Development of Activator Technology for Flotation Desulphurization of High-Sulphur Bauxite

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Abstract

With the rapid advancement of China's alumina industry, the depletion of high-grade bauxite resources has intensified, making the efficient utilization of high-sulphur bauxite a critical challenge for the industry's sustainable development. Traditional flotation desulphurization methods, while effective, rely on strong acid activators such as sulphuric acid and copper sulphate, which pose significant drawbacks including high corrosiveness, environmental pollution, and elevated costs. These limitations are particularly pronounced when processing high-sulphur bauxite with substantial clay content, leading to reduced desulphurization efficiency. Addressing this issue, the development of an environmentally friendly, efficient, and stable desulphurization activator has emerged as a pressing technological imperative. This study introduces an innovative composite activator system based on phytic acid for the desulphurization of high-sulphur bauxite. Through the optimization of its chemical structure and physical properties, the proposed activator significantly enhances desulphurization efficiency while concurrently reducing energy consumption and environmental impact. The research encompasses a comprehensive analysis of the mineralogical characteristics of high-sulphur bauxite, comparative flotation desulphurization experiments using conventional activators, and the development and application of the novel activator in high-sulphur bauxite processing. Experimental results demonstrate that the new activator not only exhibits high selectivity in sulphide removal but also minimizes the dissolution of valuable aluminium minerals, aligning with the principles of green metallurgy. When applied to raw ore with a sulphur content of 5.04 %, the flotation desulphurization process utilizing the composite activator reduced collector consumption by over 20 % compared to traditional methods. Employing a "one roughing, three cleaning, and three scavenging" closed-circuit flotation process, the system achieved a high-quality aluminium concentrate with a yield of 87.9 % and a sulphur content of 0.47 %, alongside a sulphur concentrate with a yield of 12.1 % and a sulphur content of 38.3 %.The novel activator offers a groundbreaking solution for the efficient utilization of high-sulphur bauxite resources, holding significant theoretical and practical value for advancing sustainable practices in bauxite resource development. Its application is expected to contribute substantially to the industry's efforts in resource optimization and environmental stewardship.

Keywords: High-Sulphur Bauxite, Flotation Desulphurization, Activator.

1. Introduction

With the rapid development of China's alumina industry, the demand for high-grade bauxite has steadily increased, leading to a gradual decline in the quality of existing bauxite reserves. Simultaneously, the vast domestic resources of high-sulphur bauxite have not received adequate attention, posing a severe threat to the sustainable development of China's aluminium industry. Addressing the challenges of sulphur removal from low-quality, high-sulphur bauxite and achieving its cost-effective utilization have long been critical issues hindering the high-quality development of the alumina industry.

Flotation desulphurization is currently one of the most advanced methods for bauxite desulphurization. This technique is well-suited for processing high-sulphur bauxite ores, offering excellent desulphurization performance, economic efficiency, and technical feasibility. Traditional activators such as sulphuric acid or copper sulphate have been widely employed. However, sulphuric acid, as a strong acid, exhibits high corrosiveness, environmental hazards, safety risks, and detrimental effects on worker health. Its industrial application is further complicated by challenges in transportation, storage, production management, and pipeline corrosion. Copper sulphate, while effective, is costly and also corrosive, leading to long-term damage to flotation equipment and pipelines, thereby compromising the desulphurization process. Moreover, conventional activators demonstrate poor performance in activating high-sulphur bauxite slurries with high clay content, adversely affecting the quality of the final bauxite concentrate after flotation. Consequently, the development of a novel activator for high-sulphur bauxite flotation under weakly acidic or acid-free conditions is of paramount importance. Such innovation is critical to achieving cleaner production in mineral processing plants, enhancing economic efficiency, and promoting sustainable mining practices [1].

The research and development of new desulphurization activators aim to address the limitations of traditional methods, including low efficiency, high costs, and poor environmental adaptability. By optimizing the chemical structure and physical properties of activators, their activity and selectivity in the desulphurization process can be significantly enhanced, enabling efficient sulphide removal while minimizing damage to valuable mineral components. Furthermore, the application of novel activators can reduce energy consumption and waste emissions, aligning with the principles of green production.

Globally, increasingly stringent environmental regulations and demands for resource efficiency have positioned the development of advanced desulphurization activators as a key industry focus. These innovations not only help enterprises meet environmental standards and enhance market competitiveness but also facilitate the comprehensive utilization of bauxite resources, driving sustainable development across the sector [2].

In summary, the development of novel desulphurization activators represents an effective strategy to address current challenges in bauxite resource exploitation. It serves as an essential pathway toward achieving dual objectives: the efficient utilization of high-sulphur bauxite and environmental protection. With ongoing advancements in scientific research and technological innovation, these next-generation activators are poised to demonstrate even broader application prospects in the field of bauxite resource development.

2. Characterization of Bauxite Ore

2.1 Mineralogical Characterization

The ore samples were selected from high-sulphur bauxite deposits in a specific region of Guizhou Province. Mineralogical analysis of the samples was conducted using X-ray fluorescence (XRF) spectroscopy and QEMSCAN (Quantitative Evaluation of Minerals by Scanning Electron Microscopy). Sulphur content was determined by an infrared carbon-sulphur analyser, while organic carbon was measured via titration. The multi-element analysis results of the ore samples are summarized in Table 1.

Table 1. Multi-element analysis results of ore samples (%).

Al_2O_3	SiO_2	Fe_2O_3	TiO_2	K_2O	Na_2O	CaO	MgO	Loss on Ignition	S	C	A/S
58.31	10.39	9.5	2.51	0.35	0.11	0.79	0.39	16.4	5.04	0.35	5.61

From the results in Table 2-1, it can be observed that: the sulphur (S) content in the ore sample is 5.04 %, which classifies the bauxite as high-sulphur grade according to the Chinese bauxite ore classification standard (GB3497-83). The sample exhibits an Al_2O_3 content of 58.31 % and an aluminium-to-silica ratio (A/S) of 5.61, meeting the requirements for raw material in Bayer process alumina production. The mineral phase composition of the sample was determined by X-ray diffraction (XRD), and the analysis results are presented in Table 2.

Table 2. Mineral phase analysis results of ore samples (%).

Diaspore	Boehmite	Chlorite	Kaolinite	Illite	Pyrite
55.5	4	8	12	3.5	9.8
Dolomite	**Calcite**	**Anatase**	**Rutile**	**Světlogorskite**	
2	1.4	2.1	0.3	0.5	

From the results in Table 2, it can be concluded that: The aluminium-bearing minerals in the ore sample are predominantly diaspore, with minor amounts of boehmite. The silicon-bearing minerals mainly consist of kaolinite and illite, while sulphur is primarily present as pyrite. Based on the chemical composition and mineral phase characteristics of the sample, the ore is classified as diaspore-type high-sulphur bauxite, wherein sulphur predominantly exists in the form of pyrite.

2.2 Particle Size Distribution of Major Minerals

The bauxite ore sample was crushed to a particle size below 1 mm. The particle size distribution of the major minerals in the sample was quantitatively determined using QEMSCAN (Quantitative Evaluation of Minerals by Scanning Electron Microscopy), and the results are presented in Table 3.

Table 3. Particle size distribution of major minerals in ore samples (%).

Size Fraction (mm)	Diaspore		Pyrite	
	Content	Cumulative	Content	Cumulative
+0.300	2.95	2.95	0.03	0.03
0.150–0.300	30.23	33.18	26.52	26.55
0.075–0.150	26.35	59.53	32.55	59.11
0.038–0.075	10.08	69.61	12.23	71.34
0.019–0.038	5.40	75.01	10.94	82.27
0.010–0.019	7.25	82.26	9.20	91.48
-0.010	17.74	100.00	8.52	100.00

The results indicate that diaspore and pyrite in the sample are predominantly concentrated in the 0.075–0.300 mm size fraction, exhibiting a fine-grained and heterogeneously distributed texture. In the <0.010 mm size fraction, diaspore and pyrite account for 17.74 % and 8.52 % of the total content, respectively.

The liberation degree of major minerals in the ore sample was determined using QEMSCAN (Quantitative Evaluation of Minerals by Scanning Electron Microscopy), and the results are presented in Tables 4 and 5. Analysis of Table 4: the results indicate that 15.31 % of diaspore in the crushed sample is fully liberated, primarily concentrated in the < 0.010 mm size fraction. Rich composite particles (grains with > 80 % target mineral content) account for 61.16 %, predominantly in the > 0.075 mm fraction.

Analysis of Table 5: pyrite exhibits poor liberation in the crushed sample, with only 12.42 % fully liberated particles, mainly in the < 0.010 mm fraction. Rich composite particles (grains with > 80 % pyrite content) constitute 51.41 %, predominantly in the > 0.075 mm fraction. Combined with mineral scanning images, pyrite is partially intergrown with diaspore or embedded in gangue minerals (e.g., kaolinite, illite), exhibiting irregular boundaries that complicate its separation from diaspore.

Table 4. Liberation degree analysis of diaspore in ore samples (%).

Size Fraction (mm)	Composite Particles (Liberation Degree Range)					Liberated Particles
	0–20%	20–40%	40–60%	60–80%	80–100%	100%
+0.075	1.52	0.31	2.19	6.98	49.01	0.00
-0.075+0.038	0.13	0.40	0.40	2.39	6.61	0.00
-0.038+0.019	0.11	0.17	0.77	1.09	2.99	0.21
-0.019+0.010	0.12	0.45	1.55	1.41	1.40	1.27
-0.010	0.09	0.54	1.34	1.59	1.15	13.83
Total	1.96	1.87	6.25	13.45	61.16	15.31

Table 5. Liberation degree analysis of pyrite in ore samples (%).

Size Fraction (mm)	Composite Particles (Liberation Degree Range)					Liberated Particles
	0–20%	20–40%	40–60%	60–80%	80–100%	100%
+0.075	7.31	5.94	5.35	3.94	35.58	0.00
-0.075+0.038	0.86	0.66	1.02	1.90	5.53	2.23
-0.038+0.019	0.58	0.75	0.85	1.05	6.05	1.91
-0.019+0.010	1.02	0.53	0.67	0.93	3.13	2.67
-0.010	0.41	0.68	0.79	0.95	1.11	5.61
Total	10.18	8.54	8.68	8.76	51.41	12.42

3. Experimental Study on Flotation Desulphurization Using Conventional Activators

The high-sulphur bauxite ore sample contains a harmful sulphur (S) impurity content of 5.04 %, primarily existing in the form of pyrite (FeS_2). During alumina production, pyrite is gradually oxidized to form various sulphur compounds (e.g., sulphates, sulphites). The presence of these compounds not only increases alkali consumption and elevates iron impurity levels in the final alumina product, thereby degrading product quality, but also significantly accelerates corrosion rates in critical equipment systems, including the slurry heating system, digestion system, and evaporation system [3]. Furthermore, these sulphur compounds introduce operational challenges in red mud settling and separation as well as liquor evaporation processes. Therefore, to meet the quality requirements for alumina production, it is imperative to implement pre-desulphurization upgrading pretreatment of the raw ore.

Through systematic experimental investigations on flotation parameters—including process configuration, grinding fineness, pH value, and reagent dosages—the optimal conditions were determined as follows:

- Flotation flowsheet: One roughing, three cleaning, and three scavenging stages.
- Grinding fineness: 80.25 % passing 0.075 mm.
- pH: 9.

- Reagents dosages:
  - Depressant: 2000 g/t
  - Activator: 100 g/t
  - Collector: 900 g/t
  - Frother: 1/2.5 of the collector dosage (i.e., 360 g/t).

The reagents employed included:

- pH modifier: Sodium carbonate (Na_2CO_3)
- Depressant: Sodium silicate (Na_2SiO_3)
- Collector: Composite xanthate
- Frother: Pine oil
- Conventional activator: Copper sulphate pentahydrate ($CuSO_4 \cdot 5H_2O$).

Closed-circuit flotation tests were conducted. The flowsheet of the closed-circuit tests is shown in Figure 1, and the experimental results are summarized in Table 6.

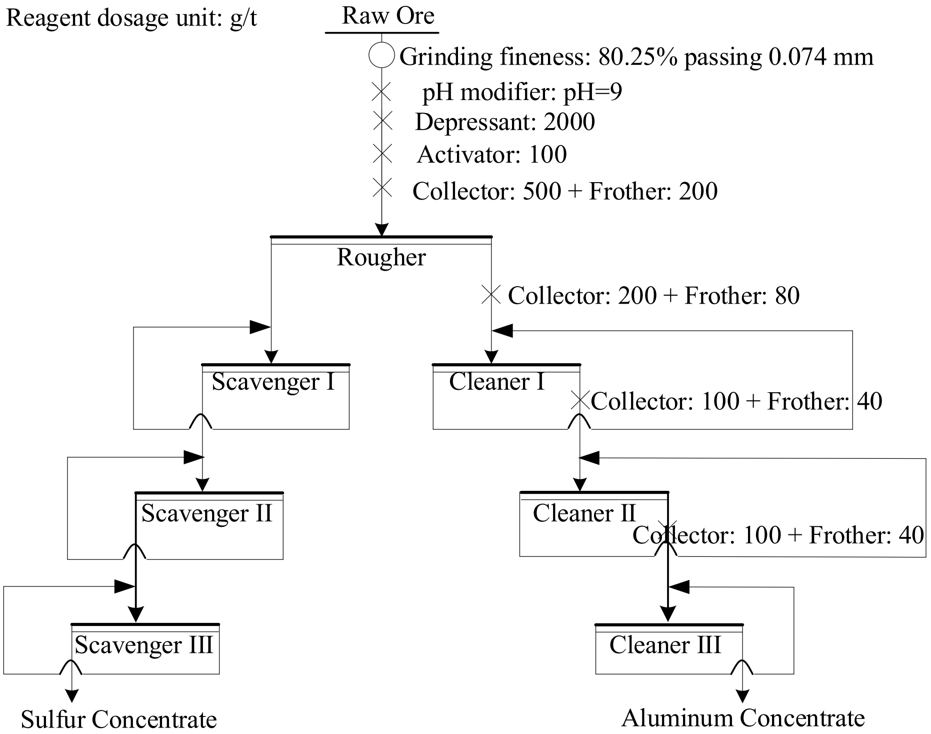

Figure 1. Closed-circuit test flowsheet.

Table 6. Closed-circuit test results (%).

Product	Yield	S	C
Aluminium Concentrate	87.67	0.55	0.30
Sulphur Concentrate	12.33	36.97	0.67
Total	100	5.04	0.35

From the experimental results in Table 6, it can be observed that the raw ore contains 5.04 % sulphur. Through the application of the closed-circuit test flowsheet ("one roughing, three cleaning, and three scavenging stages"), an aluminium concentrate with a yield of 87.67 % and a sulphur content of 0.55 % is obtained. Additionally, a sulphur concentrate with a yield of 12.33 % and a sulphur content of 36.97 % is produced.

4. Experimental Research on the Development of Novel Activators

To advance the optimization of flotation desulphurization technology and explore novel high-efficiency activators, a comprehensive literature review was conducted, revealing the following key insights on the activation of Pyrite. Effective activators must eliminate oxide/hydroxide layers on pyrite surfaces. Organic acids such as oxalic acid ($H_2C_2O_4$) and phytic acid ($C_6H_{18}O_{24}P_6$) can replace sulphuric acid due to their lower acidity coefficients. Experimental studies by Huang et al. demonstrated that oxalic acid reacts with hydrophobic insoluble residues on pyrite surfaces, generating hydrophilic compounds (e.g., $CaCO_3$, $Ca(OH)_2$, $Fe(OH)_3$), thereby removing hydrophilic calcium coatings and activating pyrite. Ammonium Salt Activators: Xie et al. found that ammonium sulphate($(NH_4)_2SO_4$), ammonium carbonate($(NH_4)_2CO_3$), and ammonium bicarbonate (NH_4HCO_3) effectively restore pyrite floatability without requiring copper sulphate or sulphuric acid. These reagents stabilize pulp pH below 9.0 and remove $Ca(OH)_2/Fe(OH)_3$ layers from pyrite surfaces. Their activation mechanisms involve three aspects: desorption of calcium species, precipitation in solution, and direct activation. PS Analysis Insights: Ammonium-based activators enhance pyrite floatability through: Hydrated ammonia molecules destabilizing hydration layers at solid-liquid interfaces ions desorbing and precipitating Ca^{2+} from both pulp and mineral surfaces buffering effects on pulp pH. These actions collectively remove hydrophilic $CaSO_4$ and $Fe(OH)_3$ coatings from pyrite surfaces. Additionally, hydrolysis-generated ions lower pulp pH, promoting electrochemical reactions between xanthate and pyrite to form hydrophobic dixanthogen layers. Hydrated ammonia molecules also disperse hydrophilic slime coatings on pyrite surfaces, achieving comprehensive activation [4–8].

In this study, a series of compounds with potential activation efficacy were selected for experimentation, including organic acid salts, oxalic acid dihydrate ($H_2C_2O_4 \cdot 2H_2O$), phytic acid ($C_6H_{18}O_{24}P_6$); Inorganic salts: Ammonium carbonate ($(NH_2)_2CO_3$), ammonium bicarbonate (NH_4HCO_3), ammonium sulphate ($(NH_4)_2SO_4$).

4.1 Screening Experimental Study on Novel Single-Type Activators

To refine research objectives, a preliminary screening of the afore mentioned novel single-type activators was conducted. The experimental procedure is illustrated in Figure 2, and the corresponding results are summarized in Table 7.

The experimental results reveal that:

1) Among the ammonium salt activators, ammonium carbonate ($(NH_4)_2CO_3$) exhibits the highest activation efficacy, followed by ammonium sulphate ($(NH_4)_2SO_4$) and ammonium bicarbonate (NH_4HCO_3);
2) Phytic acid ($C_6H_{18}O_{24}P_6$) demonstrates superior activation performance compared to oxalic acid dihydrate ($H_2C_2O_4 \cdot 2H_2O$).

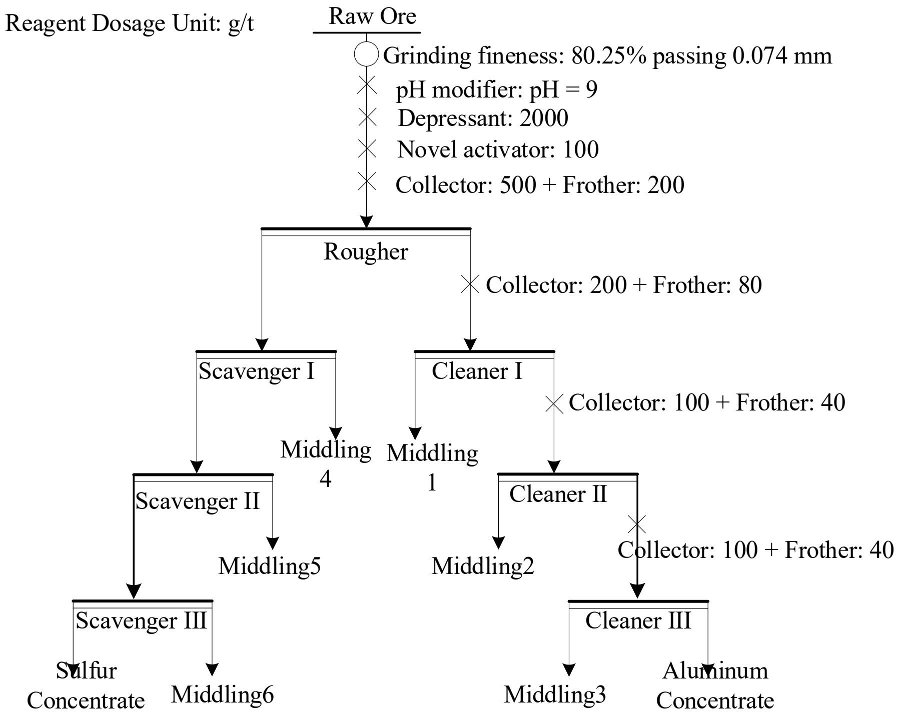

Figure 2. Flowsheet of the flotation desulphurization test using novel activators.

4.2 Comparative Study on Flotation Desulphurization Using Novel Composite Activators Derived from Phytic Acid

Research has shown that single activators struggle to meet industrial demands due to insufficient activation efficacy and high reagent consumption [9]. Thus, the development of composite activators represents a critical future direction.

(1) Ammonium Phytate (2) Copper Phytate (3) Iron Phytate

Figure 3. Photograph of novel composite activators derived from phytic acid.

Phytic acid ($C_6H_{18}O_{24}P_6$) exhibits acidic properties and strong chelating capabilities, enabling it to form metal-phytate complexes with ions such as Cu^{2+}, Fe^{3+}, and Al^{3+}. Based on phytic acid, novel composite activators—including copper phytate [$Cu_6(C_6H_6O_{24}P_6)$], iron phytate [$Fe_4(C_6H_6O_{24}P_6)$], aluminium phytate [$Al_4(C_6H_6O_{24}P_6)$], and ammonium phytate [$(NH_4)_{12}(C_6H_6O_{24}P_6)$]—were synthesized and evaluated for flotation desulphurization [10]. Photographs of these composite activators are shown in Figure 3. The experimental procedure followed Figure 2, and results are summarized in Table 8.

Aluminium concentrates produced using copper phytate [$Cu_6(C_6H_6O_{24}P_6)$], iron phytate [$Fe_4(C_6H_6O_{24}P_6)$], and ammonium phytate [$(NH_4)_{12}(C_6H_6O_{24}P_6)$] exhibited sulphur (S) contents below 0.45 %, while sulphur concentrates exceeded 39 % S. Copper phytate achieved optimal performance, yielding an aluminium concentrate with 68.03 % yield and 0.42 % S, alongside a sulphur concentrate with 7.53 % yield and 40.09 % S. Composite activators significantly enhanced pyrite activation and flotation efficiency.

4.3 Experimental Study on Composite Activators for Flotation Desulphurization

Systematic trials identified ammonium carbonate ($(NH_4)_2CO_3$), phytic acid ($C_6H_{18}O_{24}P_6$), copper phytate [$Cu_6(C_6H_6O_{24}P_6)$], and ammonium phytate [$(NH_4)_{12}(C_6H_6O_{24}P_6)$] as high-performance activators. To further optimize desulphurization, synergistic combinations of these activators were designed and tested. The study aimed to identify the most effective composite formulation and determine its optimal dosage ratio.

By adjusting the ratio between Cu^{2+} and NH_4^+, phytic acid-based composite activators were prepared. The corresponding molar ratios and the resulting chemical formulas of the activators are summarized in Table 9. This study primarily investigated the impact of composite activator ratios on flotation desulphurization, and the experimental results are summarized in Table 10.

The experimental results indicate that as the number of Cu^{2+} ions in the composite activator increases, the sulphur content in the aluminium concentrate initially decreases and then rises, while the sulphur content in the sulphur concentrate gradually increases before stabilizing. When the ratio of Cu^{2+} to NH_4^+ is 3:6, the lowest sulphur content in the aluminium concentrate (0.37 %) and the highest sulphur content in the sulphur concentrate (40.66 %) are achieved. This demonstrates that the phytic acid-derived metal complex [$Cu_3(NH_4)_6(C_6H_6O_{24}P_6)$] exhibits the optimal performance in flotation desulphurization.

4.4 Closed-Circuit Test Study of Novel Activators

Through parametric optimization studies, the novel composite activator demonstrated optimal performance at a dosage of 150 g/t, yielding an aluminium concentrate with a yield of 68.23 % and a sulphur content of 0.37 %. When using [$Cu_3(NH_4)_6(C_6H_6O_{24}P_6)$] as the activator under the open-circuit test flowsheet ("one roughing, three cleaning, and three scavenging stages"), the following results were achieved: Aluminium concentrate: 68.11 % yield, 0.37 % sulphur content; Sulphur concentrate: 7.41 % yield, 40.66 % sulphur content.

Building on the open-circuit tests, closed-circuit flotation desulphurization tests were conducted using the novel activator to evaluate the reliability and feasibility of the entire flotation process flowsheet. The experimental results are summarized in Table 11.

Table 7. Screening test results of novel single-type activators (%)

Activator Type	Product	Yield (%)	Element Content (%)	
			S	C
$CuSO_4$	Aluminium Concentrate	67.43	0.49	0.28
	Middling 3	3.01	1.88	0.31
	Middling 2	4.24	2.53	0.32
	Middling1	5.85	4.42	0.36
	Middling 4	7.12	6.51	0.41
	Middling5	2.75	13.32	0.49
	Middling6	1.51	23.01	0.61
	Sulphur Concentrate	8.09	38.38	0.77
$(NH_4)_2CO_3$	Aluminium Concentrate	67.71	0.46	0.30
	Middling 3	2.81	1.91	0.33
	Middling 2	4.23	2.47	0.35
	Middling1	5.44	3.68	0.35
	Middling 4	7.38	6.31	0.37
	Middling5	2.87	13.33	0.45
	Middling6	1.62	23.94	0.58
	Sulphur Concentrate	7.94	39.41	0.73
NH_4HCO_3	Aluminium Concentrate	67.46	0.47	0.29
	Middling 3	2.96	1.85	0.31
	Middling 2	4.33	2.32	0.35
	Middling1	5.72	3.73	0.36
	Middling 4	7.12	6.57	0.38
	Middling5	2.81	14.51	0.49
	Middling6	1.77	23.47	0.61
	Sulphur Concentrate	7.83	39.18	0.76
$(NH_4)_2SO_4$	Aluminium Concentrate	67.16	0.47	0.29
	Middling 3	2.54	1.67	66.83
	Middling 2	4.32	2.21	3.21
	Middling1	6.24	3.53	4.34
	Middling 4	6.95	6.19	6.08
	Middling5	2.93	13.85	7.22
	Middling6	2.03	23.23	2.85
	Sulphur Concentrate	7.83	39.11	1.91
$H_2C_2O_4{\cdot}2H_2O$	Aluminium Concentrate	67.35	0.46	0.30
	Middling 3	2.26	1.89	0.30
	Middling 2	4.21	2.35	0.33
	Middling1	6.13	3.64	0.35
	Middling 4	7.52	6.88	0.39
	Middling5	3.06	13.89	0.49
	Middling6	1.98	23.53	0.64
	Sulphur Concentrate	7.49	39.42	0.76
$C_6H_{18}O_{24}P_6$	Aluminium Concentrate	67.13	0.46	0.30
	Middling 3	2.81	2.05	0.31
	Middling 2	4.67	3.27	0.31
	Middling1	6.06	5.01	0.34
	Middling 4	6.91	6.46	0.39
	Middling5	3.18	13.15	0.44
	Middling6	1.89	23.41	0.61
	Sulphur Concentrate	7.35	39.53	0.74

Table 8. Results of comparative flotation desulphurization tests using novel composite activators derived from phytic acid (%).

Activator Type	Product	Yield (%)	Element Content (%)	
			S	C
$[Cu_6(C_6H_4O_{24}P_6)]$	Aluminium Concentrate	68.03	0.42	0.29
	Middling 3	3.08	1.81	0.31
	Middling 2	4.32	3.61	0.30
	Middling1	6.05	4.72	0.33
	Middling 4	6.42	6.46	0.38
	Middling5	2.83	13.96	0.45
	Middling6	1.74	24.35	0.62
	Sulphur Concentrate	7.53	40.09	0.76
$[Fe_4(C_6H_4O_{24}P_6)]$	Aluminium Concentrate	68.52	0.45	0.29
	Middling 3	2.42	1.93	0.31
	Middling 2	4.75	3.35	0.30
	Middling1	5.48	5.07	0.33
	Middling 4	6.36	6.39	0.41
	Middling5	3.05	13.11	0.44
	Middling6	1.77	23.15	0.62
	Sulphur Concentrate	7.65	39.57	0.74
$[Al_4(C_6H_4O_{24}P_6)]$	Aluminium Concentrate	67.65	0.47	0.29
	Middling 3	2.62	1.87	0.31
	Middling 2	4.64	2.91	0.33
	Middling1	5.82	3.25	0.33
	Middling 4	6.56	6.35	0.41
	Middling5	3.18	14.51	0.42
	Middling6	1.92	23.46	0.65
	Sulphur Concentrate	7.61	39.68	0.71
$[(NH_4)_{12}(C_6H_4O_{24}P_6)]$	Aluminium Concentrate	67.14	0.43	0.29
	Middling 3	3.02	1.93	0.31
	Middling 2	4.75	3.48	0.31
	Middling1	5.94	5.67	0.34
	Middling 4	7.34	7.24	0.39
	Middling5	3.05	13.92	0.44
	Middling6	1.71	23.13	0.61
	Sulphur Concentrate	7.05	40.21	0.74

Table 9. Composite activators with varied cu^{2+}/nh_4^+ ratios.

No.	Chemical Formula	m(Cu^{2+})	2n(NH_4^+)
A	$[Cu(NH_4)_{10}(C_6H_6O_{24}P_6)]$	1	5
B	$[Cu_2(NH_4)_8(C_6H_6O_{24}P_6)]$	2	4
C	$[Cu_3(NH_4)_6(C_6H_6O_{24}P_6)]$	3	3
D	$[Cu_4(NH_4)_4(C_6H_6O_{24}P_6)]$	4	2
E	$[Cu_5(NH_4)_2(C_6H_6O_{24}P_6)]$	5	1

Table 10. Ratio optimization study of phytic acid-based composite activators (wt.%).

Activator Type	**Product**	**Yield (%)**	**Element Content (%)**	
			S	**C**
$[Cu(NH_4)_{10}(C_6H_6O_{24}P_6)]$	Aluminium Concentrate	68.45	0.40	0.29
	Middling 3	3.43	2.05	0.32
	Middling 2	3.99	2.73	0.35
	Middling1	5.02	4.98	0.36
	Middling 4	7.18	7.04	0.41
	Middling5	2.68	14.93	0.42
	Middling6	1.97	26.52	0.51
	Sulphur Concentrate	7.29	39.85	0.73
$[Cu_2(NH_4)_8(C_6H_6O_{24}P_6)]$	Aluminium Concentrate	67.28	0.38	0.30
	Middling 3	3.13	1.87	0.30
	Middling 2	4.25	2.33	0.31
	Middling1	6.06	4.62	0.34
	Middling 4	7.28	6.57	0.38
	Middling5	2.49	14.76	0.42
	Middling6	1.99	24.94	0.52
	Sulphur Concentrate	7.52	39.89	0.71
$[Cu_3(NH_4)_6(C_6H_6O_{24}P_6)]$	Aluminium Concentrate	68.11	0.37	0.29
	Middling 3	3.46	1.98	0.31
	Middling 2	4.03	2.53	0.33
	Middling1	5.11	4.85	0.35
	Middling 4	7.25	6.57	0.39
	Middling5	2.81	14.76	0.46
	Middling6	1.82	25.52	0.53
	Sulphur Concentrate	7.41	40.66	0.74
$[Cu_4(NH_4)_4(C_6H_6O_{24}P_6)]$	Aluminium Concentrate	68.34	0.39	0.30
	Middling 3	3.07	2.06	0.30
	Middling 2	4.55	3.43	0.31
	Middling1	5.89	4.96	0.35
	Middling 4	6.53	7.88	0.39
	Middling5	2.94	15.16	0.42
	Middling6	1.62	25.24	0.51
	Sulphur Concentrate	7.06	40.91	0.71
$[Cu_5(NH_4)_2(C_6H_6O_{24}P_6)]$	Aluminium Concentrate	68.05	0.39	0.29
	Middling 3	2.77	2.26	0.29
	Middling 2	4.76	3.55	0.31
	Middling1	6.08	5.56	0.35
	Middling 4	6.85	7.38	0.41
	Middling5	2.71	15.41	0.45
	Middling6	1.72	24.34	0.64
	Sulphur Concentrate	7.06	40.49	0.75

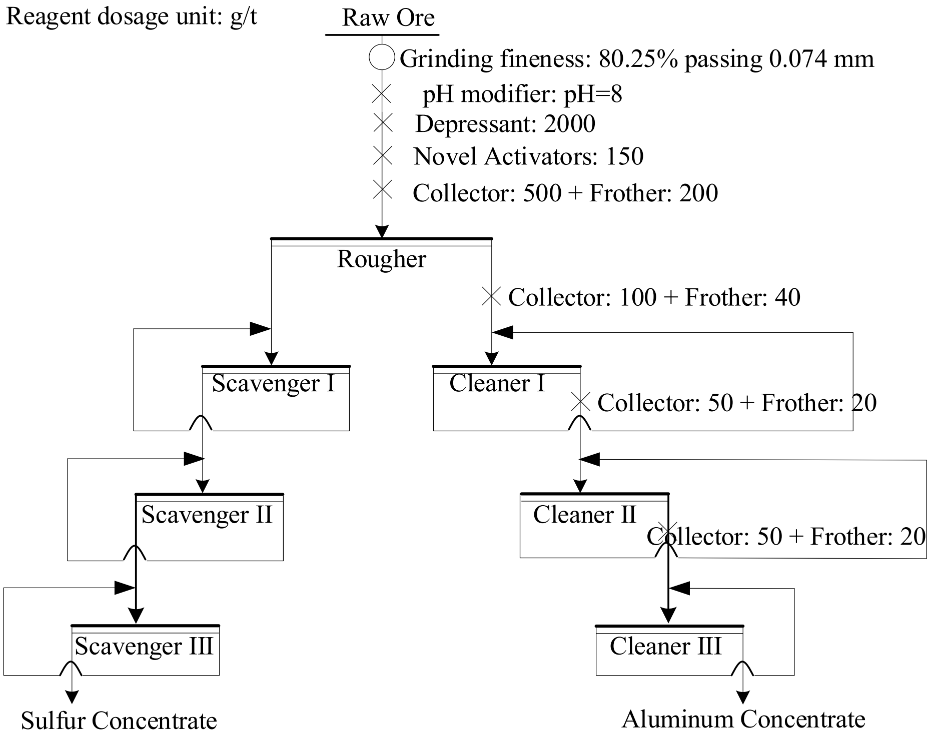

Figure 4. Flowsheet of the closed-circuit flotation desulphurization test using novel activators.

From the experimental results in Table 11, it can be concluded that the raw ore sample contains 5.04 % sulphur. Through the closed-circuit test flowsheet ("one roughing, three cleaning, and three scavenging stages"), an aluminium concentrate with a yield of 87.92 % and a sulphur content of 0.47 % is obtained, along with a sulphur concentrate exhibiting a yield of 12.08 % and a sulphur content of 38.34 %.

Table 11. Results of closed-circuit flotation desulphurization tests using novel activators (%).

Product	Yield	S	C
Aluminium Concentrate	87.92	0.47	0.29
Sulphur Concentrate	12.08	38.34	0.75
Total	100	5.04	0.35

5. Conclusions

(1) The aluminium-bearing minerals in the ore sample are predominantly diaspore with minor gibbsite, while the silicon-bearing minerals are mainly illite and kaolinite, and the sulphur-bearing mineral is primarily pyrite. The sample contains 58.31 % Al_2O_3, an aluminium-to-silica (A/S) ratio of 5.61, and 5.04 % sulphur. Diaspore and pyrite are predominantly concentrated in the 0.075–0.300 mm size fraction, exhibiting fine-grained and uneven distribution. The liberation degree of diaspore is only 17.74 %, primarily in the < 0.010 mm fraction, while pyrite achieves a liberation degree of 12.42 %, also concentrated in the < 0.010 mm fraction. Pyrite is closely intergrown with diaspore, with fine-grained embedded textures.

(2) For the raw ore containing 5.04 % sulphur, a closed-circuit flotation desulphurization test was conducted using conventional activator copper sulphate ($CuSO_4$). The process adopted the "one roughing, three cleaning, and three scavenging" flotation flowsheet with the following parameters: Grinding fineness: 80.25 % passing 0.074 mm, pH: 9; reagent dosages: depressant: 2000 g/t; Activator: 100 g/t; Collector: 900 g/t; Frother: 1/3 of the collector dosage (300 g/t). The test yielded: Aluminium concentrate: 86.91 % yield, 0.55 % sulphur content; Sulphur concentrate: 13.09 % yield, 34.87 % sulphur content.

(3) Impact of Composite Activator Ratios on Desulphurization Performance Experimental studies on phytic acid-based composite activators with varied Cu^{2+}/NH_4^+ ratios revealed the following trends: Aluminium concentrate sulphur content initially decreased with increasing Cu^{2+} content but subsequently increased, while sulphur concentrate sulphur content gradually rose and stabilized. Optimal performance was achieved at a Cu^{2+}:NH_4^+ ratio of 3:6, corresponding to the phytic acid-derived metal complex $[Cu_3(NH_4)_6(C_6H_6O_{24}P_6)]$. This formulation yielded: Aluminium concentrate: 0.37 % sulphur content (lowest observed); Sulphur concentrate: 40.66 % sulphur content (highest grade). These results confirm that $[Cu_3(NH_4)_6(C_6H_6O_{24}P_6)]$ exhibits optimal flotation desulphurization efficacy, balancing sulphur removal efficiency and concentrate quality.

(4) Optimization of Flotation Desulphurization Using Novel Composite Activators: Comparative studies revealed that collector dosage was reduced by over 20 % when replacing the conventional activator copper sulphate ($CuSO_4$) (collector dosage: 900 g/t) with the novel composite activator (collector dosage: 700 g/t). For the raw ore containing 5.04 % sulphur, the closed-circuit test under the "one roughing, three cleaning, and three scavenging" flowsheet achieved: Aluminium concentrate: 87.92 % yield, 0.47 % sulphur content; Sulphur concentrate: 12.08 % yield, 38.34 % sulphur content.

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