the investigated bauxite. When CaO is present, it reacts rapidly with water to form calcium hydroxide [$Ca(OH)_2$] according to the highly exothermic reaction $CaO + H_2O \rightarrow Ca(OH)_2$ + heat. Therefore, the occurrence and behavior of calcium-bearing minerals should be considered in relation to their actual mineralogical form rather than being expressed simply in terms of CaO. In flotation experiments with NaOl, the most suitable particle size was obtained as -75 to +53 µm. Comparison with MLA data of calcium-based minerals at this particle size shows that liberation occurs. The CaO content in the resulting aluminum concentrate is approximately 12%.

3.3. Flotation studies using SLS

In flotation studies conducted with different particle sizes, the experimental conditions were designed by standardizing all conditions except the collector type (Table 3). The results of flotation experiments conducted with different particle sizes and different collector amounts are given in Figs. 9-11.

SLS binds to Ca^{2+} sites on the mineral surface via chemisorption (energy ~ -40-50 kJ/mol). The sulphate group (OSO_3^-) interacts ionically with Ca, causing the alkyl chain to orient outwards, making the surface hydrophobic. FTIR analysis confirms SLS adsorption with C-H stretching bands (2925 cm^{-1}, 2855 cm^{-1}) and S=O shifts (1265 cm^{-1}, 1185 cm^{-1}), indicating strong chemical binding.

Floating experiments with an SLS collector showed the best performance. Here, the high tendency of SLS to be chemically absorbed onto the surface increased selectivity, enabling efficient removal of calcium-derived minerals.

From a metallurgical perspective, the flotation response should be evaluated not only in terms of gangue removal but also in terms of the preservation and upgrading of the aluminum-bearing fraction. The investigated ore contains diaspore as the principal aluminum-bearing mineral, together with

significant amounts of calcite and several silica-, iron-, and titanium-bearing minerals. Therefore, the objective of reverse flotation was to selectively transfer the undesirable gangue minerals to the froth product while retaining diaspore in the flotation concentrate. Starch was used as a depressant to promote this selectivity by suppressing the flotation of aluminum-bearing minerals. The flotation

Table 3. Flotation experimental conditions with SLS collector type

Material	Diaspore
Depressant – Starch	1500 g/Mg
Collector	SLS (g/Mg)
Frothing Agent – MIBC	35 g/Mg
pH Regulator-H_3PO_4	5.5 pH
Solid Ratio	30 %
Airflow Rate	2 dm^3
Temperature	23.5 °C
Mixing Speed	800 rpm
Flotation Cell Volume	2.2 dm^3

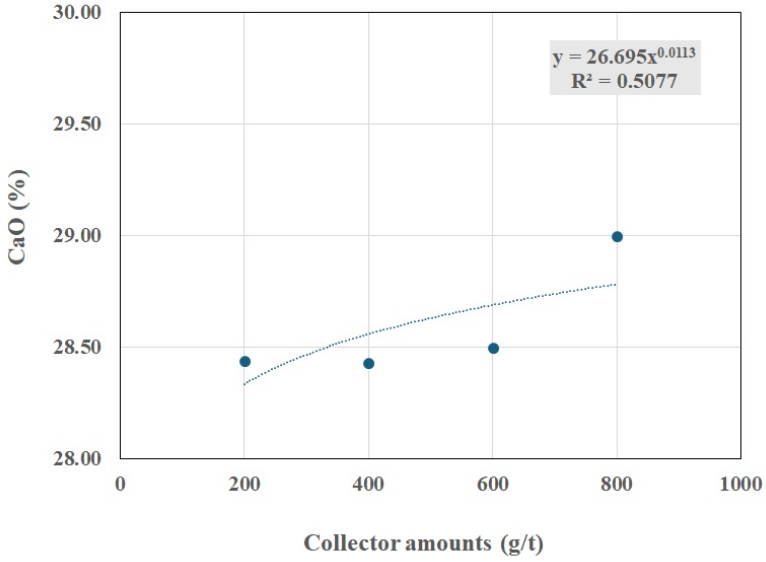

Fig. 9. CaO % results obtained in aluminum concentrate (cell) during flotation with SLS at -212+106 µm

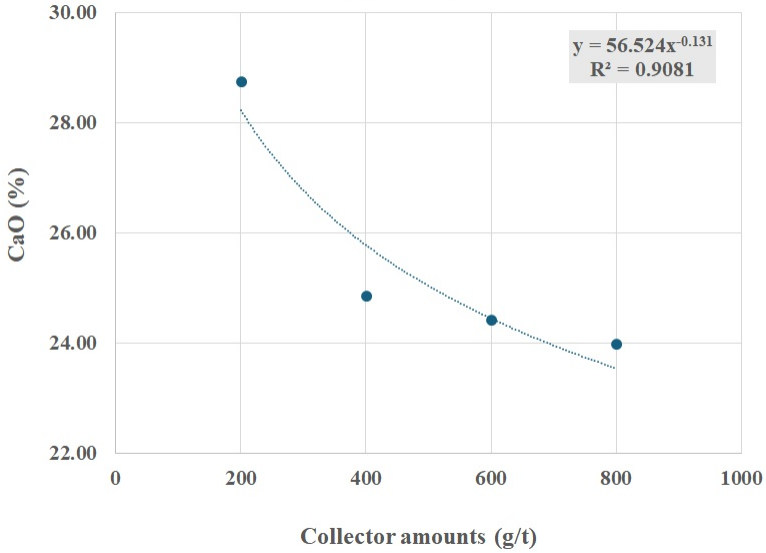

Fig. 10. CaO % results obtained in aluminum concentrate (cell) during flotation with SLS at -106+75 µm

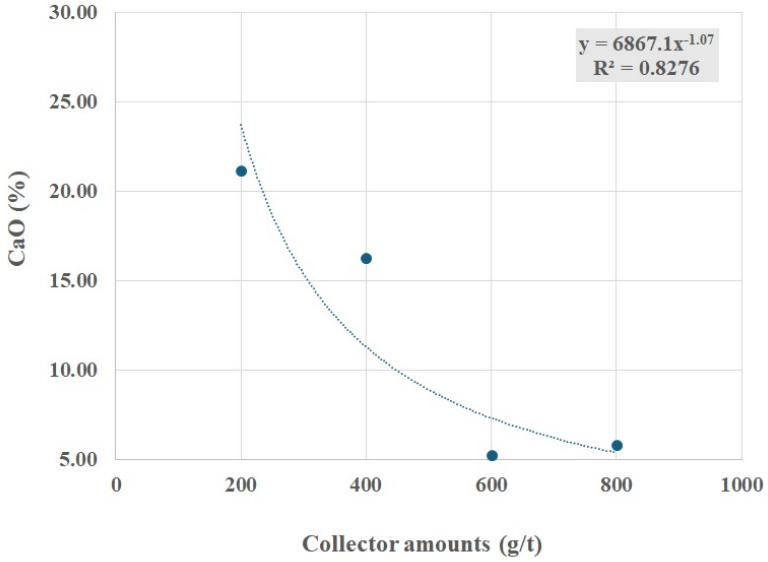

Fig. 11. CaO % results obtained in aluminum concentrate (cell) during flotation with SLS at -75+53 µm

results indicate that particle size strongly affected this separation. In particular, the −75+53 µm fraction provided the most favorable flotation conditions, which is consistent with the MLA observations indicating adequate liberation of calcium-bearing minerals in this size range.

Comparing the two anionic collectors further showed that collector chemistry influenced the selectivity of calcium-bearing gangue removal. Although both NaOL and SLS promoted flotation of calcium-bearing minerals, SLS produced the more favorable flotation response under the investigated conditions. This behavior is consistent with the observed removal of calcium-derived minerals and indicates that SLS provided a more selective surface modification under the acidic operating conditions employed in this study. Consequently, the combination of SLS, pH 5.5, and the −75+53 µm particle-size fraction was identified as the most favorable condition for reducing calcium impurities while maintaining the aluminum-bearing fraction in the concentrate.

3.4. Modelling studies

Nonlinear regression analysis is a powerful statistical modelling technique widely employed to describe complex relationships between dependent and independent variables that cannot be adequately represented by linear functions. In mineral processing and flotation studies, many physicochemical processes, including flotation kinetics, reagent adsorption, bubble-particle interactions, and surface charge behaviour, exhibit inherently nonlinear characteristics. Consequently, nonlinear regression methods are frequently utilized to model experimental data and estimate process parameters with high accuracy.

The fundamental objective of nonlinear regression is to determine the set of model parameters that minimizes the discrepancy between experimentally measured values and model predictions. In general, a nonlinear model can be expressed as;

$$Y = f(X, \beta) + \varepsilon \quad (1)$$

where Y represents the dependent variable, X denotes the independent variable, (\beta) corresponds to the model parameters, and ε is the random error term. Parameter estimation is typically performed using the least-squares criterion, in which the sum of squared residuals (SSR) between observed and predicted values is minimized.

Unlike linear regression, nonlinear regression models require iterative optimization procedures because analytical solutions are generally unavailable. Commonly used optimization algorithms include the Gauss–Newton, Levenberg–Marquardt, and Trust-Region methods. Among these approaches, the Levenberg–Marquardt algorithm is particularly preferred due to its computational efficiency, numerical stability, and rapid convergence properties.

Model-fitting quality is commonly assessed using several statistical indicators, including the coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE). High (R^2) values together with low RMSE and MAE values indicate good agreement between experimental observations and model predictions. These statistical criteria provide an objective basis for evaluating the reliability and predictive capability of the developed models.

In this study, nonlinear regression analysis was used to evaluate the relationship between particle size, collector type, and CaO% grade. The experimental data obtained were fitted using appropriate nonlinear models, and model parameters were estimated through iterative least-squares optimization. The resulting regression models were subsequently used to interpret the effects of particle size and collector adsorption on mineral surface charge behavior and flotation selectivity.

The equation obtained using the nonlinear regression technique with the data obtained from flotation results performed with NaOl and SLS within the scope of the study is given below:

$$\%\mathrm{CaO} = 26.2 \text{ x } \mathrm{AC}^{(4.35*\mathrm{SS}^{-1.17})} \tag{2}$$

where AC is amount of collectors (g/t), while SS is sieve size / particle size (μm).

The trendlines shown in Figs. 8–10 were used only to visualize the general tendency of the experimental data. The experimental datasets were subsequently subjected to nonlinear regression analysis, and the model parameters were re-estimated to obtain the final regression equations. Therefore, the R^2 values associated with the trendlines should not be considered as the goodness-of-fit indicators of the final nonlinear regression models.

Although the preliminary trendlines shown in Figs. 8–10 yielded relatively low R^2 values, the purpose of these lines was not to provide the final predictive relationship. Instead, the experimental data were subsequently fitted using a nonlinear regression approach, in which the model coefficients were optimized to minimize the difference between the experimental and predicted values. The resulting optimized equations were then used to evaluate the model using R^2, MAE, and RMSE.

The predictive performance and reliability of regression models are commonly evaluated using statistical error metrics that quantify the deviation between experimental observations and model predictions. Among these metrics, Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) are widely used because of their simplicity and effectiveness in assessing model accuracy.

Mean Absolute Error (MAE) represents the average magnitude of prediction errors without considering their direction. It is calculated as the arithmetic mean of the absolute differences between observed and predicted values and can be expressed as:

$$\mathrm{MAE} = \frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}|\mathrm{y} - \mathrm{y_i}| \tag{3}$$

where y is the measured value, y_i is the predicted value, n is the number of samples.

MAE provides a direct measure of the average prediction error in the same units as the original data, making its interpretation straightforward. Since all residuals contribute equally to the final value, MAE is less sensitive to outliers and extreme deviations than RMSE. Consequently, it is often preferred when a balanced assessment of overall model performance is required.

Root Mean Square Error (RMSE) is another widely used metric for evaluating the goodness-of-fit of regression models. RMSE is defined as the square root of the average squared differences between observed and predicted values:

$$\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{t} - \mathrm{t_i})^2} \tag{4}$$

where t is the measured value, t_i is the predicted value, n is the number of samples.

Because the residuals are squared before averaging, RMSE assigns greater weight to larger errors. As a result, RMSE is particularly sensitive to outliers and substantial prediction deviations. This characteristic makes RMSE an effective indicator when large prediction errors are considered more critical than smaller ones.

Both MAE and RMSE are expressed in the same units as the measured variable, facilitating direct interpretation of model accuracy. Lower MAE and RMSE values indicate better agreement between experimental data and model predictions. A model with MAE and RMSE values near zero is generally considered to have strong predictive capability.

Table 4. Statistical comparison of experimental and model data for different collector types for diaspore samples

Rating	NaOl	SLS
RMSE	5.35	9.23
MAE	3.88	2.22
R^2	0.95	0.89

Comparing MAE and RMSE can also reveal the distribution of prediction errors. When RMSE is substantially higher than MAE, it suggests large residuals or outliers in the dataset. Conversely, similar MAE and RMSE values indicate that prediction errors are relatively uniform across observations.

The NaOl-based model exhibited the highest coefficient of determination ($R^2 = 0.95$), indicating that approximately 95% of the variability in the experimental data was explained by the developed regression equation. In contrast, the SLS model yielded a lower R^2 of 0.89, suggesting comparatively weaker explanatory power. The higher R^2 for NaOl indicates a stronger correlation between predicted and observed values and a better overall model fit.

Regarding error statistics, the NaOl model produced an RMSE of 5.35, considerably lower than that of the SLS model (RMSE = 9.23). Since RMSE places greater emphasis on large prediction errors, the lower RMSE obtained for NaOl suggests that this model generated fewer substantial deviations from the experimental observations and provided a more reliable representation of the dataset.

However, the MAE values revealed a different trend. The SLS model produced a lower MAE value (2.22) compared with the NaOl model (3.88), indicating that the average magnitude of prediction errors was smaller for SLS. This finding suggests that although the SLS model had lower average prediction errors, it was more susceptible to occasional large deviations, as reflected in its relatively high RMSE.

The discrepancy between MAE and RMSE for the SLS model indicates several larger residuals or outliers in the dataset. Conversely, the relatively close RMSE and MAE values obtained for NaOl imply a more uniform distribution of residual errors and a more stable predictive performance.

4. Conclusions

The present study investigated the influence of particle size, collector type, and surface electrokinetic properties on the flotation separation of calcium-bearing minerals from low-grade diasporic bauxite ore. Mineralogical characterization, flotation experiments, zeta potential measurements, and nonlinear regression modelling were integrated to evaluate the beneficiation behavior of the ore and to establish suitable operating conditions for improving Bayer-process feed quality.

The MLA results demonstrated that diaspore was the dominant mineral phase in all investigated size fractions, whereas calcite represented the principal calcium-bearing gangue mineral. The mineralogical distribution indicated that the liberation characteristics of calcite and diaspore were strongly dependent on particle size, directly affecting flotation selectivity and beneficiation efficiency.

Zeta potential measurements revealed that both particle size and collector type significantly influenced the electrokinetic behavior of the mineral surfaces. Decreasing particle size increased the specific surface area and enhanced collector adsorption, resulting in more pronounced changes in surface charge. These findings confirmed that zeta potential analysis is an effective tool for understanding collector–mineral interactions and optimizing flotation conditions for selective separation.

Reverse flotation experiments demonstrated that particle size played a critical role in the removal of calcium-bearing minerals. Among the investigated size fractions, the −75+53 μm fraction exhibited the most favorable flotation performance, indicating that adequate liberation of calcite and associated gangue minerals had been achieved within this size range. The flotation results further showed that acidic operating conditions (pH 5.5) enhanced the selective flotation of calcium-bearing minerals while maintaining the depression of valuable diaspore particles.

The performance of sodium oleate (NaOl) and sodium lauryl sulphate (SLS) collectors was compared under identical flotation conditions. Although both collectors were capable of floating calcium-bearing minerals, SLS exhibited superior flotation selectivity due to its strong chemisorption onto calcium-rich mineral surfaces. The adsorption mechanism of SLS promoted hydrophobicity development and

facilitated the effective removal of calcite and dolomite from the bauxite ore. Consequently, SLS produced the most favorable metallurgical performance among the collectors investigated.

To quantitatively evaluate the relationship between particle size, collector dosage, and flotation response, nonlinear regression models were developed. The statistical evaluation indicated that the NaOl provided a better overall fit to the experimental data, yielding an R^2 value of 0.95 compared with 0.89 for the SLS. Furthermore, the NaOl model exhibited a lower RMSE value (5.35), suggesting greater robustness and predictive capability. However, the lower MAE value obtained for the SLS model (2.22) indicated smaller average prediction errors. These results suggest that while the NaOl model offered superior mathematical stability, the SLS collector achieved superior flotation performance from a process perspective.

Overall, the findings demonstrate that the combined use of particle size optimization, electrokinetic characterization, and appropriate collector selection can significantly improve the flotation separation of calcium-bearing minerals from diasporic bauxite ores. The results indicate that flotation conducted at acidic pH using SLS as a collector and a particle size range of −75+53 µm provides the most favorable conditions for reducing calcium impurities and improving the quality of bauxite feed intended for alumina production via the Bayer process. Future studies should focus on detailed surface characterization using advanced spectroscopic techniques and on developing reagent schemes that simultaneously maximize calcium removal and improve silica modulus.

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References

ASTM International., ASTM E2865-12, 2022. *Standard Guide for Measurement of Electrophoretic Mobility and Zeta Potential of Nanoparticles in Aqueous Media Using a Microelectrophoresis Method*, ASTM International, West Conshohocken, PA, USA.

DENG, L., WANG, H., DENG, J., HUANG, B., 2015. *Flotation behavior and mechanism of phenyl phosphonic acid in separation of diaspore and kaolinite.* Transactions of Nonferrous Metals Society of China, 25(6).

DELGADO, A. V., GONZÁLEZ-CABALLERO, F., HUNTER, R. J., KOOPAL, L. K., LYKLEMA, J., 2007. *Measurement and interpretation of electrokinetic phenomena*, Journal of Colloid and Interface Science, 309, 194–224.

FENG, Q., ZHAO, S., WEN, S., CAO, Q., 2009. *Activation mechanism of lead ions in the flotation of ilmenite using sodium oleate.* International Journal of Mineral Processing, 93(1), 79-83.

FRANKS, G. and V., MEAGHER, L., 2003. *The isoelectric points of sapphire crystals and alpha-alumina powder,* Colloids and Surfaces A: Physicochemical and Engineering Aspects, Volume 214, Issues 1–3, Pages 99-110, ISSN 0927-7757, https://doi.org/10.1016/S0927-7757(02)00366-7.

FUERSTENAU, M.C., 2005. *Froth Flotation: A Century of Innovation.* SME (Society for Mining, Metallurgy, and Exploration), Littleton, CO, USA.

GAO, B., LI, J., YUAN, X., AND CHEN, P., 2024. *Gas parameter characteristics in Reflux Flotation Cell,* Vibroengineering Procedia, Vol. 55, pp. 145–149, Sep. 2024, https://doi.org/10.21595/vp.2024.24399

GIBSON, B., WONYEN, D.G., CHEHREH CHELGANI, S., 2017. *A review of pretreatment of diasporic bauxite ores by flotation separation*, Minerals Engineering, Volume 114, Pages 64-73, ISSN 0892-6875, https://doi.org/10.1016/j.mineng.2017.09.009.

GUNGOREN, C., GUVEN, O., CINAR, M., OZDEMIR, O., 2020. *An investigation of the effect of clay type on coal flotation along with DLVO theoretical analyses.* International Journal of Coal Preparation and Utilization, 40(3), 210–222. https://doi.org/10.1080/19392699.2019.1603146.

GÜRSOY, Y., H., FİLAR, A., UMUCU, Y., 2026. The Importance of Zeta Potential Measurement in The Flotation of Diaspore and Calcium Minerals, 20th Balkan Mineral Processing Congress, İstanbul/ TÜRKİYE, pp, 897-912.

HAI-PU, L., JIAN-WEI, L., DIAN-ZUO, W., 2010. *Flotation separation of diaspore from kaolinite, pyrophyllite and illite using three cationic collectors*. Minerals Engineering, 23(1), 1-7.

HAO, H., LI, L., YUAN, Z., LIU, M., ZHANG, Y., 2011. *Flotation of kaolinite and diaspore with hexadecyl dimethyl benzyl ammonium chloride.* Mining Science and Technology (China), 21(5), 665-669.

HU, Y., HE, P., ZHANG, Z., 2003. *Electrokinetic behavior and flotation of kaolinite in CTAB solutions.* Minerals Engineering, 16(11), 1221-1223.

JIANG, L., ZHANG, Y., XU, L., 2010. *Flotation of aluminosilicate minerals using alkylguanidine collectors.* Mining Science and Technology (China), 20(4), 588-593.

LAITINEN, O., HÄKKINEN, A., HEISKANEN, K., 2016. E*lectrokinetic flotation of diasporic bauxite.* Minerals Engineering, 92, 36-43.

LI, H., LI, S., ZHANG, Q., 2010. *Flotation separation of diaspore from kaolinite, pyrophyllite and illite using three cationic collectors.* Mining Science and Technology (China), 20(3), 436-440.

LONGHUA X., YUEHUA H., FAQIN D., ZHIYONG G., HOUQIN W., ZHEN W., 2014, *Anisotropic adsorption of oleate on diaspore and kaolinite crystals: Implications for their flotation separation,* Applied Surface Science, Volume 321, Pages 331-338, ISSN 0169-4332, https://doi.org/10.1016/j.apsusc.2014.10.042.

MASSOLA, C.P., CHAVES, A.P., LIMA, J.R.B., 2009. *Flotation of diasporic-bauxite ore with a new amphoteric collector.* Proceedings of the VI International Mineral Processing Seminar, 283-292.

SLEPPY, W.C., 2002. *Aluminum Compounds,* Introduction. In Kirk-Othmer Encyclopedia of Chemical Technology, (Ed.). https://doi.org/10.1002/0471238961.0914201819120516.a01.pub2

SOMASUNDARAN, P., 1975. *Interfacial chemistry of particulate flotation.* Advances in Interfacial Phenomena of Particulate/Solution/Gas Systems: Applications to Flotation Research, 47-79.

STAROV, V.M. (Ed.)., 2010. *Nanoscience: Colloidal and Interfacial Aspects (1st ed.).* CRC Press. https://doi.org/10.1201/EBK1420065008

XIA, L., WANG, J., WANG, Y., 2009. *Flotation of kaolinite and diaspore with hexadecyl dimethyl benzyl ammonium chloride.* Mining Science and Technology, 19(6), 766-770.

YAO, W., LI, M., ZHANG, M., CUI, R., JIANG, H., LI, Y., ZHOU, D., 2019. *Effects of grinding media on flotation performance of calcite,* Minerals Engineering, Volume 132, Pages 92-94,

ISSN 0892-6875, https://doi.org/10.1016/j.mineng.2018.12.005.

WU, W., CHEN, T., SHAO, Y., YE, G., TONG, X., 2022. *The flotation separation of molybdenite from talc using zinc sulfate in sodium silicate system and related mechanism,* Colloids and Surfaces A: Physicochemical and Engineering Aspects, Volume 641, 128451, ISSN 0927-7757, https://doi.org/10.1016/j.colsurfa.2022.128451.

YU, R., ZHENG, S., ZHANG, Y., 2016. *Flotation separation of diaspore from aluminosilicates using dodecyl tertiary amine.* Journal of Central South University, 23(6), 1359-1365.

YU-LIN, X., YONG, H., XUE-LAN, Z., 2011. *Effect of metal ions on zeta potential of diaspore.* Journal of Central South University (Science and Technology), 42(8), 2241-2246.

YU-HUA, W., JIAN-WEI, L., DIAN-ZUO, W., 2008. *Flotation of kaolinite and diaspore with hexadecyl trimethyl ammonium bromide.* Journal of China University of Mining and Technology, 18(3), 422-425.

YUHUA, W., JIANWEI, L., DIANZUO, W., 2003. *Flotation separation of diaspore from kaolinite, pyrophyllite and illite using three cationic collectors.* Journal of China University of Mining and Technology, 13(2), 131-135.

YU-REN J., BIN-NAN Z., XIAO-HONG Z., LI-YI Z., 2010. *Flotation of diaspore and aluminosilicate minerals applying novel carboxyl hydroxamic acids as collector,* Hydrometallurgy, Volume 104, Issue 1, Pages 112-118, ISSN 0304-386X, https://doi.org/10.1016/j.hydromet.2010.05.006.

ZHAO, S., FENG, Q., ZHANG, Y., 2003. *Effect of pH on the adsorption of dodecylamine on kaolinite and diaspore.* Journal of Central South University of Technology, 10(4), 365-369.