

Article

Valorization of Feldspar Processing Tailings by Flotation: Effects of Reagent Scheme, Flotation Cell and Bubble Size

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Abstract

This study investigates the potential for recovering valuable minerals from feldspar tailings generated during industrial processing and commonly discarded as waste, causing both economic losses and environmental concerns. A hydrocyclone overflow sample obtained from a feldspar processing plant in the Muğla region of Türkiye was characterized and evaluated for the production of a marketable feldspar concentrate by flotation. Bulk and selective reverse flotation tests were performed using Denver and TK Lab flotation cells incorporating different impeller–stator configurations to evaluate the combined effects of reagent chemistry, flotation cell hydrodynamics, and bubble characteristics on flotation performance. The Sauter mean bubble diameter (d_{32}) was measured under both two-phase and three-phase conditions to characterize bubble size. Compared with the conventional plant reagent scheme (Derna-7 and Der A4), the sequential flotation scheme employing sulfonate collectors (R801–R825) for Fe–Ti-bearing minerals followed by the amine collector DAHC for mica significantly improved impurity rejection. The highest concentrate quality was achieved in the TK Lab Cell, producing a feldspar concentrate containing as low as 0.49% Fe_2O_3 while maintaining a total alkali content of 9.57%, satisfying the Fe_2O_3 requirement for second-grade ceramic applications. Despite producing larger bubbles than the Denver Cell, the TK Lab Cell exhibited superior rejection of Fe–Ti-bearing minerals. The consistently larger bubbles generated by the TK Lab Cell, irrespective of the reagent scheme employed, indicate that the different impeller–stator configurations played a key role in governing bubble generation and gas dispersion, while reagent chemistry primarily modified bubble characteristics within the hydrodynamic environment established by each flotation cell. The results demonstrate that flotation performance is governed by the combined effects of reagent chemistry, flotation cell hydrodynamics, and bubble characteristics, providing new insights into the sustainable valorization of feldspar processing tailings.

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Keywords: feldspar tailing; flotation; flotation machine; bubble size; reagent scheme; tailing valorization

1. Introduction

Feldspar minerals are essential industrial raw materials utilized extensively across various sectors, most notably in glass, ceramics, plastics, and paint manufacturing. Their unique chemical and physical properties provide significant advantages; for instance, they serve as a primary alumina source in glass production to enhance durability, and

their low melting temperatures facilitate energy savings in the ceramics industry. Furthermore, feldspar acts as a critical filler in the plastics and paint industries, improving the mechanical and physical properties of the final products. The strategic importance of this mineral group has been further underscored by its inclusion in the European Union's 2023 Critical Raw Materials Act, which highlights its economic significance and potential supply risks [1]. Beyond traditional applications, feldspar is now integral to green energy technologies such as solar panels and LED lighting, and digital transformation processes [2].

Türkiye holds a prominent position in the global feldspar market, possessing substantial reserves and production capacities. The country's major deposits are located in the Muğla, Aydın, and Bilecik regions, particularly featuring rich albite (sodium feldspar) reserves. Producing approximately 13 million tons annually, Türkiye is the world's leading feldspar producer and a major supplier to the European glass and ceramic industries, with export value of approximately 275 M \$ [3–5]. In feldspar beneficiation plants, fine slimes are commonly removed before flotation, and magnetic separation processes are used to eliminate mica and Fe–Ti-bearing impurities. Slime coatings are considered a major challenge in flotation because they interfere with particle–bubble attachment and increase reagent consumption [6–8]. The deposition of slimes on both valuable mineral surfaces and air bubbles has been reported to contribute significantly to the observed reduction in flotation recovery. Furthermore, fine slimes can reduce the selectivity of magnetic separation by increasing the entrainment and mechanical retention of non-magnetic particles in the magnetic product [9,10]. Consequently, considerable amounts of feldspar-bearing slime tailings are generated and commonly discarded as waste, resulting in both economic losses and environmental challenges.

The industrial value of feldspar is strongly dependent on its alkali content and the concentration of coloring impurities, particularly iron-bearing minerals. According to the quality requirements reported by Zhang [11], Na-feldspar used in the glass industry should contain 63–70% SiO_2 , 16–20% Al_2O_3 , less than 0.3% Fe_2O_3 , and at least 8% Na_2O , whereas K-feldspar products should contain less than 0.2% Fe_2O_3 and more than 11% K_2O . Similarly, for ceramic applications, high-grade Feldspar concentrates are required to contain more than 12% total alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O}$), less than 0.15% Fe_2O_3 , and more than 17% Al_2O_3 , while even second-grade ceramic products generally require Fe_2O_3 contents below 0.5%. In addition, TiO_2 is also a coloring impurity restricted in ceramic and glass industry specifications, and Fe_2O_3 and TiO_2 contents of approximately 0.3% or below are generally required for marketable feldspar concentrates [11]. Similarly, combined $\text{Fe}_2\text{O}_3 + \text{TiO}_2$ contents in the range of 0.07–0.3% are typically specified for commercially acceptable feldspar concentrates. These specifications highlight the importance of removing Fe–Ti-bearing minerals and mica from feldspar resources in order to produce marketable concentrates suitable for glass and ceramic industries [12]. Nevertheless, the quality specifications of feldspar products are not uniform across all industrial applications. Some grades of feldspar are also utilized as fillers in plastics, paint, sealants, adhesives, etc., though to a lesser extent [13].

Flotation is the most widely used beneficiation method for feldspar and has therefore been the subject of extensive research [12,14–17]. Reverse flotation is generally preferred because of its economic efficiency, since feldspar typically contains only low concentrations of impurities. As a result, selectively floating minor gangue minerals such as mica and iron/titanium-bearing minerals is more cost-effective than floating the bulk feldspar. In this process, collectors selectively adsorb onto gangue surfaces, thereby inducing hydrophobicity and facilitating their removal via the froth phase [18].

The selective removal of mineral impurities from feldspar has been extensively studied using various cationic collectors in single- and multi-stage flotation processes. The flo-

tation concentration of Turkish Na-feldspar obtained from the Çine-Aydın region was investigated using different collector combinations. It was determined that the combined use of AERO 3030C (cationic collector) with AERO 801 and AERO 825 (anionic collectors) provided more selective results for the removal of Fe- and Ti-bearing impurities compared to the individual use of these collectors. Under the optimum reagent combination, a high-quality feldspar concentrate containing 0.018% Fe_2O_3 , 0.135% TiO_2 , 11.02% Na_2O , and 0.22% K_2O was obtained. These results showed that mixed collector systems can improve selectivity and enhance concentrate quality in feldspar flotation [19]. Similarly, Noorbakhsh and Andargoli [20] investigated the beneficiation of feldspar ore from the Damghan region of Iran (0.31% Fe_2O_3). Amine-based cationic collectors were initially used, followed by the application of the anionic collectors Aero 801 and Aero 845 in an acidic medium, resulting in a reduction of the Fe_2O_3 content to 0.11%.

Terzi and Kurşun [21] stated that the wastes generated from feldspar processing plants should not only be considered as materials for disposal, but also as potential secondary resources due to the valuable minerals they contain. In the study, the flotation recovery of TiO_2 -bearing minerals from feldspar wastes was investigated, and the best results were obtained using the R845 (anionic type) collector, pine oil as frother, and at pH 3 conditions. Under the optimum flotation conditions, a concentrate containing 39% TiO_2 was obtained from the $-0.106 + 0.038$ mm size fraction with 89.52% recovery. The results showed that re-evaluating feldspar wastes by flotation could provide both economic benefits and a reduction in waste amount.

Bubble size is a critical parameter in flotation because it directly affects particle–bubble collision and attachment probabilities, froth stability, and consequently separation performance [22–24]. Bubble size is influenced by both operating conditions and reagent regime. In particular, the use of fine bubbles has been reported to improve the recovery and selectivity of fine particles by enhancing particle–bubble interactions and reducing detachment [25,26]. Therefore, bubble size control has attracted considerable attention in the flotation of fine mineral particles. Jameson [27] reported that reducing bubble diameter and increasing the local shear rate significantly improve the probability of particle–bubble collisions and flotation kinetics for ultrafine particles. The study also emphasized that conventional flotation cells generally show poor recovery outside the optimum particle size range of approximately 20–120 μm .

Karagüzel and Çobanoğlu [28] investigated the removal of Fe- and Ti-bearing coloring minerals from feldspathic slimes smaller than 38 μm obtained from feldspar flotation plants using a laboratory-scale Jameson flotation cell, which is known for its ability to generate fine bubbles and high-intensity mixing conditions. The slime sample consisted mainly of albite and contained 1.06% $\text{Fe}_2\text{O}_3 + \text{TiO}_2$. In the flotation experiments, anionic BD-15 and cationic G-TAP collectors, sodium hexametaphosphate as dispersant, and Aerofroth 65 as frother were used. It was determined that single-stage flotation did not provide sufficient selectivity; therefore, a flowsheet combining rougher flotation and stage-wise flotation was proposed. Under optimum conditions (Jg: 0.65 cm/s, jet velocity: 10.6 m/s, and bias factor: 0.8), a ceramic-grade Na-feldspar concentrate containing 0.11% Fe_2O_3 and 0.07% TiO_2 was obtained with approximately 70% recovery. In a related study, Karagüzel [29] investigated the applicability of dissolved air flotation (DAF) for the beneficiation of feldspathic slimes smaller than 38 μm . In the study, BD-15 and Na-oleate were used as collectors, $\text{Na}(\text{PO}_4)_6$ as a dispersant, and pine oil as a frother; the traditional conditioning and charged-bubble methods were compared. It was determined that the fine bubbles (10–100 μm) generated in the DAF system achieved more selective flotation, especially with the charged-bubble method. The optimum flotation performance was achieved at pH 4 with a BD-15 dosage of 500 mg/L, a 5 min rising time, a 5 min drainage time, and charged bubble conditioning. Under these conditions, an albite concentrate con-

taining 0.33% $\text{Fe}_2\text{O}_3 + \text{TiO}_2$ was obtained from a slime sample containing 1.06% $\text{Fe}_2\text{O}_3 + \text{TiO}_2$, and the product was found suitable for ceramic applications.

Although these studies clearly demonstrated the importance of fine bubbles for feldspar flotation, Yáñez et al. [30] argued that bubble size alone cannot fully explain flotation performance. Because fine particles tend to follow fluid streamlines and exhibit low collision probabilities with bubbles, appropriate hydrodynamic conditions characterized by elevated shear rates and energy dissipation are also required to enhance particle–bubble interactions. Consequently, flotation performance cannot be attributed solely to bubble size distribution, as cell hydrodynamics also play a critical role in determining recovery and selectivity.

Gas dispersion characteristics are among the most important hydrodynamic parameters governing flotation performance. As emphasized by Finch et al. [31] and Harris [32], machine-related variables such as impeller speed, air flow rate, and flotation cell design do not directly determine metallurgical performance; rather, they establish the hydrodynamic environment by controlling mixing intensity, solids suspension, gas dispersion, and bubble–particle interactions. Experimental studies by Gorain et al. [33,34] demonstrated that impeller type, impeller speed, and air flow rate significantly influence gas dispersion characteristics, including bubble size distribution, gas holdup, superficial gas velocity, and bubble surface area flux. More recently, Mesa et al. [35] further showed that rotor–stator configuration directly affects bubble size distribution, froth stability, and flotation performance. Therefore, understanding the relationship between flotation cell design, gas dispersion, and bubble characteristics is essential for optimizing flotation performance.

Bubble size is influenced not only by the flotation technology employed but also by impeller design and reagent chemistry. Much of the current understanding of bubble formation, coalescence, and bubble size distribution has been derived from two-phase air–water systems, where physical and chemical variables can be evaluated under controlled conditions. Nevertheless, no systematic study has been reported on the combined influence of impeller design and collector chemistry on bubble size distribution during feldspar flotation.

This study investigates the effects of impeller design and collector chemistry on bubble size in the flotation of feldspar tailings. The relationship between bubble-size characteristics and flotation performance was systematically examined using both bulk and selective flotation approaches, with particular emphasis on the rejection of Fe–Ti-bearing minerals and mica, as well as feldspar recovery. Based on the flotation performance obtained, the potential of feldspar tailings as a source of commercial-grade feldspar concentrates was also assessed.

2. Materials and Methods

2.1. Materials

The sample used in this study was obtained from a feldspar processing plant in the Muğla region. The feldspar processing plant employs a conventional beneficiation flowsheet consisting of grinding, classification, and flotation stages. Hydrocyclone classification is used to separate fine slimes from the flotation feed in the feldspar plant. While the hydrocyclone underflow is processed further through flotation for the removal of mica and colored impurities, the overflow stream is discharged as tailings. The sample investigated in this study was collected from this overflow stream. Despite being rejected from the main process, the material contains considerable quantities of feldspar, indicating its potential for reprocessing and resource recovery.

Malvern Mastersizer 2000 was used to assess the size fraction. Figure 1 presents the particle size distribution of the tailings sample. The analysis revealed d_{80} and d_{50} particle sizes of 70 μm and 34 μm , respectively.

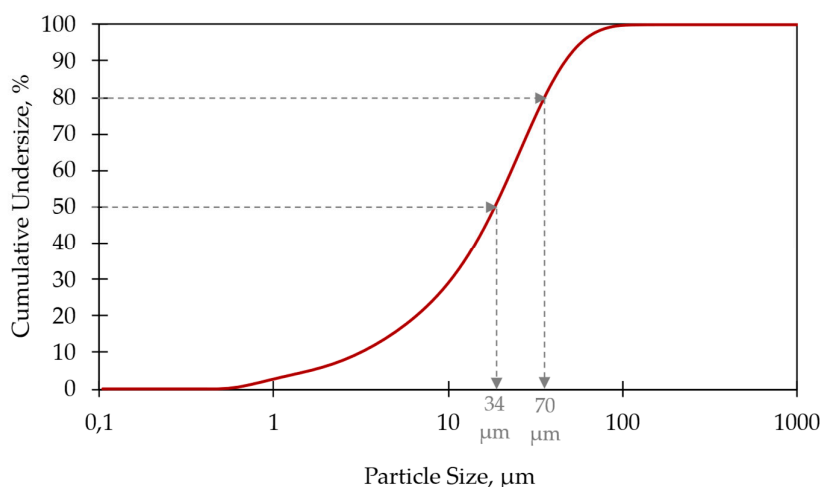


Figure 1. Particle size distribution of the feldspar tailing sample.

Following particle size distribution analysis, the tailings sample was characterized using chemical and mineralogical techniques. The chemical composition was determined by X-ray fluorescence (XRF) analysis, while mineralogical characterization was carried out using X-ray diffraction (XRD). XRF analysis was conducted using Panalytical Epsilon 3 (Malvern Panalytical, Worcestershire, UK). XRD measurements were conducted on a Panalytical X'Pert Pro diffractometer (Malvern Panalytical, Worcestershire, UK) with Cu $K\alpha$ radiation, and mineral phases were identified using the PDF4/Minerals ICDD database. The XRF and XRD results are presented in Table 1 and Figure 2, respectively.

Table 1. Chemical analyses of the tailings sample.

Component	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	K ₂ O	CaO	TiO ₂	Fe ₂ O ₃	Cl	F	LOI
Content, %	6.61	3.04	14.79	69.69	0.18	1.87	0.61	0.31	1.25	0.02	0.37	1.18

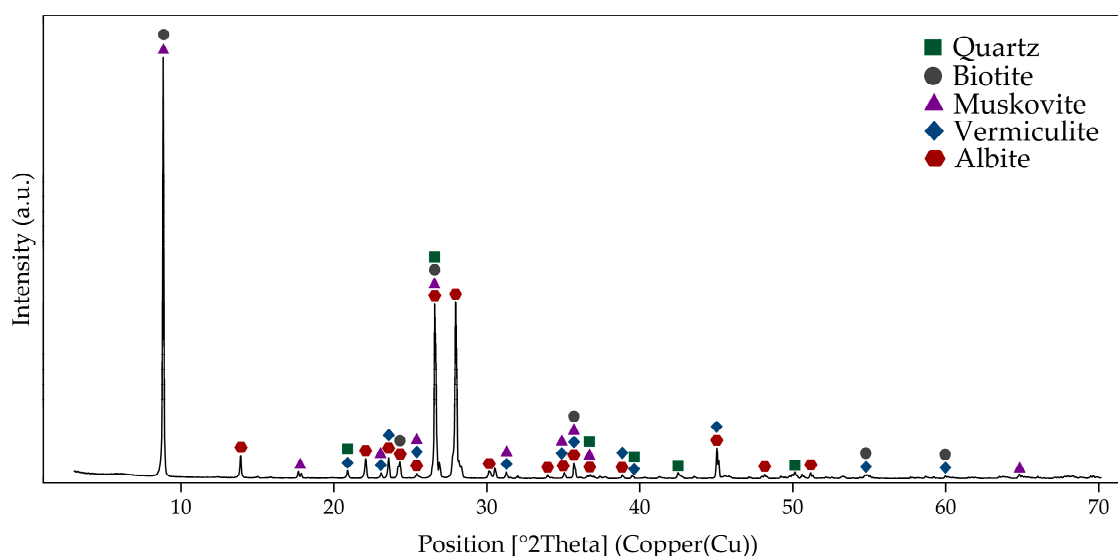


Figure 2. XRD analysis of the tailings sample.

According to the chemical analysis results, the tailings sample contains 1.25% Fe₂O₃, 6.61% Na₂O, 1.87% K₂O, 0.31% TiO₂, and 69.69% SiO₂. The semi-quantitative mineralogical composition of the tailings sample was determined to be approximately 55–60% feldspar, 20–25% mica, and 15–20% quartz. These estimations were conducted using the Reference Intensity Ratio (RIR) method [36]. The calculations were based on the highest intensity diffraction peaks of the constituent minerals and their respective calibration constants. To account for potential analytical errors, the mineral abundances are reported within 5% intervals.

2.2. Method

2.2.1. Flotation Test

All tests were performed using a Denver-type flotation cell (Denver, USA) and a TK Lab Cell manufactured by Tüfekçioğlu (Ankara, Türkiye), a company specializing in the design and production of laboratory-scale flotation equipment. Both cells had a working volume of 1 L, and the impeller speed was maintained at 1100 rpm throughout all experiments. Figure 3 presents schematic illustrations of the experimental apparatus employed in this study, comprising (a) the Denver cell and (b) the TK Lab Cell. The stator structures of the two flotation cells differ considerably. The Denver cell employs a radial blade-type stator with multiple flow-directing elements surrounding the impeller, whereas the TK Lab Cell incorporates a cylindrical cage-type stator consisting of vertical bars. These structural differences may lead to variations in the hydrodynamic characteristics of the flotation system, including turbulence intensity, shear conditions, and bubble breakup behavior. The potential effects of these differences on bubble size distribution and flotation performance were evaluated in this study using both two-phase (gas–liquid) and three-phase (gas–liquid–solid) systems.

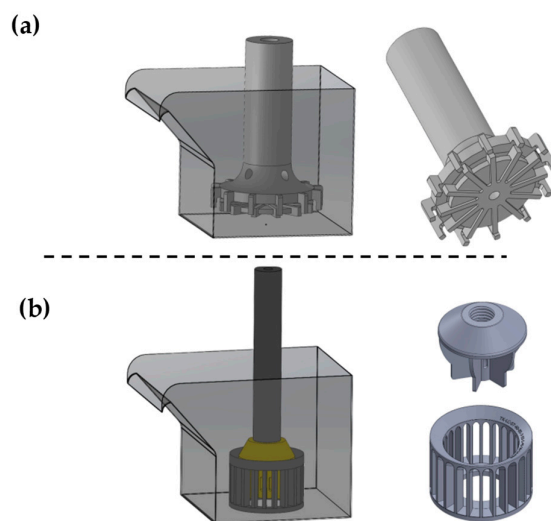


Figure 3. Schematic views of the flotation cells and their rotor–stator assemblies: (a) Denver Cell and (b) TK Lab Cell.

Superficial gas velocity (J_g) is an important gas dispersion parameter in flotation systems and is defined as the volumetric air flow rate entering the flotation cell divided by the cross-sectional area of the cell at the pulp–froth interface. It can be expressed as Formula (1).

$$J_g = \frac{Q_g}{A} \quad (1)$$

Q_g is the air flow rate, and A is the cross-sectional area of the flotation cell. J_g influences gas dispersion behavior and has been reported to affect bubble size characteristics in flotation systems. Previous studies have shown that changes in gas velocity alter bubble formation, bubble–bubble interactions, and coalescence behavior, which may ultimately influence the resulting bubble size [37,38]. The air flow rate (Q_g) was determined using the inverted graduated-cylinder method. A water-filled graduated cylinder was inverted and submerged into the flotation cell, and the displaced air volume collected inside the cylinder was recorded as a function of time. The volumetric air flow rate was then calculated from the measured air volume and collection time and subsequently used to calculate superficial gas velocity (J_g). Each measurement was repeated three times, and the average value was reported.

Both flotation cells were self-aerated and operated at the same pulp volume (1 L), solid-to-liquid ratio (25 wt%), and impeller speed (1100 rpm). The naturally induced air-flow rates, measured using a flow meter, were 3.5 L/min for the Denver Cell and 5.5 L/min for the TK Lab Cell. This difference may be attributed to the different impeller–stator configurations of the flotation cells. The cage-type rotor–stator configuration of the TK Lab Cell is considered to provide a more open flow path for air dispersion, which may contribute to the higher airflow rate under the same operating conditions. Accordingly, the superficial gas velocity (J_g) was measured and used as a hydrodynamic parameter to account for differences in gas dispersion between the Denver and TK Lab Cell flotation machines and to support the interpretation of the observed bubble size distributions and flotation performance.

Flotation tests were conducted to evaluate two different reagent schemes for the removal of Fe/Ti-bearing minerals and mica during feldspar beneficiation. In the current plant operation, Derna 7 (Derboteks, İstanbul, Türkiye) and Der A4 (Derboteks, İstanbul, Türkiye) are used together to float both iron-bearing minerals and mica. In this study, both the existing plant reagent scheme and an alternative selective flotation approach were investigated. In the selective flotation approach, Fe/Ti-bearing minerals were floated separately using R801 and R825 (sulfonate-type anionic collectors, Cytec, Woodland Park, USA), followed by the selective flotation of mica using DAHC (dodecylamine hydrochloride, a cationic collector, 97% purity, Thermo Scientific, Tokyo, Japan). The reagent dosages employed in this study were established through a series of preliminary flotation tests while maintaining the industrial reagent scheme currently used in the feldspar processing plant [39]. The reagents were applied in five successive additions, as this addition strategy provided the most favorable balance between impurity rejection and feldspar recovery. The stage-wise reagent addition strategy adopted in this study follows the approach reported in previous feldspar flotation studies, in which collectors were introduced sequentially during flotation [28,40].

The natural pulp pH was maintained because previous studies have employed the Derna-7/Der A4 reagent scheme under natural pulp pH conditions [41–43]. In the selective flotation tests, Fe/Ti-bearing oxide minerals were first floated at pH 3.5 using the R801 and R825 collectors. Subsequently, mica minerals were floated in a second stage at pH 2.5 using DAHC as the collector. These pH ranges are consistent with the literature. In feldspar flotation, mica minerals, which possess a permanently negatively charged surface, are typically floated with amine collectors in the acidic pH range of 2.5–3.5, whereas Fe/Ti-bearing oxide minerals, whose surfaces are generally positively charged at the flotation pH, are floated with anionic sulfonate collectors [44–46].

Due to the limited information available on the Derna 7 and Der A4 chemicals, FTIR analyses have been conducted in the literature to determine their chemical structures. Derna 7 is classified as an ethoxylated non-ionic collector due to its negligible effect on surface charge and the detection of C–O–C stretching bands typical of non-ionic surfac-

tants. In contrast, Der A4 is identified as a cationic amine-type surfactant according to the FTIR spectrum [43].

The parameter conditions for the conducted tests are presented in Table 2. Following flotation, the floating and sinking products were dried and subsequently analyzed by X-ray fluorescence (XRF) spectroscopy to determine their chemical composition.

Table 2. Conditions for flotation tests.

Bulk Reverse Flotation		Selective Reverse Flotation	
pH	Natural (8–8.5)	pH	3.5
Derna-7, g/t	20 + 20 + 20 + 20 + 20	R801, g/t	50 + 50
Der A4, g/t	4 + 4 + 4 + 4 + 4	R825, g/t	50 + 50
Condition time	5 + 3 + 3 + 3 + 3	pH	2.5
Flotation time	3 + 3 + 3 + 3 + 3	DAHC, g/t	100 + 100
		Condition time	5 + 3 + 5 + 3
		Flotation time	2.5 + 2.5 + 2 + 1.5

2.2.2. Bubble Size Measurement

Bubble size measurements were conducted to evaluate the relationship between flotation performance and bubble characteristics in different flotation cells. Measurements were performed under both two-phase (gas–liquid) and three-phase (gas–liquid–solid) conditions. The two-phase measurements were carried out using the same reagent conditions as the corresponding flotation tests but without mineral particles, whereas the three-phase measurements were performed under identical conditions in the presence of mineral particles. Images captured at each stage were analyzed to determine the bubble size distribution and calculate the Sauter mean diameter using ImageJ software (version 1.8.0). Bubble images were captured from the top of the flotation cell, and a ruler positioned on the left side of the imaging area was used to define the reference length for spatial calibration. Prior to each analysis, the pixel-to-length conversion was performed using the “Set Scale” function of ImageJ, in which a known length of the ruler was defined as the reference; this calibration enabled the bubble dimensions to be expressed in real length units. Bubble diameters were then determined using the “Measure” function, taking the Feret diameter, corresponding to the longest axis of each bubble, as the characteristic bubble dimension. Representative top-view images of fine and coarse bubbles and the corresponding diameter measurements are presented in Figure 4. The Sauter mean diameter (d_{32}) was calculated from measurements of approximately 200–300 bubbles per image, providing a statistically reliable representation of the average bubble size under different experimental conditions. The standard deviations of the bubble diameter measurements at each condition are shown as error bars.

The Sauter mean diameter (d_{32}), defined as the volume-to-surface mean bubble diameter, was used to characterize the bubble size distribution. It was calculated according to Formula (2):

$$d_{32} = \frac{\sum n_i d_i^3}{\sum n_i d_i^2} \quad (2)$$

where n_i is the number of bubbles with diameter d_i .

The calculated Sauter mean diameter values were used as a representative parameter of bubble size to assess hydrodynamic differences between the flotation cells and their influence on flotation recovery and selectivity.

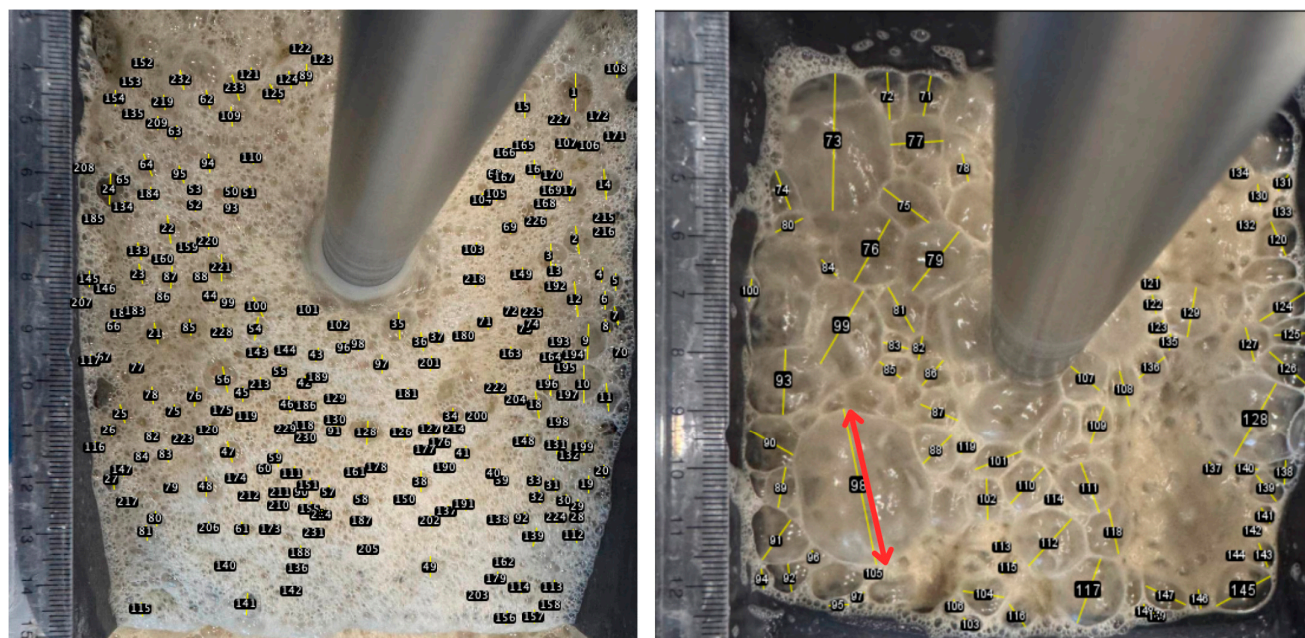


Figure 4. Representative top-view images of fine (**left**) and coarse (**right**) bubbles analyzed using ImageJ software. (The red arrow indicates the bubble diameter, and the black outlines identify the measured bubbles.)

3. Experimental Results

3.1. Bulk Reverse Flotation

Bulk reverse flotation experiments were conducted on the tailings sample at natural pulp pH using Derna-7 (100 g/t) and Der A4 (20 g/t) as collectors, which were added in five stages during flotation. The tests were performed using both the Denver and TK Lab Cell flotation machines to compare their flotation performance under identical reagent conditions. The flotation efficiencies and the content of the sink and float products obtained from the two flotation machines are presented in Figure 5a,b.

As shown in Figure 5a, the float product obtained from the Denver Cell contained higher Fe_2O_3 and TiO_2 contents but lower recoveries of these impurities than that from the TK Lab Cell. In addition, the lower Na_2O and K_2O recoveries indicate reduced feldspar losses to the float product, suggesting a more selective separation by the Denver Cell. As shown in Figure 5b, the sink products obtained from the Denver and TK Lab Cell exhibited very similar chemical compositions, indicating comparable feldspar concentrate grades. However, the Denver Cell achieved significantly higher Na_2O and K_2O recoveries (94.9% and 95.1%) than the TK Lab Cell (74.3% and 74.0%), resulting in substantially higher feldspar recovery despite the similar concentrate content.

Despite the higher alkali recoveries obtained with the Denver Cell, the removal of Fe–Ti-bearing impurities remained limited for both flotation devices. The high Fe_2O_3 and TiO_2 recoveries in the sink products indicate that a significant portion of the impurity minerals remained associated with the feldspar fraction. Therefore, the applied bulk flotation conditions did not provide sufficient selectivity to effectively remove Fe–Ti-bearing minerals, thereby preventing the production of a high-purity feldspar concentrate.

To better understand the influence of bubble characteristics on flotation performance, the Sauter mean bubble diameter (d_{32}) was measured for both flotation cells under two-phase and three-phase conditions using combined additions of Derna-7 (100 g/t) and Der A4 (20 g/t), applied in five successive stages (20 g/t Derna-7 and 4 g/t Der A4 per stage). Figure 6 shows the Sauter mean bubble diameter (d_{32}) for the TK Lab and Denver Cell

under two-phase and three-phase conditions. Bubble sizes were consistently larger in the TK Lab Cell than in the Denver Cell. In both cells, three-phase flotation produced larger bubbles than two-phase flotation. Reagent addition generally affected bubble size, although the trend varied with dosage. Despite the larger bubbles generated in the TK Lab Cell, no improvement in separation recovery was observed.

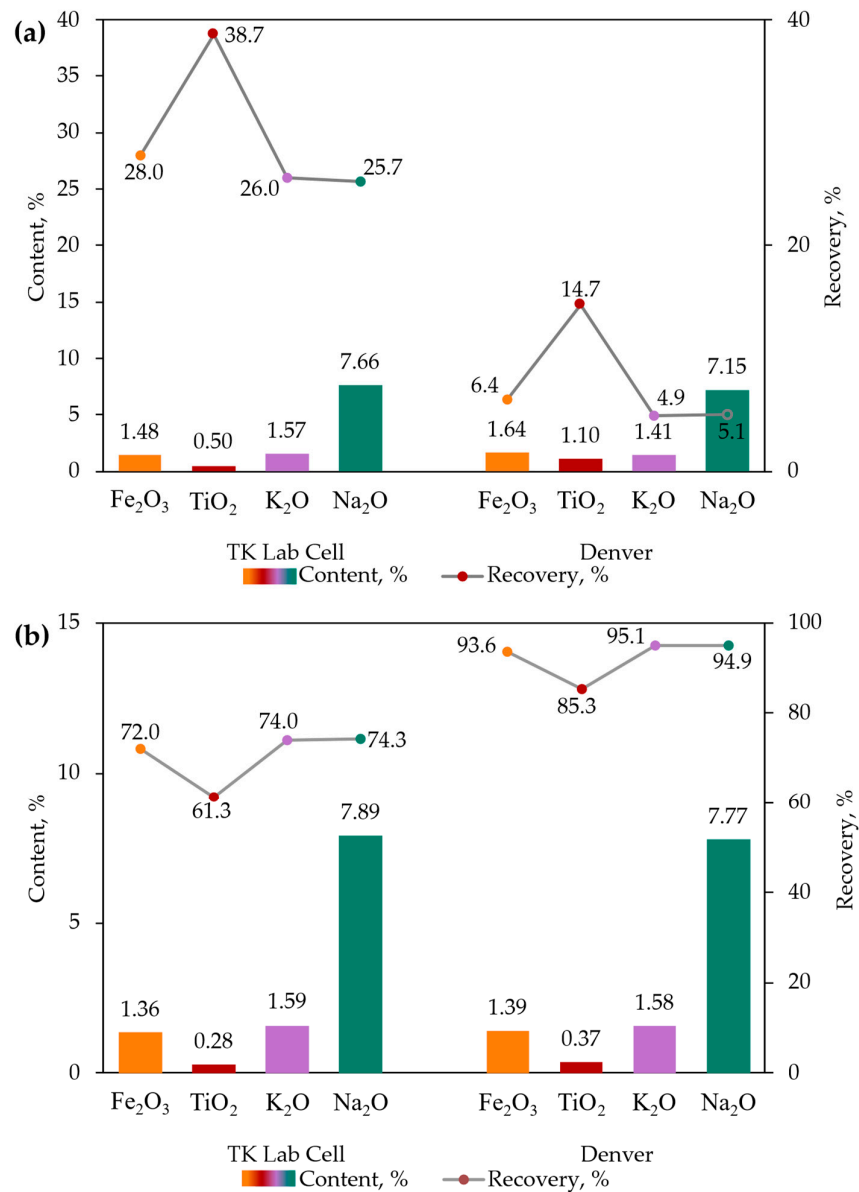


Figure 5. Contents and flotation efficiencies obtained using the bulk flotation reagent scheme in the Denver Cell and TK Lab Cell (a) float product, (b) sink product.

The observed variation in bubble size can also be attributed to the presence of solid particles in the flotation pulp. Grau and Heiskanen [47] reported that the addition of quartz increased the Sauter mean bubble diameter, with the effect becoming more pronounced at solids concentrations above 20 wt.%. They suggested that the increase in slurry viscosity and the damping of turbulence promoted the formation of larger bubbles. Similar observations were previously reported by Tucker et al. [48], who also found that increasing solids concentration resulted in larger bubbles in laboratory flotation cells. These findings are consistent with the present study, where larger bubble diameters were ob-

served under three-phase flotation conditions, confirming the influence of suspended solids on bubble generation and gas dispersion.

Superficial gas velocity measurements revealed significant differences in gas dispersion behavior between the two flotation cells. The J_g value of the TK Lab Cell (0.0637 cm/s) was approximately 7.2 times higher than that of the Denver cell (0.0088 cm/s). According to flotation hydrodynamic theory, increased gas flux enhances bubble–bubble collision frequency and may promote bubble coalescence, resulting in larger bubble diameters. This trend was consistent with the bubble size measurements obtained in the present study, where the TK Lab Cell generated larger bubbles than the Denver cell.

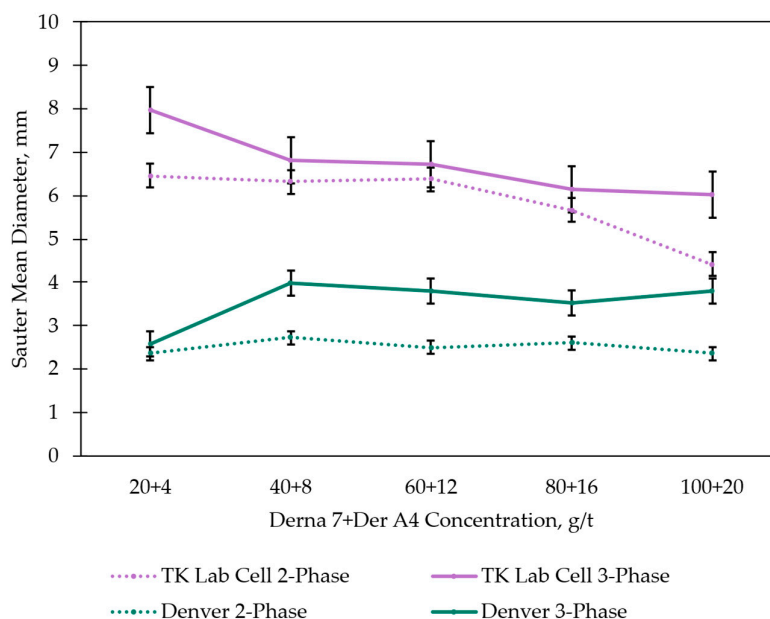


Figure 6. Comparison of Sauter mean diameter from bulk flotation test using Denver and TK Lab Cell.

3.2. Selective Reverse Flotation

To further improve the rejection of Fe–Ti-bearing minerals and mica and enhance feldspar concentrate quality, a selective reverse flotation approach was investigated using both flotation cells. The bulk flotation results demonstrated that, although high feldspar recoveries were achieved, the plant reagent scheme based on Derna-7 and Der A4 did not provide sufficient selectivity for impurity removal. Therefore, the plant reagent scheme was replaced with a selective reagent scheme employing sulfonate- and amine-type collectors in two flotation stages. In the first stage, Fe–Ti-bearing oxide minerals were floated using the sulfonate-type collectors R801 (100 g/t) and R825 (100 g/t). In the second stage, the sink product obtained from the first stage was subjected to mica flotation using the amine-type collector DAHC (200 g/t). The results of the selective flotation experiments conducted in the Denver and TK Lab Cell are presented in Figure 7a,b.

Selective flotation using the sulfonate–amine reagent scheme significantly improved the rejection of Fe–Ti-bearing minerals compared with the bulk flotation results (Figure 7a,b). In the float products (Figure 7a), the TK Lab Cell exhibited higher Fe_2O_3 flotation recovery than the Denver Cell, whereas the Na_2O flotation efficiencies were nearly identical at approximately 30% for both flotation cells, indicating comparable feldspar losses to the float product. In the sink products (Figure 7b), the Fe_2O_3 contents were markedly reduced compared with those obtained by bulk flotation, reaching 0.95% in the Denver Cell

and 0.49% in the TK Lab Cell, while the total alkali contents remained high at 9.41% and 9.57%, respectively. The Na₂O flotation efficiencies were nearly identical for the Denver Cell (70.4%) and TK Lab Cell (70.6%). These results demonstrate that the selective flotation approach, together with the sulfonate–amine reagent scheme, improved impurity rejection, with the TK Lab Cell providing more effective rejection of Fe-bearing minerals without increasing feldspar losses to the float product. Moreover, the TiO₂ content of this concentrate (0.24%) is below the limit of approximately 0.3% generally reported for ceramic-grade feldspar products [11]; therefore, the concentrate obtained with the TK Lab Cell satisfies both the Fe₂O₃ and TiO₂ requirements for second-grade ceramic applications.

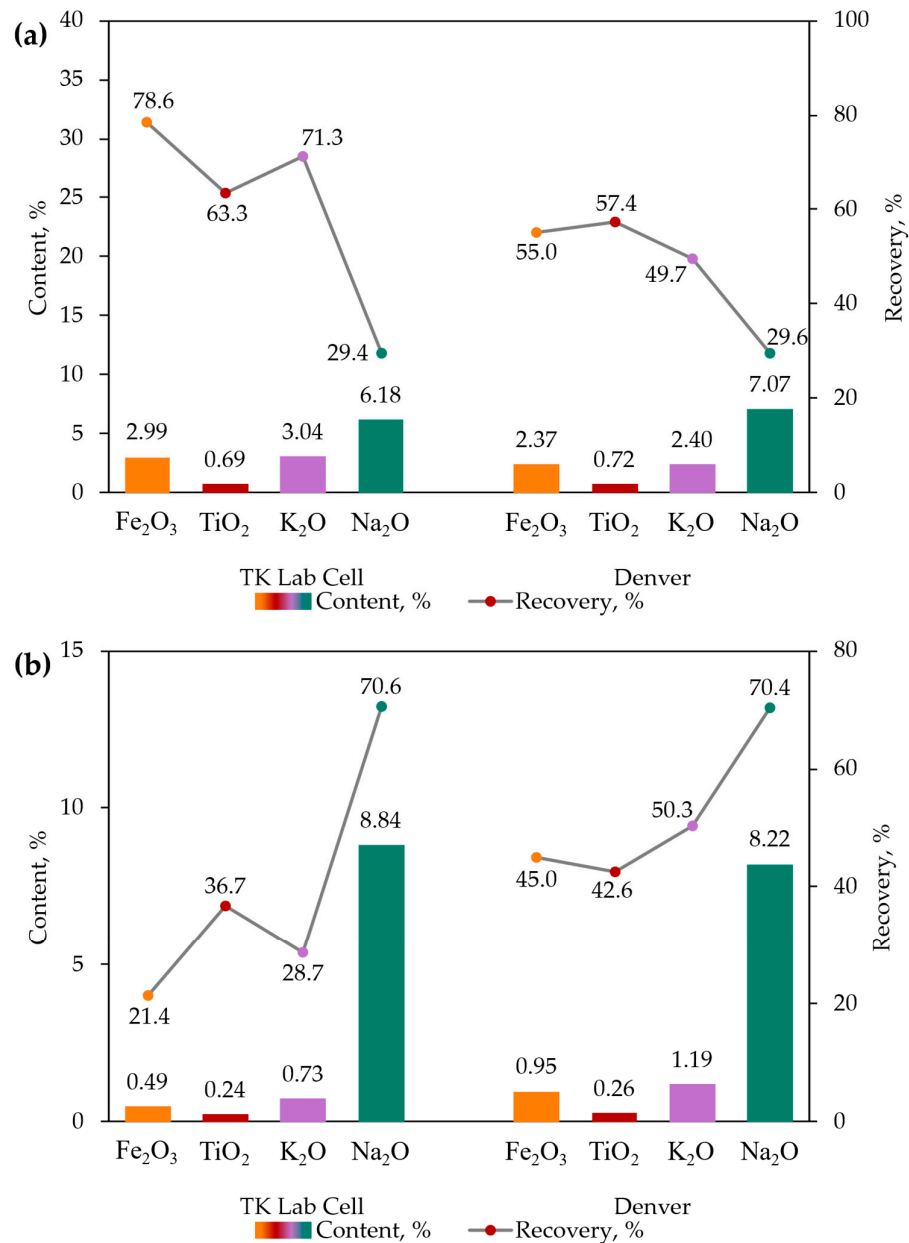


Figure 7. Contents and flotation efficiencies obtained using the selective flotation reagent scheme in the Denver Cell and TK Lab Cell ((a) float product, (b) sink product).

Figure 8 presents the Sauter mean bubble diameter (d_{32}) measured at each stage of the selective flotation process in the TK Lab and Denver cells using the sulfonate–amine

reagent scheme. The first two flotation stages were carried out using the sulfonate collectors R801 and R825 for Fe–Ti oxide flotation, while the last two stages employed the amine collector DAHC for mica flotation. As shown in Figure 8, the sulfonate collectors (R801–R825) produced relatively fine bubbles during the Fe–Ti oxide flotation stage, whereas the addition of DAHC during the mica flotation stage markedly increased the bubble diameter. Compared with the bulk flotation experiments (Figure 6), bubble sizes were generally smaller during selective flotation, particularly in the Fe–Ti oxide flotation stage. However, bubble diameters increased after DAHC addition and approached those observed in the bulk flotation tests. These results indicate that bubble size is influenced not only by flotation cell design but also by the reagent scheme.

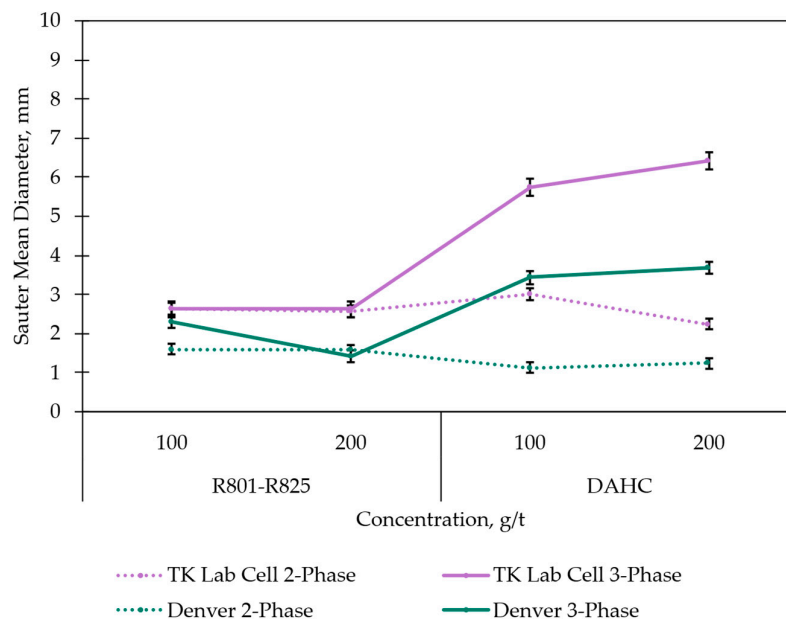


Figure 8. Comparison of Sauter mean diameter from selective flotation test using Denver and TK Lab Cell.

The larger bubbles observed during the mica flotation stage may be associated not only with the use of the amine collector (DAHC) but also with the plate-like morphology of mica particles. Such particles can modify local hydrodynamic conditions and bubble–particle interactions, potentially promoting bubble coalescence and increasing bubble diameter. The influence of particle morphology on bubble stability and froth hydrodynamics has also been discussed in previous studies. Bournival et al. [49] reported that particle characteristics, particularly particle shape, play an important role in determining bubble stability and froth behavior. Non-spherical particles can modify the geometry of the liquid film and alter local hydrodynamic conditions at the bubble surface, thereby influencing bubble coalescence and froth stability. Consistent with these observations, Bhambhani et al. [50] demonstrated that the platy morphology of mica significantly influences particle transport through the froth, resulting in greater entrainment than more equant gangue minerals and highlighting the important role of particle shape in flotation performance. In a subsequent study, Bhambhani et al. [51] demonstrated that the transport of platy mica particles within the froth is governed by the balance between the upward hydrodynamic drag generated by rising bubbles and the downward drainage driven by gravity. Owing to their high aspect ratio, platy mica particles experience greater drag forces and lower settling velocities than more equant gangue minerals, thereby enhancing particle transport and retention within the froth. These findings support the interpretation that

both the plate-like morphology of mica particles and the associated changes in froth hydrodynamics may have contributed to the larger bubble diameters observed during the mica flotation stage in the present study.

The differences in bubble size observed between the Denver and TK Lab flotation cells are likely related to differences in their hydrodynamic characteristics and gas dispersion mechanisms. Similar observations were reported by Grau and Heiskanen [47], who demonstrated that flotation cell design, operating conditions, and rotor–stator configuration significantly influence bubble generation and the resulting Sauter mean bubble diameter. Since bubble size directly affects the available bubble surface area for particle attachment, these hydrodynamic differences can contribute to variations in flotation performance.

Consequently, the present results demonstrate that bubble characteristics during selective flotation are governed by the combined influence of flotation cell hydrodynamics, reagent chemistry, and particle properties. The interaction among these factors governs bubble generation, particle–bubble attachment, and froth stability, ultimately influencing the recovery and selectivity of feldspar flotation.

3.3. Relationship Between Bubble Size and Mass Pull

To investigate the relationship between bubble size and flotation performance, the Sauter mean bubble diameter was compared with mass pull under bulk and selective flotation conditions. Mass pull, defined as the percentage of the feed mass recovered in the froth product, was used to evaluate the amount of material transferred to the froth phase during flotation. Figure 9 shows the relationship between bubble size and mass pull during bulk flotation. Although the reagents were added stepwise during the flotation tests (Table 2), the dosages shown in Figures 9 and 10 represent the total cumulative dosage applied per test. In the TK Lab Cell, both bubble size and mass pull generally decreased with increasing reagent dosage, whereas the Denver Cell exhibited only minor changes in bubble size and relatively low mass pull throughout the tests. The TK Lab Cell consistently produced larger bubbles and higher mass pull than the Denver Cell.

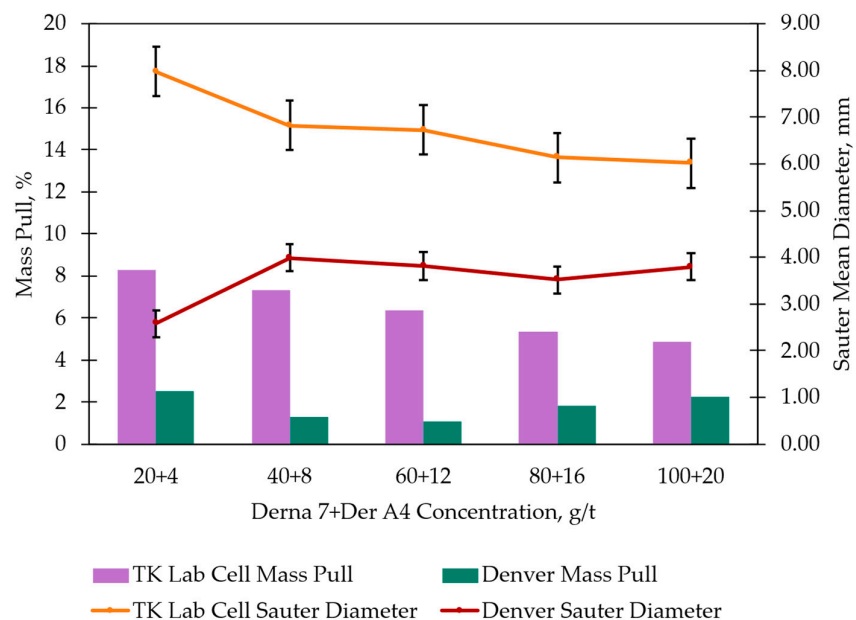


Figure 9. Comparison of mass pull and Sauter mean diameter for bulk flotation tests.

Figure 10 shows the relationship during selective flotation. Bubble size remained small during oxide flotation with R801–R825 and increased markedly after DAHC addition. Mass pull also increased during the mica flotation stage, particularly in the Denver Cell.

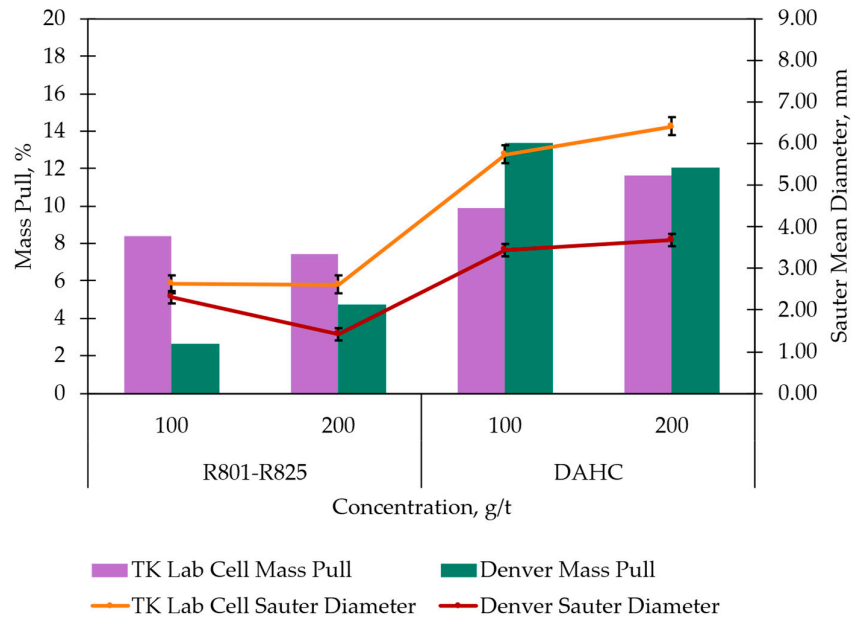


Figure 10. Comparison of mass pull and Sauter mean diameter for selective flotation tests.

The trends observed in Figures 9 and 10 indicate that the relationship between bubble size and mass pull varied with reagent dosage and reagent type. Flotation performance depends on the combined effects of bubble size, reagent type, and flotation cell hydrodynamics rather than on a single parameter alone. These findings indicate that larger bubbles were generally associated with higher mass pull, particularly in the TK Lab Cell, whereas the finer bubbles generated in the Denver Cell resulted in lower mass pull but improved feldspar recovery.

Regardless of the reagent scheme employed and the corresponding variations in mass pull, the TK Lab Cell consistently generated larger bubbles than the Denver Cell under both bulk and selective flotation conditions. Although reagent chemistry influenced bubble size within each flotation stage, the relative difference between the two flotation cells remained essentially unchanged. These observations suggest that the hydrodynamic conditions established by the respective impeller–stator configurations primarily governed bubble generation and gas dispersion, whereas the reagent scheme mainly influenced bubble size within the hydrodynamic environment characteristic of each flotation cell. Therefore, the effect of reagent chemistry on bubble characteristics should be interpreted in conjunction with flotation cell hydrodynamics, as both factors collectively determine the bubble size distribution and, consequently, flotation performance.

3.4. Implications for Sustainable Valorization

The experimental results demonstrated that feldspar tailings containing significant amounts of feldspar can be effectively upgraded through selective flotation. The proposed reagent scheme enabled the production of low-iron feldspar concentrates while maintaining acceptable alkali contents. In addition to reagent selection, flotation cell design was found to significantly influence separation performance. Although the Denver Cell generated finer bubbles, the TK Lab Cell provided superior impurity rejection under opti-

mized conditions. Therefore, both the reagent scheme and flotation cell characteristics should be considered in the development of sustainable flowsheets for feldspar slime valorization. Based on these findings, a conceptual process flowsheet is proposed to maximize resource recovery, improve concentrate quality, and minimize tailings generation. A conceptual process flowsheet based on the experimental results is presented in Figure 11, highlighting the role of reagent selection and flotation cell design in sustainable feldspar tailing valorization.

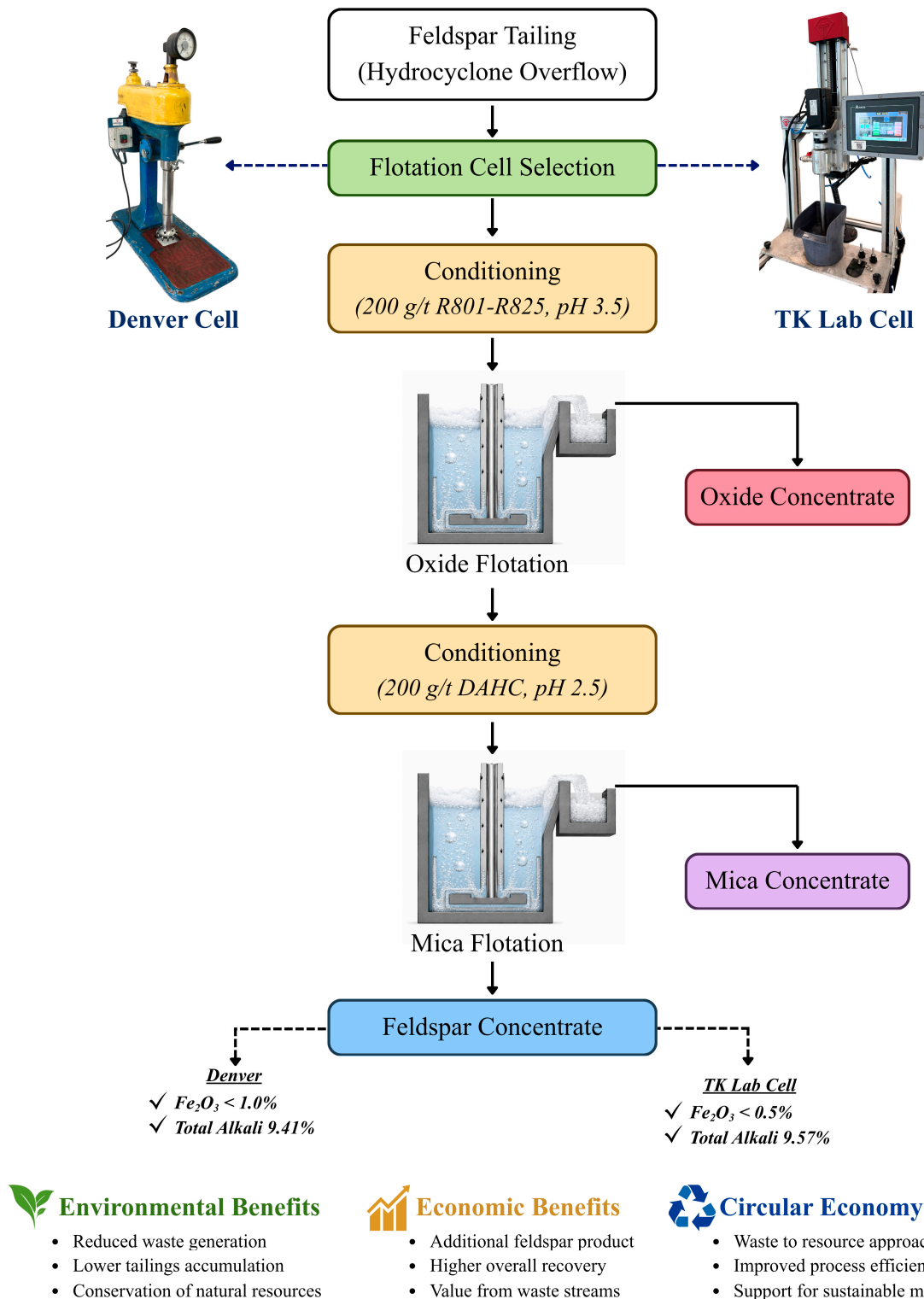


Figure 11. Proposed sustainable flotation flowsheet highlighting the influence of reagent scheme and flotation cell design on feldspar tailings valorization.

The proposed flotation flowsheet contributes to sustainable mineral processing by enabling the recovery of valuable feldspar from waste slimes that are otherwise disposed of in tailings facilities. Reprocessing these tailings reduces the demand for primary raw materials, minimizes waste generation, and improves resource efficiency. Therefore, the

developed approach supports circular economy principles and provides both environmental and economic benefits through the valorization of industrial waste streams.

4. Discussion

The present study demonstrates that the flotation performance of feldspar tailings is governed by the combined effects of reagent chemistry, flotation cell hydrodynamics, and bubble characteristics rather than by a single operating parameter. Although the influence of bubble size on flotation has been extensively reported in the literature, the results obtained in this study indicate that bubble size alone cannot fully account for the observed differences in separation recovery among flotation cells.

The conventional plant reagent scheme, consisting of the combined addition of Derna-7 and Der A4, produced high feldspar recoveries but failed to provide sufficient rejection of Fe–Ti-bearing minerals. The high impurity contents remaining in the sink products indicate that the simultaneous flotation of different gangue minerals reduced flotation selectivity. In contrast, the sequential reagent scheme employing sulfonate collectors (R801 and R825) followed by the amine collector (DAHC) significantly improved impurity rejection while maintaining satisfactory alkali recovery. The improvement is attributed to the selective adsorption behavior of the collectors, allowing oxide minerals and mica to be floated independently under their respective optimum flotation conditions. The better performance of selective flotation compared with bulk flotation can be explained by the staged removal of different gangue minerals. According to Bulatovic [44], feldspar ores containing mica and iron-bearing minerals are generally treated by sequential flotation to improve selectivity. Similarly, in this study, the use of sulfonate collectors for Fe–Ti-bearing minerals followed by DAHC for mica flotation resulted in more effective impurity removal than the bulk flotation approach. In the bulk reverse flotation stage, the natural pulp pH (8.0–8.5) and the mixed collector system (Derna 7 and Der A4) were selected based on the current plant practice. Under these conditions, the non-ionic Derna 7 and cationic Der A4 provide complementary adsorption characteristics toward Fe–Ti-bearing minerals and mica, and the flotation response results from the combined effects of collector chemistry and pulp pH rather than a single adsorption mechanism [52]. In contrast, the selective flotation conditions were designed according to the surface charge characteristics of the impurity minerals and the adsorption behavior of the collectors. Fe–Ti-bearing oxide minerals were floated at pH 3.5 using the anionic sulfonate collectors R801 and R825. Since the point of zero charge (PZC) of most iron oxides is around pH 6–8, their surfaces are positively charged at pH 3.5, favoring the adsorption of negatively charged sulfonate species [28,53,54]. Subsequently, mica was floated at pH 2.5 using DAHC. Unlike iron oxides, mica possesses a permanent negative structural charge due to isomorphic substitution and therefore readily adsorbs protonated amine species (RNH_3^+) through electrostatic attraction, resulting in enhanced flotation selectivity [55–58].

An important outcome of this work is that flotation performance could not be correlated solely with bubble size. The Denver flotation cell consistently generated finer bubbles than the TK Lab Cell under both two-phase and three-phase conditions. According to classical flotation theory, smaller bubbles provide a larger specific surface area, thereby increasing particle–bubble collision probability and improving flotation kinetics, particularly for fine particles [22,25,27]. However, despite producing larger bubbles, the TK Lab Cell showed better rejection of Fe–Ti-bearing minerals and produced a higher-quality feldspar concentrate. This suggests that bubble size alone did not control flotation performance.

The observed differences are more reasonably explained by variations in flotation cell hydrodynamics. The two flotation cells employ different rotor–stator configurations, which directly influence gas dispersion, turbulence intensity, bubble breakup, and solids

suspension. Finch et al. [31] emphasized that machine variables such as impeller design and air flow primarily influence flotation through their effect on gas dispersion characteristics rather than through direct metallurgical responses. Similarly, Grau and Heiskanen [47] demonstrated that flotation cell design significantly affects bubble generation and bubble size distribution. The substantially higher superficial gas velocity measured in the TK Lab Cell further supports this interpretation. The higher gas flux increased bubble generation and bubble–bubble interactions, resulting in larger bubbles while simultaneously modifying the hydrodynamic environment responsible for particle transport and froth formation. Consequently, the superior flotation performance obtained in the TK Lab Cell appears to result from more favorable hydrodynamic conditions rather than from bubble size alone. Although the TK Lab Cell achieved better impurity removal, it resulted in lower alkali recoveries than the Denver cell. In contrast, the Denver cell provided higher Na₂O and K₂O recoveries (94.9% and 95.1%, respectively), but removed impurities less effectively. This indicates a trade-off between impurity rejection and alkali recovery. Therefore, the selection of the flotation cell depends on whether the priority is higher concentrate purity or higher feldspar recovery. The Na₂O recovery of approximately 70% obtained in the selective flotation also suggests that part of the feldspar was lost to the floating products. Although this may reduce the overall recovery, additional scavenger stages or further process optimization could be considered to recover part of these losses while maintaining concentrate quality. Considering that the feed material consists of feldspar processing tailings, this level of feldspar loss may still be considered acceptable for valorization purposes. In addition, a cleaning circuit can also be applied to remove impurities from the bulk concentrate.

Bubble size measurements also revealed systematic differences between two-phase and three-phase systems. In both flotation cells, larger bubbles were observed in the presence of solid particles than in air–water systems. This behavior is consistent with previous studies by Tucker et al. [48] and Grau and Heiskanen [47], who reported that suspended solids increase slurry viscosity and damp local turbulence, thereby promoting bubble coalescence and increasing the Sauter mean diameter. The agreement between the present results and previous investigations confirms that bubble size measurements performed only under two-phase conditions cannot fully represent the hydrodynamic behavior occurring during actual flotation operations.

The selective flotation tests further demonstrated that reagent chemistry strongly influenced bubble characteristics. During the flotation of Fe–Ti-bearing minerals using sulfonate collectors, relatively fine bubbles were generated in both flotation cells. Following the addition of DAHC during mica flotation, bubble diameters increased considerably. This behavior is likely associated not only with the surface-active characteristics of the amine collector but also with the morphology of mica particles. Plate-like mica particles modify local hydrodynamic conditions within the pulp and froth, promoting bubble coalescence and increasing bubble stability. Similar effects of particle morphology on froth transport and bubble behavior have been reported by Bournival et al. [49] and Bhambhani et al. [50,51], who demonstrated that platy particles alter froth drainage and particle transport owing to their high aspect ratios. These observations suggest that both reagent chemistry and particle morphology contributed to the changes in bubble size observed during the selective flotation stages.

The measured d_{50} (34 μm) and d_{80} (70 μm) values indicate that a substantial portion of the sample falls within the fine size range (<38 μm) where flotation efficiency is known to decline markedly [59]. Particles within this size range exhibit weak attachment due to their low inertia, which reduces the probability of collision with air bubbles; at the same time, their large specific surface area can increase reagent consumption and make them more susceptible to slime coating. In addition, hydrophilic particles finer than approxi-

mately 20 μm can be non-selectively transported into the froth phase along with water, as particles of this size lack sufficient inertia to drain back into the pulp (entrainment) [60]. Therefore, the impeller design and bubble size control examined in this study play a particularly important role in improving collision and attachment efficiency for the fine particle fraction present in the sample, thereby enhancing selective flotation performance.

The relationship between bubble size and mass pull further illustrates the complexity of flotation systems. During the bulk flotation stage and the Fe/Ti flotation stage (R801–R825), lower mass pull generally coincided with smaller bubble diameters. However, this relationship changed after the addition of DAHC. Although the Denver Cell continued to produce smaller bubbles than the TK Lab Cell, the mass pull increased markedly. This indicates that bubble size alone cannot explain the observed flotation behavior. The plate-like morphology of mica particles and the associated changes in froth characteristics are likely to enhance particle transport and froth carrying capacity, resulting in higher mass pull despite the smaller bubble diameter. This interpretation is consistent with the findings of Bhambhani et al. [50], who showed that the platy morphology of mica promotes particle transport through the froth and results in greater entrainment than more equant gangue minerals.

Beyond the flotation mechanisms, the results demonstrate the considerable potential for valorizing feldspar processing tailings. The investigated hydrocyclone overflow, commonly discarded as waste, contained approximately 55–60% feldspar and was successfully upgraded to a concentrate containing 0.49% Fe_2O_3 , 0.24% TiO_2 and 9.57% total alkalis. The Fe_2O_3 and TiO_2 contents satisfy the requirement for second-grade ceramic applications. Since the material already exists in a fine particle size suitable for flotation, the proposed process does not require an additional grinding stage, reducing both energy consumption and processing costs. Consequently, reprocessing feldspar tailings offers both economic and environmental benefits by recovering valuable minerals from an existing waste stream while simultaneously reducing the volume of material requiring disposal.

Taken together, the present study demonstrates that feldspar processing tailings can be successfully upgraded into a valuable feldspar product. The results also provide further insight into the effects of reagent scheme, bubble size, and flotation cell design on flotation performance. Although only selected flotation parameters were investigated, the findings highlight the importance of considering these factors together when evaluating and optimizing flotation performance.

5. Conclusions

Feldspar slimes generated during industrial feldspar processing contain significant amounts of recoverable feldspar and can be successfully upgraded by selective flotation. Since the hydrocyclone overflow was treated directly without additional grinding or size reduction, the proposed process offers a potentially more economical and energy-efficient alternative for tailings reprocessing.

The sequential flotation scheme using R801–R825 for Fe–Ti-bearing minerals and DAHC for mica significantly improved concentrate quality in flotation cells with different impeller–stator configurations (Denver and TK Lab Cells). The highest concentrate quality was achieved in the TK Lab Cell, producing a feldspar concentrate containing as low as 0.49% Fe_2O_3 while maintaining total alkali contents between 9.41% and 9.57%, demonstrating its suitability for industrial applications.

The Denver Cell generally achieved higher feldspar recovery, whereas the TK Lab Cell provided more selective rejection of Fe–Ti-bearing minerals despite generating larger bubbles. These findings indicate that flotation performance is governed not only by bubble size but also by the combined effects of reagent chemistry and flotation cell hydrodynamics.

The findings demonstrate that selective flotation provides an effective route for recovering valuable feldspar from processing tailings while reducing waste generation and improving resource efficiency. The proposed approach has the potential to lower processing costs and support the sustainable valorization of feldspar processing tailings.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

LED	Light Emitting Diode
DAF	Dissolved Air Flotation
XRF	X-Ray Fluorescence
XRD	X-Ray Diffraction
ICDD	International Centre for Diffraction Data

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