

## Article

# Study on the Inhibition and Activation of Pyrite Under Low Alkalinity Conditions Created by Hydrogen Peroxide and Lime

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## Abstract

High alkalinity facilitates copper–sulfur flotation separation but also leads to issues such as high reagent consumption, pipeline scaling, and gold loss in tailings. The ore from a copper mine in Serbia contains 2.86% copper, 1.64 g/t gold, and 20.39% sulfur, with copper occurring mainly in covellite and enargite. To achieve efficient separation and recovery of copper–sulfur, a systematic study was conducted using micro-flotation, Scanning Electron Microscopy (SEM), X-ray photoelectron spectroscopy (XPS) and contact angle analysis to investigate the inhibition and activation patterns of pyrite under low and high alkalinity conditions. The results indicate that the combined use of hydrogen peroxide and lime as inhibitor enables efficient separation of pyrite and covellite under low-alkalinity conditions. This effect is attributed to its ability to enhance oxidation of the pyrite surface, which generates more hydrophilic substances. Under low-alkalinity conditions (slurry pH = 10) regulated with hydrogen peroxide and lime in a covellite flotation cycle, and under acidic conditions (slurry pH = 6) in the pyrite flotation cycle, satisfactory results are obtained in both flotation cycles in comparison with industrial data. The copper flotation index was similar, but pyrite and gold recovery increased by 2.3% and ~4%, respectively, over those using lime alone. This process reduced the activator dosage required for pyrite activation substantially, while improving gold recovery. Results demonstrate an efficient method for copper–sulfur separation and recovery, providing theoretical guidance or industrial production processes.

**Keywords:** copper-sulfur separation; low-alkalinity; hydrogen peroxide; flotation; covellite; pyrite



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## 1. Introduction

Pyrite (FeS<sub>2</sub>) is a common iron sulfide mineral and an important raw material for the preparation of sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) and sulfur [1–4]. Covellite (CuS), an important raw material for copper smelting, is a widespread copper sulfide mineral accounting for approximately 70% of the world's total copper reserves [5,6]. The intergrowth or association of covellite and pyrite is extremely common in nature [7]. The natural floatability of covellite is similar to but slightly higher than that of pyrite [8–10]. Under low-alkalinity conditions, efficient separation of the two minerals is difficult to achieve. Currently, the most commonly used method for effective separation is the inhibition of pyrite flotation in a high-alkalinity environment, which increases the difference in floatability between the two [11,12].

The efficient separation and recovery of pyrite and covellite is essential for resource utilization. Commonly used pyrite inhibitors include lime, cyanide, sulfur oxides, and oxidizing agents [13,14]. Lime inhibitors inhibit the flotation recovery of pyrite by adjusting the slurry pH. A higher pH increases the  $\text{OH}^-$  concentration and the hydrophilic hydroxide content on the surface of pyrite, thereby inhibiting the flotation recovery of pyrite. Although lime possesses many advantages in pyrite inhibition, the excessive lime addition often leads to scaling, solidification, and pipeline blockage. The dosage of lime is difficult to control, and an excessively high slurry alkalinity leads to high collector consumption, which is not favorable for comprehensive resource recycling. Many researchers have thus focused on inhibitors of pyrite in low-alkalinity media [15,16]. For pyrite containing the precious metal gold, flotation conditions also significantly influence gold recovery.

Oxidizing agents are attractive alternatives due to their wide availability, low cost, and good selectivity. They also exert a smaller impact on associated valuable metals and are suitable for use over a wider slurry pH range [17]. Therefore, they are widely applied in copper–sulfur separation. Hydrogen peroxide ( $\text{H}_2\text{O}_2$ ), a clean and efficient oxidant with low human toxicity, has recently become more widely used in mineral processing. Khoso et al. [18] achieve the selective separation of chalcopyrite and pyrite using  $\text{H}_2\text{O}_2$  at a pH of 9.0, with the recovery of chalcopyrite exceeding 84% and that of pyrite being lower than 24%. Infrared and X-ray photoelectron spectroscopy (XPS) analyses revealed that  $\text{H}_2\text{O}_2$  treatment substantially altered the surface properties of pyrite, rendering it highly hydrophilic and inhibiting collector adsorption, thereby reducing its floatability. Wang et al. [19] have shown that the surface oxidation of pyrite is increased and dixanthogen formation is decreased under high-alkalinity slurry flotation. This leads to the reduced adsorption of xanthate, which in turn inhibits the flotation of pyrite. Ozun et al. [20] have reported that pyrite is a chemically active mineral whose surface oxidizes when exposed to the atmosphere and aqueous environments during mining and flotation. The oxidation process results in the creation of a hydrophilic surface, which affects collector adsorption and flotation effects. Luo et al. [21] have regulated the dissolved oxygen concentration in slurry by adjusting the relative proportion of  $\text{O}_2/\text{N}_2$  during aeration. The generation of dixanthogen and avoidance of excessive iron oxide/hydroxide formation on the pyrite surface contribute to the regulation of pyrite recovery by flotation. Copper flotation is associated with various issues, such as a low ore grade, high pyrite content, and complex mineral dissemination relationships [22,23]. For pyrite, a carrier mineral for common gold monomers, the effects of cyanide and hydroxides must be minimized. In other words, efficient recovery of elemental gold can only proceed in low-alkalinity environments [24]. Yuan [25], Yang [26], and Khosol et al. [18] have systematically evaluated low-alkalinity flotation systems. Besides inhibiting the flotation performance of pyrite by adjusting the environment of the flotation slurry to low alkalinity, the researchers also introduced oxidizing agents to further enhance the inhibitory effect. In addition to oxidation treatment in a low-alkalinity solution environment, the oxidizing agent dosage was reduced to 1/3 of the original dosage. The efficient formation of a passivation layer on the pyrite surface was achieved, which significantly inhibited floatability and effectively reduced the sulfur grade by 10%–20% in the copper concentrate.

In this paper, the depression and activation mechanisms of pyrite under high-alkali and low-alkali conditions were systematically investigated. The research findings were successfully applied at a mine in Serbia, achieving effective copper and sulfur copper–sulfur separation and recovery. The low-alkali process significantly improved the production indicators of the beneficiation plant while reducing reagent consumption, providing valuable insights for similar mining operations.

## 2. Materials and Methods

### 2.1. Ore Sample

The main chemical composition, particle size distribution and liberation relationship analysis of ore sample are presented in Tables 1–3.

**Table 1.** Main Chemical Composition of Ore from the Upper Zone of a Copper-Gold Mine in Sebia (Unit: %, \*: g/t).

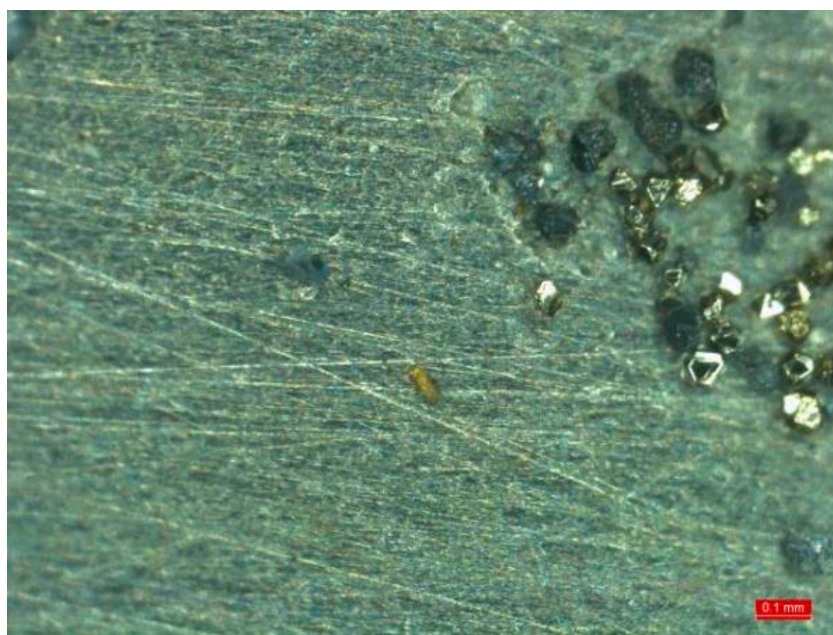
| Elements | Cu  | Au * | S     | As    | Fe    | Pb   | SO <sub>3</sub> | Zn   | SiO <sub>2</sub> |
|----------|-----|------|-------|-------|-------|------|-----------------|------|------------------|
| Contents | 2.8 | 1.64 | 20.39 | 0.035 | 18.87 | 0.01 | 3.74            | 0.02 | 3.74             |

As shown in Table 1, the main valuable elements in the raw ore were copper, gold, and sulfur. Copper and gold grades were 2.8% and 2.16 g/t, respectively, whereas sulfur possessed a lower value.

Tables 2 and 3 show the mineralogical results of the ore sample. As shown in Table 2, 85.88% of the copper sulfides was completely liberated at a particle size of 70% passing 75  $\mu\text{m}$ . Rich intergrowths with  $50\% \leq X < 100\%$  accounted for 10.08%, whereas lean intergrowths ( $X < 50\%$ ) accounted for only 4.04%.

Results shown in Table 3 indicate that at a particle size of 70% passing 75  $\mu\text{m}$ , 83.77% of the pyrite was completely liberated, with the vast majority being in the floatable particle size range. Rich intergrowths accounted for 6.12% of the pyrite. It is noted that the pyrite in  $<10 \mu\text{m}$  size fraction that is difficult to recover by flotation accounted for only 1.17%. Lean intergrowths accounted for 6.74% of the pyrite. Floatable pyrite accounted for 92.99% of the total pyrite ( $>10 \mu\text{m}$  and  $X > 50\%$ ).

At a particle size of 70% passing 75  $\mu\text{m}$ , the concentrate obtained by gravity concentration was examined manually using an optical stereomicroscope (Nikon Corporation, Tokyo, Japan) and subjected to MLA testing. Six liberated native gold particles with a particle size of up to 17  $\mu\text{m}$  were observed, with no encapsulated gold observed. Figure 1 shows the concentrated liberated native gold particles.



**Figure 1.** Liberated Gold in Raw Ore (Optical Microscope Image).

Table 2. Particle Size Distribution and Liberation Relationship Analysis of Copper Sulfides in Ore.

| Copper–Sulfur Mineral<br>Intergrowth Type | Yield (%) | Intergrowth Association |             | Copper Sulfide Particle Size Distribution (%) |             |             |             |              |         |
|-------------------------------------------|-----------|-------------------------|-------------|-----------------------------------------------|-------------|-------------|-------------|--------------|---------|
|                                           |           | With Py                 | With Others | −10 μm                                        | −20 + 10 μm | −38 + 20 μm | −74 + 38 μm | −150 + 74 μm | +150 μm |
| X = 100%                                  | 85.88     | --                      | --          | 0.62                                          | 14.7        | 26.15       | 30.03       | 14.12        | 0.26    |
| 80% ≤ X < 100%                            | 6.22      | 4.34                    | 1.88        | --                                            | 0.12        | 0.77        | 2.26        | 2.81         | 0.26    |
| 50% ≤ X < 80%                             | 3.86      | 3.29                    | 0.57        | --                                            | 0.24        | 1.47        | 1.74        | 0.41         | --      |
| X < 50%                                   | 4.04      | 3.07                    | 0.97        | 0.6                                           | 1.04        | 1.69        | 0.71        | --           | --      |
| Sum                                       | 100.00    | 10.7                    | 3.42        | 1.22                                          | 16.1        | 30.08       | 34.74       | 17.34        | 0.52    |

Note: X represents the proportion of the target mineral in the liberation particle; “Py” is the abbreviation for pyrite, used consistently throughout the text.

Table 3. Particle Size Distribution and Liberation Relationship Analysis of Pyrite.

| Type of Pyrite<br>Intergrowth | Yield (%) | Intergrowth Association |             | Pyrite Particle Size Distribution (%) |             |             |             |              |         |
|-------------------------------|-----------|-------------------------|-------------|---------------------------------------|-------------|-------------|-------------|--------------|---------|
|                               |           | With Cu                 | With Others | −10 μm                                | −20 + 10 μm | −38 + 20 μm | −74 + 38 μm | −150 + 74 μm | +150 μm |
| X = 100%                      | 83.77     | --                      | --          | 0.23                                  | 18.47       | 30.35       | 27.41       | 7.22         | 0.09    |
| 80% ≤ X < 100%                | 6.12      | 2.08                    | 4.04        | 0.01                                  | 0.24        | 1.43        | 3.06        | 1.38         | --      |
| 50% ≤ X < 80%                 | 3.37      | 0.58                    | 2.79        | 0.03                                  | 0.49        | 0.96        | 1.73        | 0.16         | --      |
| X < 50%                       | 6.74      | 0.63                    | 6.11        | 0.90                                  | 2.22        | 2.51        | 1.10        | 0.01         | --      |
| Sum                           | 100.00    | 3.29                    | 12.94       | 1.17                                  | 21.42       | 35.25       | 33.30       | 8.77         | 0.09    |

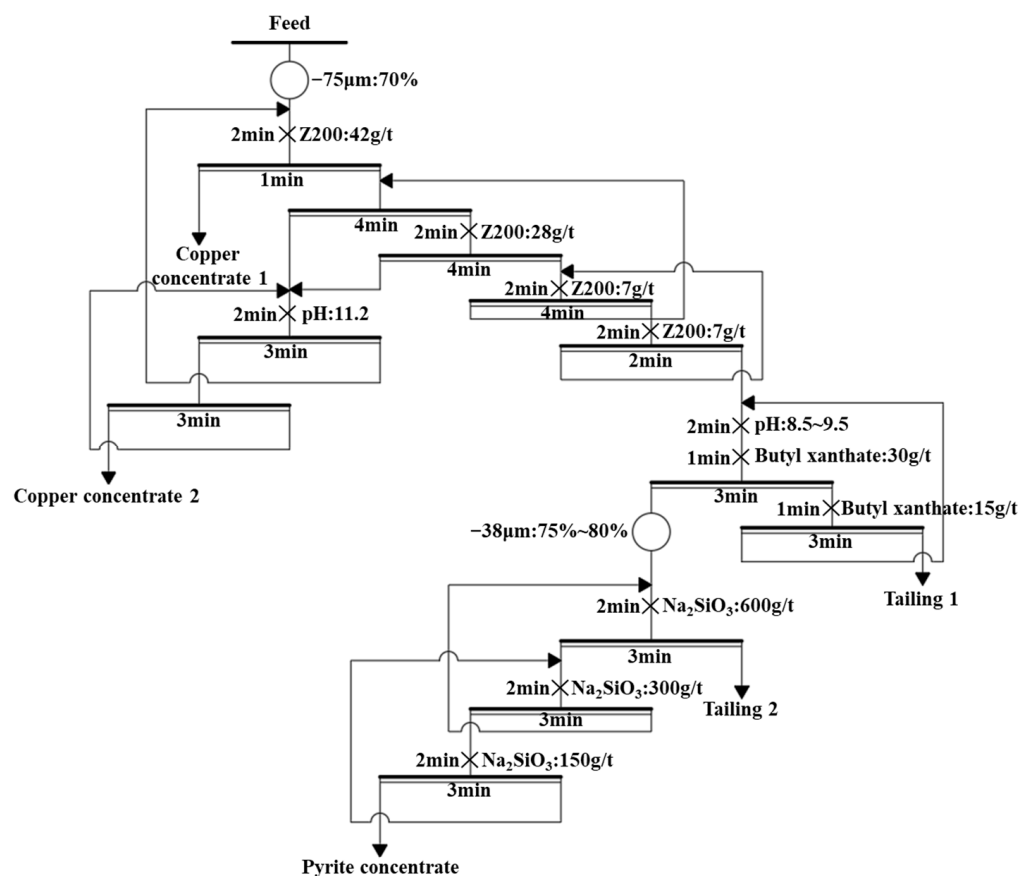
The results of a chemical phase analysis are summarized in Table 4. Covellite is the main copper sulfide mineral contained in the ore sample, and the major gangue minerals include pyrite and quartz, with pyrite being the primary gold carrier. Therefore, it is necessary to perform the efficient separation and recovery of copper and sulfur.

**Table 4.** Chemical Phase Analysis of Serbia Gold–Copper Ore.

| Mineral Species                                | Mineral Content/% |
|------------------------------------------------|-------------------|
| Covellite (CuS)                                | 11.49             |
| Tennantite (Cu <sub>3</sub> AsS <sub>4</sub> ) | 0.89              |
| Pyrite (FeS <sub>2</sub> )                     | 39.31             |
| Quartz (SiO <sub>2</sub> )                     | 27.74             |

## 2.2. Flotation Process of the Mine

At present, the preferential flotation process is adopted at processing plant (Figure 2). Lime is used as the pyrite inhibitor, Z200 is used as the collector, and the slurry pH is maintained at approximately 12. Current flotation indicators on the site are shown in Table 5, the obtained copper concentrate has a copper grade of 21.88%, copper recovery of 94.38%, and gold recovery of 32.23%. The sulfur concentrate has a sulfur grade of 49.40%, recovery of 56.70%, and gold recovery of 53.87%. Major production issues are as follows: (1) high dosage of lime (approximately 5 kg/t), resulting in a sticky flotation foam and a high tendency for slurry pipeline blockage, and (2) low sulfur flotation recovery rate and low gold recovery during sulfur flotation. A low-alkalinity process, in which lime is partially replaced by an oxidizing agent, is an effective method to reduce the amount of lime used while increasing the recovery of gold during sulfur separation.



**Figure 2.** Current Production Flowchart of the Serbia Copper Mine.

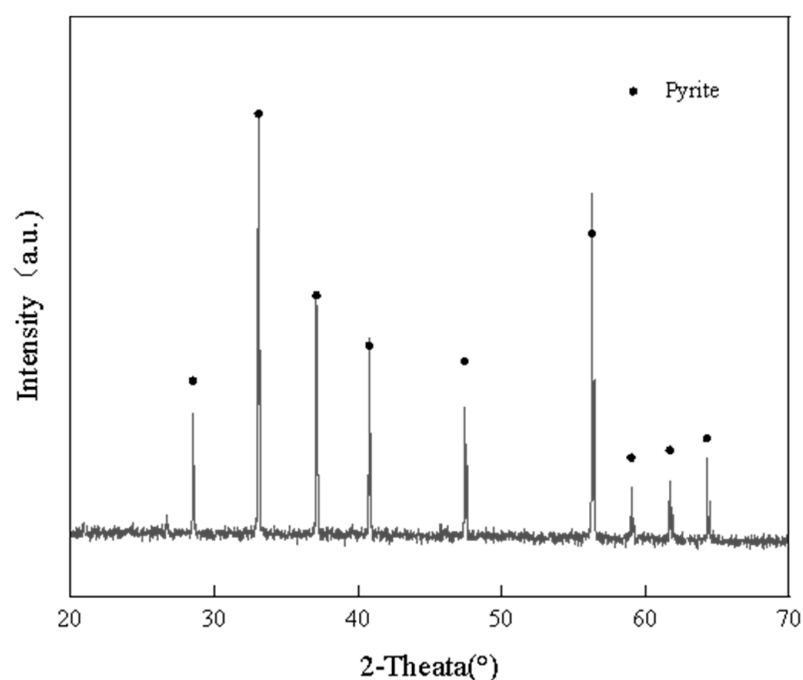
**Table 5.** Current Flotation indicators of the Serbia Copper Mine.

| Product                  | Yield (%) | Grade (%) |                         |       | Recovery (%) |        |        |
|--------------------------|-----------|-----------|-------------------------|-------|--------------|--------|--------|
|                          |           | Cu        | Au (g·t <sup>−1</sup> ) | S     | Cu           | Au     | S      |
| Copper Concentrate 1     | 7.57      | 30.35     | 4.07                    | 34.70 | 80.42        | 18.81  | 12.89  |
| Copper Concentrate 2     | 4.76      | 8.39      | 4.62                    | 36.80 | 13.97        | 13.42  | 8.58   |
| Pyrite Concentrate       | 23.41     | 0.52      | 3.77                    | 49.40 | 4.26         | 53.87  | 56.70  |
| Tailing 2                | 14.53     | 0.096     | 0.78                    | 7.61  | 0.49         | 6.92   | 5.42   |
| Tailing 1                | 49.73     | 0.050     | 0.23                    | 6.73  | 0.87         | 6.98   | 16.41  |
| Feed                     | 100.00    | 2.86      | 1.64                    | 20.39 | 100.00       | 100.00 | 100.00 |
| Copper Concentrate 1 + 2 | 12.33     | 21.88     | 4.28                    | 35.51 | 94.38        | 32.23  | 21.47  |
| Tailing 1 + 2            | 64.26     | 0.06      | 0.35                    | 6.93  | 1.36         | 13.90  | 21.83  |

The tests were performed with pure pyrite mineral and raw ore sample from upper zone of the deposit from a copper mine in Serbia.

### 2.3. Pure Mineral

Figure 3 shows the X-ray diffraction (XRD) spectrum of the pure pyrite mineral sample used as the raw material for single-mineral flotation testing. As shown in Figure 3, the spectrum is free of any obvious impurity peaks. Together with chemical analyses, it revealed that the purity of pyrite exceeded 98%; the spectrum indicates that the pyrite sample fulfills the requirement for single mineral flotation tests.

**Figure 3.** XRD Pattern of Pure Pyrite Mineral.

### 2.4. Reagents

Table 6 shows the reagents used in this study, including regulators, collectors, inhibitors, and frothers. To note, H<sub>2</sub>SO<sub>4</sub>, when used, was diluted to a 1% solution with distilled water.

**Table 6.** Main Chemical Reagents Used in the Experiment.

| Chemical Formula                                                                             | Content (wt.%) | Supplier                                                 | Function     |
|----------------------------------------------------------------------------------------------|----------------|----------------------------------------------------------|--------------|
| CaO                                                                                          | 98             | Macklin Biochemical (Shanghai),<br>Shanghai, China       | Depressant   |
| H <sub>2</sub> SO <sub>4</sub>                                                               | 98.08          | Sinopharm Chemical Reagent Co., Ltd.,<br>Shanghai, China | pH regulator |
| NaBX                                                                                         | —              | Zhuzhou Flotation Reagents Co., Ltd.,<br>Zhuzhou, China  | collector    |
| MIBC                                                                                         | 99             | Shanghai EON Chemical Technology Co.,<br>Shanghai, China | frother      |
| Z200(C <sub>3</sub> H <sub>7</sub> CH(CH <sub>3</sub> )C(S)NHC <sub>2</sub> H <sub>5</sub> ) | —              | Zhuzhou Flotation Reagents Co., Ltd.,<br>Zhuzhou, China  | collector    |
| H <sub>2</sub> O <sub>2</sub>                                                                | 30             | Macklin Biochemical (Shanghai),<br>Shanghai, China       | depressant   |

### 2.5. Methods and Processes

Pure mineral flotation testing was performed using a hanging cell flotation machine (Shandong Xinhai Mining Technology & Equipment Co., Ltd., Yantai, China). During each test, 2.0 g of the mineral sample was weighed and rapidly put into the 40 mL hanging cell flotation machine using a solution at the corresponding pH. The slurry was stirred for 3 min, and the slurry pH was measured. Subsequently, the regulator, collector, and frother were added sequentially, and the slurry was mixed and reacted for 2, 2, and 1 min. Aerated flotation was performed for 3 min, and the concentrate and tailings were dried in an oven and weighed. The recovery rate (%) was calculated using the following equation:

$$\varepsilon = \frac{m_1}{m_1 + m_2} \times 100 \quad (1)$$

$\varepsilon$ —recovery rate (%),

$m_1$ —the mass of the froth product (concentrate weight, g),

$m_2$ —the mass of the in-cell product (tailing weight, g).

Raw ore flotation testing was performed using laboratory single-cell flotation machines (Shandong Xinhai Mining Technology & Equipment Co., Ltd., Yantai, China) with capacities of 1.5, 1, and 0.5 L. For each test, 500 g of the ore sample was weighed, and copper concentrate flotation and separation testing was performed based on the optimum reagent system and test procedure derived from single-mineral pyrite flotation testing.

### 2.6. Testing and Analysis

#### 2.6.1. Scanning Electron Microscopy (SEM)

The surface morphology of pure natural pyrite samples was analyzed using SEM (FEI Quanta 200, FEI Company, Hillsboro, OR, USA). Pyrite samples (2 g, particle size range:  $-74 + 45 \mu\text{m}$ ) were treated using the reagent addition sequence and reaction times used in flotation testing, subjected to solid–liquid separation, and vacuum-dried at a low temperature before use as a test material.

#### 2.6.2. Contact Angle Measurement

The wettability of mineral surfaces was characterized by measuring the contact angle using a drop shape analyzer (DSA255; KRÜSS, Hamburg, Germany). For sample preparation, an appropriately sized pyrite sample block was obtained, and one surface was ground sequentially until smooth with coarse to fine sandpaper. Subsequently, surface impurities were washed with dilute sulfuric acid, and the surface of the pyrite sample was rinsed with deionized water. The sample was then treated using the reagent ad-



dition sequence and reaction times used in flotation testing, subjected to solid–liquid separation, and vacuum-dried at a low temperature. The contact angle was measured using the sessile drop method, and the measured contact angle data were analyzed using ImageJ.js software.

#### 2.6.3. Process Mineralogy Parameter Testing Using a Mineral Liberation Analyzer (MLA)

The raw ore was crushed and ground to a fineness of 70% passing 75  $\mu\text{m}$ . Subsequently, an appropriate amount of the copper ore sample was ground into polished thin sections, which were analyzed using an MLA (Zhejiang Lante Optics Co., Ltd., Jiaxing, China) to determine the particle size of copper sulfides and pyrite and their liberation and intergrowth relationships.

#### 2.6.4. XPS Measurement

The spectra of Fe and S elements on the surfaces of pyrite from different ore sites were measured using XPS (PHI 5000 VersaProbe III, ULVAC-PHI, Inc., Chigasaki, Japan) to determine the surface properties and elemental contents of the target minerals.

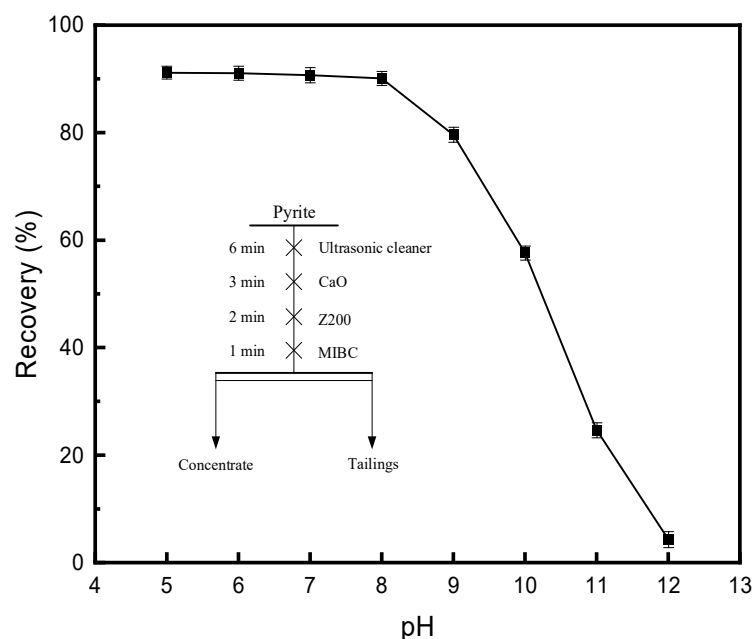
Full-spectrum scans of pyrite from different ore sites, narrow spectra of Fe and S on the pyrite surface, and raw XPS surface elemental data were obtained. Advantage 5.9931 BPM Foundation software was used to fit the spectral data and analyze the binding energies and contents of Fe and S on the surface.

### 3. Results and Discussion

#### 3.1. Effects of Different Inhibition Systems on Pyrite Flotation

##### 3.1.1. Effect of Lime on the Floatability of Pyrite in the Z200 System

Pyrite that had been ultrasonically cleaned and re-slurried was subjected to pH adjustment using lime. The dosages of Z200 and the frother methyl isobutyl carbinol (MIBC) were  $10^{-3}$  mol/L and  $10^{-4}$  mol/L, respectively. The dosages were determined based on the results of previous conditional tests. Figure 4 shows the test process and results.



**Figure 4.** Effect of Lime on Pyrite Recovery.

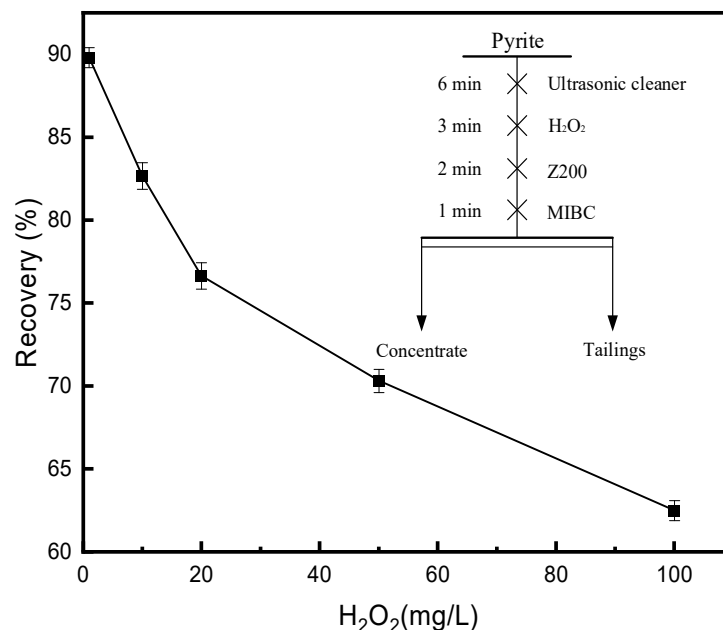
As shown in Figure 4, lime exerted a strong inhibitory effect on pyrite flotation in the Z200 system. An increase in pH from 5.27 to 12 led to a gradual reduction in concentrate



recovery, with pyrite recovery decreasing from 91.4% to 4.26%. However, it is evident that effective depression of pyrite requires a higher pH (>11) level to achieve.

### 3.1.2. Effect of $\text{H}_2\text{O}_2$ on Pyrite in the Z200 System

Given that pyrite is easily oxidized and  $\text{H}_2\text{O}_2$  exerts a strong oxidizing effect, a hydrophilic film is readily formed on the surface of pyrite when reacted with  $\text{H}_2\text{O}_2$ , thus producing an inhibitory effect. During this test, natural slurry (pH = 4.37) that had not been pH-adjusted was treated with  $\text{H}_2\text{O}_2$  as the inhibitor, Z200 as the collector (dosage:  $10^{-3}$  mol/L), and MIBC as the frother (dosage:  $10^{-4}$  mol/L). Figure 5 shows the test process and test results, respectively.



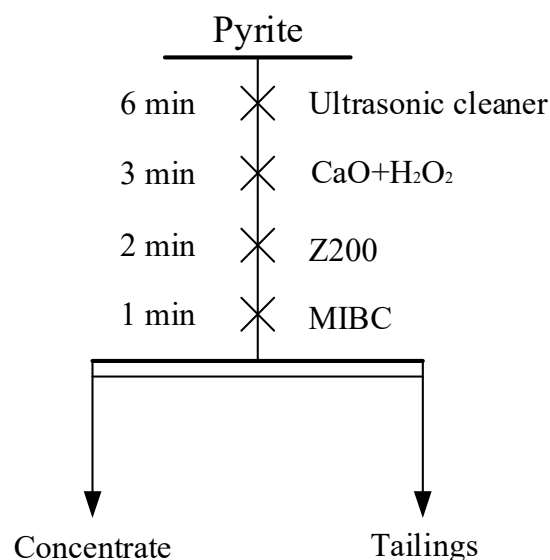
**Figure 5.** Effect of Hydrogen Peroxide Dosage on Pyrite Recovery.

As shown in Figure 5, the recovery rate decreased gradually from 89.79% to 62.51% when the  $\text{H}_2\text{O}_2$  dosage was increased from 1 mg/L to 100 mg/L in the Z200 system. Recovery exceeded 80% at a  $\text{H}_2\text{O}_2$  dosage of <10 mg/L but decreased to 62.5% when the  $\text{H}_2\text{O}_2$  dosage was increased to 100 mg/L. These results indicated that the depression effect of standalone  $\text{H}_2\text{O}_2$  on pyrite was not pronounced.

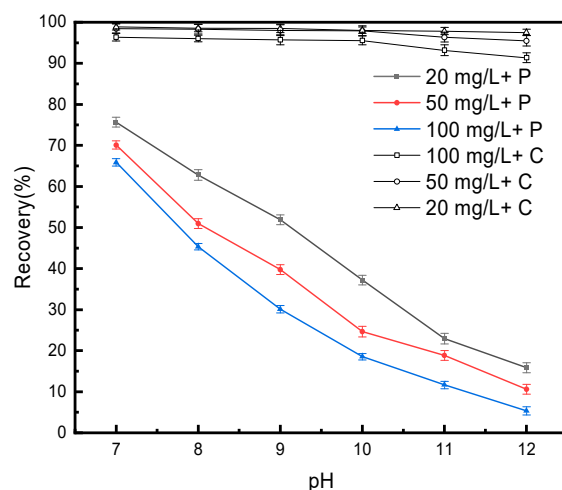
### 3.1.3. Effect of Combined Lime- $\text{H}_2\text{O}_2$ Inhibition on Pyrite in the Z200 System

To avoid excess alkalinity in the flotation solution system and excessive consumption of  $\text{H}_2\text{O}_2$ , lime +  $\text{H}_2\text{O}_2$  was used as a combined inhibitor. Z200 was used as the collector (dosage:  $10^{-3}$  mol/L), and MIBC was used as the frother (dosage:  $10^{-4}$  mol/L). Figures 6 and 7 show the test process and test results, respectively.

Figure 7 shows that a combination of lime and  $\text{H}_2\text{O}_2$  exerted an excellent inhibitory effect. The flotation recovery of pyrite decreased significantly with an increase in the pH of the solution environment. Pyrite recovery also exhibited a certain decline with increasing  $\text{H}_2\text{O}_2$  dosage; However, excessively high pH and  $\text{H}_2\text{O}_2$  dosage will inhibit covellite as Figure 7 shows. Therefore, pH = 10 and  $\text{H}_2\text{O}_2$  dosage = 50 mg/L were ultimately selected as the optimal conditions, with a corresponding pyrite recovery of 24.67%.



**Figure 6.** Flowchart of Single Mineral Flotation Test.



**Figure 7.** Effect of Lime (pH Adjustment) + Hydrogen Peroxide Mixed Depressant on Pyrite (P) and Covellite (C) Recovery.

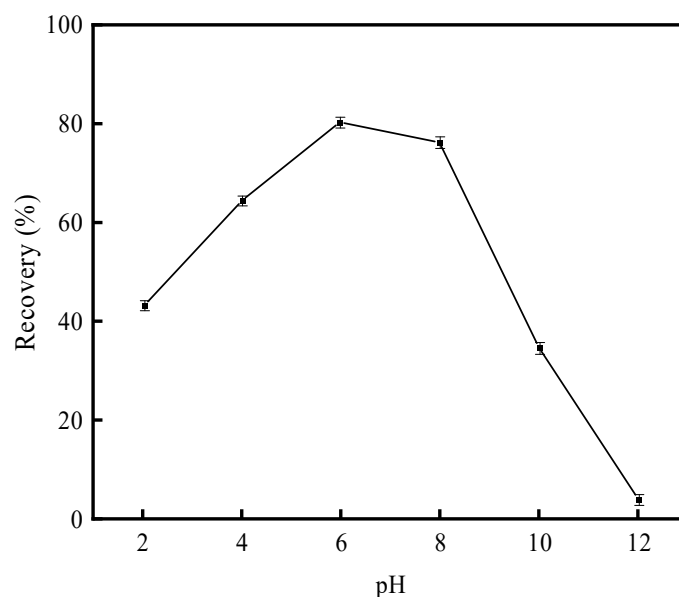
### 3.2. Activation of Depressed Pyrite

To recover the inhibited pyrite, the effects of different activators on pyrite were investigated systematically. Sulfuric acid and copper sulfate were used to investigate the effect of activator dosage on the floatability of the inhibited pyrite.

#### 3.2.1. Sulfuric Acid Activation Test

Using NaBX as the collector, pyrite recovery was evaluated with respect to the sulfuric acid dosage (pH). First, slurry pH was adjusted to 12 using the combined lime +  $\text{H}_2\text{O}_2$  inhibitor, with the  $\text{H}_2\text{O}_2$  dosage being 50 mg/L. Sulfuric acid was added for pH (from 10 to 2) adjustment after stirring. A butyl xanthate concentration of  $1 \times 10^{-4}$  mol/L was adopted, and MIBC was used as the frother. Figure 8 shows the test results.

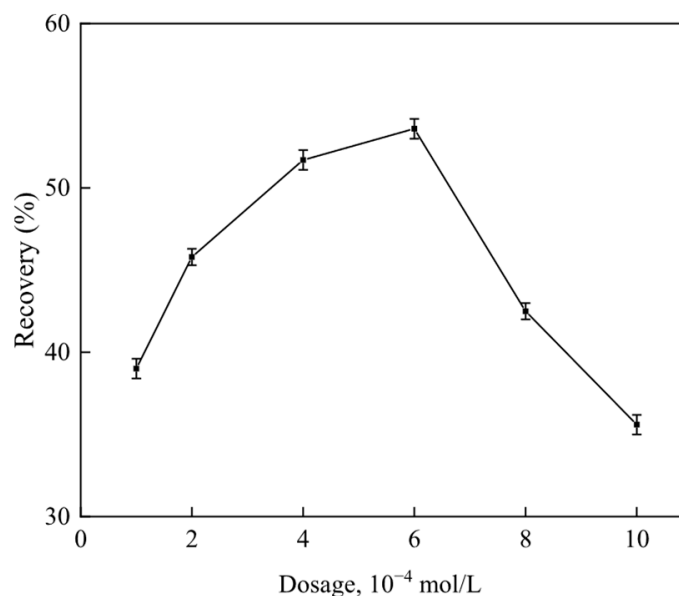
As shown in Figure 8, in the system consisting of NaBX as the collector and lime +  $\text{H}_2\text{O}_2$  as the combined inhibitor, a gradual increase in sulfuric acid dosage led to an initial increase and subsequent decrease in pyrite recovery. Optimal activation of the inhibited pyrite was achieved at a slurry pH of approximately 6, with recovery reaching 80%. Therefore, reducing the pulp pH can restore the floatability of pyrite.



**Figure 8.** Effect of Sulfuric Acid (pH Adjustment) Dosage on Flotation Recovery of Inhibited Pyrite under NaBX System.

### 3.2.2. Copper Sulfate Activation Test

Using NaBX as the collector, the effect of copper sulfate dosage on pyrite recovery was investigated. First, slurry pH was adjusted to 10 using the combined lime +  $\text{H}_2\text{O}_2$  inhibitor, with the  $\text{H}_2\text{O}_2$  dosage being 50 mg/L. Copper sulfate is added at dosage from 1 to  $10 \times 10^{-4}$  mol/L. A NaBX concentration of  $1 \times 10^{-4}$  mol/L was adopted, and MIBC was used as the frother. Figure 9 shows the test results.



**Figure 9.** Effect of Copper Sulfate Dosage on the Floatability of Inhibited Pyrite under the Z200 System.

As shown in Figure 9, the recovery of pyrite inhibited via a combination of lime and  $\text{H}_2\text{O}_2$  exhibited an initial increase and subsequent decrease with increases in the copper sulfate dosage when NaBX was used as the collector. This may be attributed to the large number of residual copper ions in the slurry. The consumption of NaBX by excessive copper sulfate led to a decrease in the NaBX concentration, resulting in a decline in collection effect and poorer activation by copper sulfate. A comparative analysis revealed that sulfuric acid

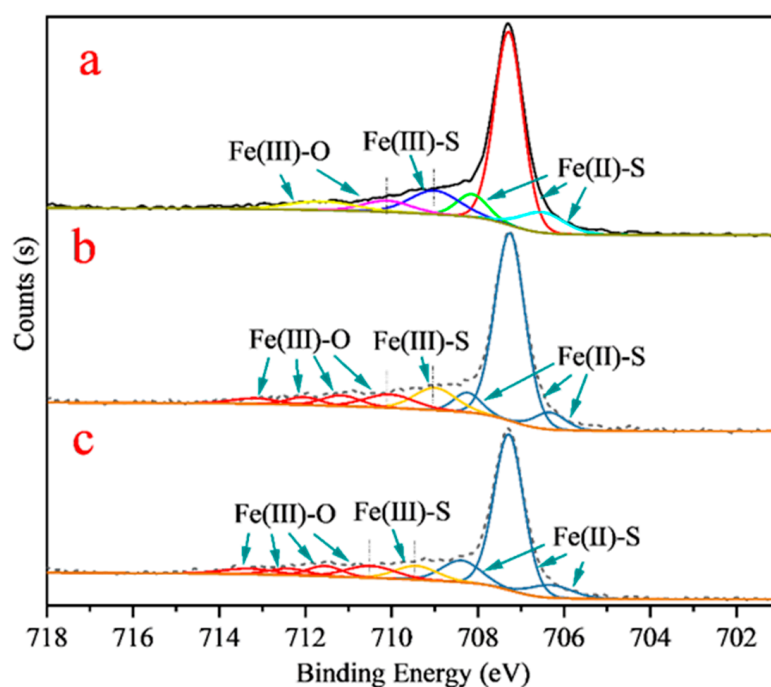
provided a better activation effect than that of copper sulfate, because the recovery rate of pyrite obtained through sulfuric acid activation is much higher. Compared to the test results of sulfuric acid restoring pyrite floatability, the activation effect of copper sulfate is somewhat inferior; therefore, sulfuric acid is the more suitable reagent.

### 3.3. XPS Analysis

To further elucidate the intrinsic causes of pyrite inhibition by lime + H<sub>2</sub>O<sub>2</sub>, an XPS analysis was performed to evaluate the elemental components and chemical states of the surfaces of pure pyrite mineral treated with the combined inhibitor (lime + H<sub>2</sub>O<sub>2</sub>) and lime alone. Table 7 and Figure 10 show the analysis results.

**Table 7.** XPS Analysis Results of Pyrite before and after Depressant Treatment.

| Species              | B.E. (eV)                                    | Atomic Concentration (at. %) |      |                                     |
|----------------------|----------------------------------------------|------------------------------|------|-------------------------------------|
|                      |                                              | Blank                        | CaO  | H <sub>2</sub> O <sub>2</sub> + CaO |
| Fe 2p <sub>3/2</sub> | Fe(II)-S                                     | 707.2 ± 0.1                  | 30.2 | 27.1                                |
|                      | Fe(III)-S                                    | 709.2 ± 0.3                  | 5.7  | 4.3                                 |
|                      | Fe(III)-O                                    | 710.3 ± 0.2                  | 4.5  | 7.23                                |
| S 2p <sub>3/2</sub>  | S <sub>2</sub> <sup>2−</sup>                 | 162.9 ± 0.1                  | 21.3 | 20.8                                |
|                      | S <sup>2−</sup>                              | 162.5 ± 0.2                  | 10.5 | 9.2                                 |
|                      | S <sub>n</sub> <sup>2−</sup> /S <sub>0</sub> | 164.3 ± 0.2                  | 3.1  | 4.6                                 |
|                      | SO <sub>4</sub> <sup>2−</sup>                | 168.7 ± 0.1                  | 1.2  | 1.8                                 |
|                      | SO <sub>3</sub> <sup>2−</sup>                | 166.5 ± 0.1                  | -    | -                                   |
| O 1s                 | O-H                                          | 532.8 ± 0.2                  | 8.0  | 24.5                                |
|                      | Me-O                                         | 530.1 ± 0.2                  | 2.3  | 12.8                                |
| Ca 2p                | Ca-O                                         | 348.1 ± 0.2                  | -    | 0.1                                 |



**Figure 10.** High-resolution Fe 2p<sub>3/2</sub> spectra on the surface of pyrite under different conditions: (a) Blank, (b) Lime, and (c) Lime combined with hydrogen peroxide.

As shown in Table 7, the contents of O existing as O-H and Fe(III)-O on the surface of untreated pyrite were 8.0% and 4.5%, respectively. After lime treatment, the values

increased considerably to 24.5% and 7.23%, respectively. Calcium ions were also detected on the pyrite surface. This suggested that the addition of lime caused the generation of a large number of hydroxides, which were co-adsorbed with calcium hydroxyl compounds to the pyrite surface and contributed to its hydrophilicity. These results are consistent with those reported by Duan Wenting et al. [27]. Upon treatment with the combined lime + H<sub>2</sub>O<sub>2</sub> inhibitor, the surface atomic concentrations of pyrite underwent further change. First, the atomic concentrations of the sulfur element existing as S<sup>2−</sup> and S<sub>2</sub><sup>2−</sup> decreased slightly, while those of sulfur existing as sulfates and sulfites increased. In addition, O contents in the form of O-H and Fe(III)-O increased by 1.04% and 0.8%, respectively, compared with those for lime treatment alone. These results indicated that oxidation occurred on the pyrite surface, leading to an increase in hydrophilic substances. This oxidation reaction was an inevitable outcome of H<sub>2</sub>O<sub>2</sub> addition, with a greater hydrophilic effect on the pyrite surface induced by the combined lime + H<sub>2</sub>O<sub>2</sub> inhibitor than that induced by lime alone.

Figure 10 shows the narrow spectrum of Fe 2p<sub>3/2</sub> on the pyrite surface. The main peak at 707.2 ± 0.1 eV was attributed to fully coordinated low-spin Fe(II)-S from the bulk position, while the two small peaks at 706.3 ± 0.2 eV and 708.2 ± 0.2 eV were designated as multiple splitting peaks of Fe(II)-S [28]. The peak located at 709.3 ± 0.3 eV may be related to Fe(III)-S due to the simultaneous oxidation of Fe<sup>2+</sup> to Fe<sup>3+</sup> and reduction in S on the surface to S<sup>2−</sup> (Equation (5)) [28–30]. Broad peaks with binding energies of 710.3 ± 0.2, 711.4 ± 0.2, 712.2 ± 0.2, and 713.2 ± 0.1 eV were attributed to the multiple splitting peaks of the oxygen or hydroxyl compounds of Fe<sup>3+</sup> (i.e., FeOOH) [28,31–33].

Comparison of curves a and b in Figure 10 revealed that the Fe(III)-O peak on the pyrite surface was strengthened after lime treatment, indicating a significant increase in the hydroxyl oxides of iron. However, the binding energies of iron in various species remained almost unchanged compared with that of blank pyrite. These results suggested that the adsorption of lime on the surface of pyrite did not cause significant changes to the chemical environment of elemental iron, leading to a low degree of chemical reaction. However, different results were obtained when curves c and b were compared. The Fe(III)-O peak was further strengthened, and the inner electron binding energies of iron in both Fe(III)-O and Fe(III)-S were clearly shifted to the left and right. This suggested that significant changes occurred in the chemical environment of iron. Such a phenomenon can be attributed to the oxidative effect of H<sub>2</sub>O<sub>2</sub> on the pyrite surface, with surface oxidation resulting in the conversion of the main surface iron species Fe(II)-S to Fe(III)-O (Equations (2)–(4)) [34].

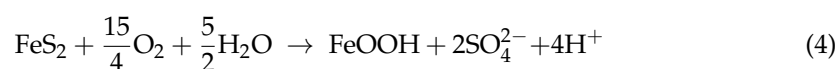
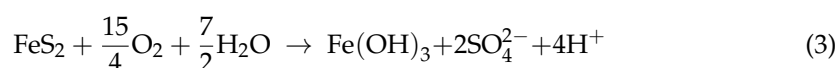
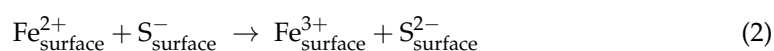
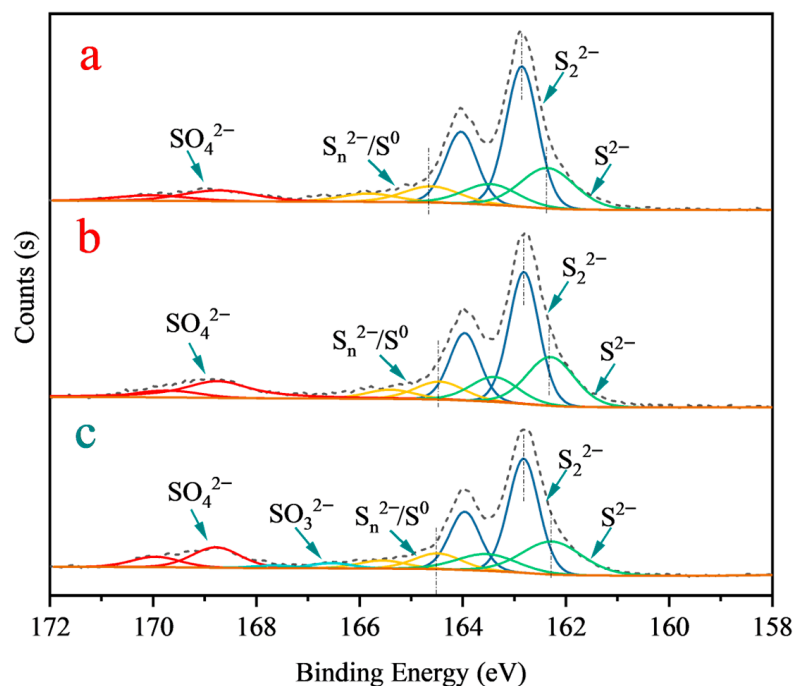
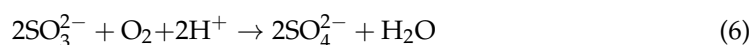
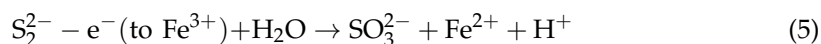


Figure 11 shows the S 2p spectra of the pyrite surface, with binding energies of 162.5 ± 0.3, 162.8 ± 0.1, and 164.4 ± 0.2 eV for S 2p<sub>3/2</sub> corresponding to monosulfides (S<sup>2−</sup>), disulfides (S<sub>2</sub><sup>2−</sup>), and hydrophobic polysulfides (S<sub>n</sub><sup>2−</sup>/S<sub>0</sub>), respectively [35,36]. Sulfur oxide species, such as sulfites (SO<sub>3</sub><sup>2−</sup>) and sulfates (SO<sub>4</sub><sup>2−</sup>), exhibited S 2p<sub>3/2</sub> peaks at 166.55 and 168.7 ± 0.1 eV, respectively [35,37]. In untreated pyrite, the concentrations of SO<sub>3</sub><sup>2−</sup> and SO<sub>4</sub><sup>2−</sup> were 0% and 1.2%, respectively. After lime treatment, the SO<sub>4</sub><sup>2−</sup> concentration increased slightly from 1.2% to 1.8%. Treatment with the combined lime + H<sub>2</sub>O<sub>2</sub> inhibitor led to a further increase in the pyrite surface SO<sub>4</sub><sup>2−</sup> concentration to 2.6%. In addition to the occurrence of new SO<sub>3</sub><sup>2−</sup> species, the S 2p peak in S<sub>2</sub><sup>2−</sup>-S<sub>n</sub><sup>2−</sup>/S<sub>0</sub>

was shifted leftward. These results suggested further enhancement of the pyrite surface oxidation process (Equations (5) and (6)).



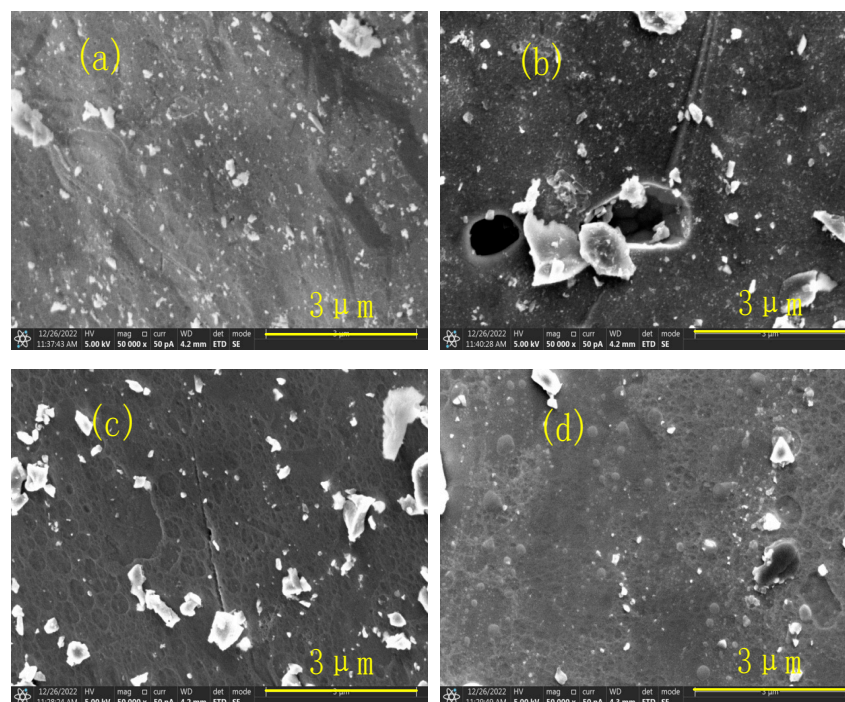
**Figure 11.** Narrow Scan of S 2p on the Pyrite Surface under different conditions: (a) Blank, (b) Lime, and (c) Lime combined with hydrogen peroxide.

Therefore, the XPS analysis results indicated that the addition of  $\text{H}_2\text{O}_2$  increased the concentration of hydrophilic iron oxide/hydroxide species on the pyrite surface.

### 3.4. SEM Analysis

Using SEM, the microscopic morphology of mineral surfaces was observed directly, providing a basis for determining the effects of different inhibitor conditions on the pyrite surface.

From the surface morphologies of pyrite under different conditions shown in Figure 12, it can be seen that the raw pyrite surface was relatively uniform. A certain amount of small debris was attached to the surface, and there were no obvious traces of oxidation or other chemical reactions. Figure 12b shows the spectrum of pyrite that had been reacted with an aqueous lime solution at a certain concentration. Compared with the raw ore, the pyrite surface remained nearly unchanged except for the presence of two natural small holes. Figure 12c shows the surface morphology of pyrite after reaction with  $\text{H}_2\text{O}_2$ . A large number of corrosion pits appeared on the pyrite surface. This indicated the occurrence of a strong chemical reaction between the pyrite surface and  $\text{H}_2\text{O}_2$ , resulting in oxidation of the mineral surface. Figure 12d shows the surface morphology of pyrite after reaction with lime +  $\text{H}_2\text{O}_2$ . In addition to the presence of corrosion pits on the surface, small bubble-like substances were also observed, likely to be caused by hydroxide deposition on the surface. The above results demonstrated that the addition of  $\text{H}_2\text{O}_2$  led to oxidation of the pyrite surface, and the combined use of  $\text{H}_2\text{O}_2$  with lime also significantly influenced the surface morphology of the mineral.

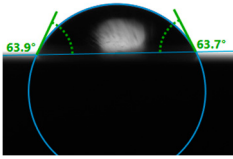
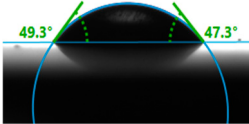
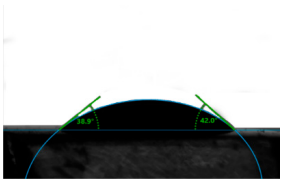


**Figure 12.** Scanning Electron Microscope Images of Pyrite Samples: (a) Pyrite; (b) Pyrite + Lime Water; (c) Pyrite + Hydrogen Peroxide; (d) Pyrite + Hydrogen Peroxide + Lime Water.

### 3.5. Contact Angle Analysis

The effects of lime +  $\text{H}_2\text{O}_2$  on pyrite floatability were investigated based on analyses of the contact angle of the pure pyrite mineral surface before and after treatment with the combined inhibitor. Table 8 shows the results of contact angle measurement and analysis.

**Table 8.** Changes in the Contact Angle of Pyrite Before and After Depressant Application.

| Test Condition           | Pyrite                                                                               |                   |
|--------------------------|--------------------------------------------------------------------------------------|-------------------|
|                          | Appearance of Contact Angle                                                          | Contact Angle (°) |
| Fresh Surface            |  | 63.8              |
| Lime                     |  | 48.3              |
| Lime + Hydrogen Peroxide |  | 40.5              |

The contact angle of the surface of untreated pyrite was  $63.8^\circ$ , indicating good floatability. After lime treatment, the contact angle was reduced to  $48.3^\circ$ , indicating the enhancement of hydrophilicity. Treatment with the combined lime +  $\text{H}_2\text{O}_2$  inhibitor led to a significant decrease in surface contact angle to  $40.5^\circ$ , indicating a considerable increase in hydrophilicity. When viewed in combination with the XPS analysis results, these findings demonstrated



that the increase in the contents of oxides and hydroxides generated on the surface of pyrite resulted in increased hydrophilicity.

### 3.6. Validation Through Actual Ore Flotation Testing

Based on the optimal parameters for pyrite inhibition and activation determined from single-mineral laboratory flotation testing, copper ore from a mine in Serbia was used as the raw material, Z200 was used as the copper collector, lime + H<sub>2</sub>O<sub>2</sub> was used as the combined inhibitor, sulfuric acid was used as the activator, and NaBX was used as the sulfur collector for validation of the feasibility of the process protocol described above for the comprehensive separation and recovery of pyrite and covellite. Figure 1 shows the test process.

The flotation test results shown in Table 9 indicated that a change in the pyrite inhibitor from lime alone to lime + H<sub>2</sub>O<sub>2</sub> led to an increase in the copper concentrate grade from 30.35% to 31.12%, with recovery remaining almost unchanged. The recovery of pyrite increased from 56.70% to 58.99%, while that of gold increased by nearly 4%. Therefore, the use of the combined lime + H<sub>2</sub>O<sub>2</sub> inhibitor effectively increased gold recovery with remarkable results.

**Table 9.** Flotation Test Results of a Copper–Gold Mine in Serbia.

| Product                  | Yield (%) | Grade (%) |                         |       | Recovery (%) |       |       |
|--------------------------|-----------|-----------|-------------------------|-------|--------------|-------|-------|
|                          |           | Cu        | Au (g·t <sup>−1</sup> ) | S     | Cu           | Au    | S     |
| Copper Concentrate 1     | 7.42      | 31.12     | 4.13                    | 34.6  | 80.74        | 18.69 | 12.59 |
| Copper Concentrate 2     | 4.68      | 8.51      | 4.58                    | 36.8  | 13.93        | 13.07 | 8.45  |
| Pyrite Concentrate       | 24.35     | 0.47      | 3.92                    | 49.4  | 4.00         | 58.20 | 58.99 |
| Tailing 2                | 14.53     | 0.084     | 0.5                     | 7.61  | 0.43         | 4.43  | 5.42  |
| Tailing 1                | 49.02     | 0.05      | 0.19                    | 6.05  | 0.91         | 5.61  | 14.55 |
| Feed                     | 100       | 2.86      | 1.64                    | 20.39 | 100          | 100   | 100   |
| Copper Concentrate 1 + 2 | 12.33     | 22.37     | 4.30                    | /     | 94.66        | 31.76 | 21.04 |
| Tailing 1 + 2            | 63.55     | 0.06      | 0.26                    | 6.41  | 1.34         | 10.04 | 19.97 |

## 4. Conclusions

1. Micro-flotation test results indicate that the addition of H<sub>2</sub>O<sub>2</sub> reduces the pH required for pyrite suppression from 12 to 10. The combined use of lime and H<sub>2</sub>O<sub>2</sub> as an inhibitor system enables efficient separation of covellite from pyrite.
2. An investigation into the mechanisms revealed that the added H<sub>2</sub>O<sub>2</sub> oxidized and corroded the pyrite surface, leading to increased oxide and hydroxide generation. This contributed to enhanced surface hydrophilicity and thereby to effective pyrite inhibition.
3. Pyrite that has been inhibited can partially regain its floatability upon the addition of sulfuric acid or copper sulfate, with sulfuric acid demonstrating greater effectiveness.
4. The Serbian copper ore exhibits a high sulfur content. When lime is used alone for pyrite inhibition, pyrite and gold recovery rates remain low. However, employing lime and H<sub>2</sub>O<sub>2</sub> as a combined inhibitor reduces lime consumption in industrial operations, maintains copper flotation performance, and increases pyrite recovery by 2.3% and gold recovery by nearly 4%.

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## Abbreviations

The following abbreviations are used in this manuscript:

|     |                                  |
|-----|----------------------------------|
| MLA | Mineral liberation analyzer      |
| SEM | Scanning electron microscopy     |
| XPS | X-ray photoelectron spectroscopy |

## References

1. Luo, S.X.; Chen, H.; Mou, Q.S.; Wu, Y.H. Research situation and progress of adsorption properties of pyrite. *Multipurp. Util. Miner. Resour.* **2020**, *5*, 27–33.
2. Chen, W.; Chen, T.; Bu, X.; Chen, F.; Ding, Y.; Zhang, C.; Deng, S.; Song, Y. Theselective flotation of chalcopyrite against galena using a lginatesas depressant. *Miner. Eng.* **2019**, *141*, 105848. [[CrossRef](#)]
3. Wang, F.L. Basic Theoretical Research on Flotation of Main Sulfide Oxide Minerals of Copper, Lead, Zinc and Iro. Ph.D. Thesis, Northeastern University, Shenyang, China, 2008.
4. Chimonyo, W.; Fletcher, B.; Peng, Y. The differential depression of anoxidized starch on the flotation of chalcopyrite and graphite. *Miner. Eng.* **2020**, *146*, 106114. [[CrossRef](#)]
5. Schlesinger, M.E.; Sole, K.C.; Davenport, W.G.; King, M.J. Chapter 1—Overview. In *Extractive Metallurgy of Copper*, 5th ed.; Schlesinger, M.E., King, M.J., Sole, K.C., Davenport, W.G., Eds.; Elsevier: Amsterdam, The Netherlands, 2011; pp. 1–12.
6. Wang, J.; Zheng, S.; Liu, W.; Chen, L.; Wen, Z.; Li, X. Prediction, evaluation and optimization of China’s copper resource supply system under carbon constraints. *Sustain. Prod. Consum.* **2023**, *39*, 285–300. [[CrossRef](#)]
7. Li, W.Y.; Bai, X.; Ge, F.; Quan, X.; Chen, M.J.; Hao, J.M. Development Status of Copper-sulfur Separation Influence Factors and Depressants. *Multipurp. Util. Miner. Resour.* **2025**, 1–18.
8. Long, Y.Y.; Yin, W.Z.; Long, K.Y. Synergistic oxidation of NaClO and KMnO<sub>4</sub> on flotation separation of chalcopyrite and pyrite and mechanism therein. *Min. Metall. Eng.* **2024**, *44*, 51–56.
9. Tang, X.; Chen, Y. A review of flotation and selective separation of pyrrhotite: A perspective from crystal structures international. *J. Min. Sci. Technol.* **2022**, *32*, 847–863. [[CrossRef](#)]
10. Shan, Z.Q.; Xia, Y.; Zhang, X.H. Copper selection experimental on a copper-gold sulphide Ore in Balai County, Lao People’s Democratic republic. *Met. Mine* **2016**, *9*, 96–99.
11. Chen, J.H.; Li, Y.Q.; Long, Q.R. Molecular structures and activity of organic depressants for marmatite, jamesonite and pyrite flotation. *Trans. Nonferrous Met. Soc. China* **2010**, *20*, 1993–1999. [[CrossRef](#)]
12. Bi, Y.X.; Yu, P.; Ding, Z.; Bai, S.J.; Wen, S.M. The Development of research on the pyrite flotation depressants. *Conserv. Util. Miner. Resour.* **2020**, *40*, 157–166.
13. Cao, Q.; Zhang, H.; Yan, Y.; Li, Y.; Liu, D. Flotation separation of pyrite and chalcopyrite with potassium permanganate as a depressant. *Chem. Pap.* **2024**, *78*, 1761–1773. [[CrossRef](#)]
14. Mu, Y.; Peng, Y.; Lauten, R.A. The depression of pyrite in selective flotation by different reagent systems—A Literature review. *Miner. Eng.* **2016**, 96–97, 143–156. [[CrossRef](#)]
15. Li, S.H.; Ma, Q.; Wang, L.; Yang, X. Research Progress on Activation Mechanism of Pyrite Flotation. *Multipurp. Util. Miner. Resour.* **2023**, *2*, 124–130.
16. Qi, X.; Li, X.; Liang, Y.; Wang, H.; Guo, W.; Cong, X.; Lv, F.; Zhang, H. Surface structure-dependent hydrophobicity/oleophilicity of pyrite and its influence on coal flotation. *J. Ind. Eng. Chem.* **2020**, *87*, 136–144. [[CrossRef](#)]
17. Bi, Y. Research on Selective Flotation Separation of Chalcopyrite and Pyrite Under Low Alkalinity. Ph.D. Thesis, Kunming University of Science and Technology, Kunming, China, 2023.
18. Khoso, S.A.; Fei, L.Ü.; Ya, G.A.O.; Wei, S.U.N. Xanthate interaction and flotation separation of H<sub>2</sub>O<sub>2</sub>-treated chalcopyrite and pyrite. *Trans. Nonferrous Met. Soc. China* **2019**, *29*, 2604–2614. [[CrossRef](#)]

19. Wang, Y.; Wei, D.; Wen, S.; Lin, Q.; Song, Z.; Luo, X. Enhanced pyrite depression through nitrogen-aerated flotation under low alkalinity conditions. *Adv. Powder Technol.* **2024**, *35*, 104424. [[CrossRef](#)]
20. Ozun, S.; Hassas, B.V.; Miller, J.D. Collectorless flotation of oxidized pyrite. *Colloids Surf. A Physicochem. Eng. Asp.* **2019**, *561*, 349–356. [[CrossRef](#)]
21. Luo, X.; Yang, W.; Wen, S.; Lin, Q.; Wei, D.; Li, C.; Zhang, Y.; Song, Z.; Wang, Y. Effect of regulating dissolved oxygen concentration in pulp with aerated gas on pyrite flotation. *Miner. Eng.* **2023**, *202*, 108290. [[CrossRef](#)]
22. Feng, B.; Zhang, W.; Guo, Y.; Wang, T.; Luo, G.; Wang, H.; He, G. The flotation separation of galena and pyrite using serpentine as depressant. *Powder Technol.* **2019**, *342*, 486–490. [[CrossRef](#)]
23. Lee, R.L.J.; Chen, X.; Peng, Y. Flotation performance of chalcopyrite in the presence of an elevated pyrite proportion. *Miner. Eng.* **2022**, *177*, 107387. [[CrossRef](#)]
24. Hodgkinson, G.; Sandenbergh, R.F.; Hunter, C.J.; De Wet, J.R. Pyrite flotation from gold leach residues. *Miner. Eng.* **1994**, *7*, 691–698. [[CrossRef](#)]
25. Yuan, J.; Li, Y.; Ding, Z.; Zhang, Y.; Chen, L.; Wen, S.; Bai, S. Cleaner flotation separation of chalcopyrite from pyrite at low alkalinity: Based on calcium hypochlorite oxidative modification in acid mine drainage system. *Sep. Purif. Technol.* **2024**, *344*, 127325. [[CrossRef](#)]
26. Yang, X.; Li, Y.; Fan, R.; Duan, W.; Huang, L.; Xiao, Q. Separation mechanism of chalcopyrite and pyrite due to H<sub>2</sub>O<sub>2</sub> treatment in low-alkaline seawater flotation system. *Miner. Eng.* **2022**, *176*, 107356. [[CrossRef](#)]
27. Duan, W.; Wang, Y.; Rao, F.; Liu, W.; Yang, Y.; Deng, R. Correlation between the mineralogical properties and oxidation rate of different minerogenetic pyrites: A Reflection on Floatability. *Min. Metall. Explor.* **2023**, *40*, 1369–1381. [[CrossRef](#)]
28. Schippers, A.; Jozsa, P.; Sand, W. Sulfur chemistry in bacterial leaching of pyrite. *Appl. Environ. Microbiol.* **1996**, *62*, 3424–3431. [[CrossRef](#)] [[PubMed](#)]
29. Holmes, P.R.; Crundwell, F.K. The kinetics of the oxidation of pyrite by ferric ions and dissolved oxygen: An electrochemical study. *Geochim. Cosmochim. Acta* **2000**, *64*, 263–274. [[CrossRef](#)]
30. Ejtemaei, M.; Nguyen, A.V. Characterisation of sphalerite and pyrite surfaces activated by copper sulphate. *Miner. Eng.* **2017**, *100*, 223–232. [[CrossRef](#)]
31. Nesbitt, H.W.; Bancroft, G.M.; Pratt, A.R.; Scaini, M.J. Sulfur and iron surface states on fractured pyrite surfaces. *Am. Mineral. Gruyter* **1998**, *83*, 1067–1076. [[CrossRef](#)]
32. Niu, X.; Chen, J.; Li, Y.; Xia, L.; Li, L.; Sun, H.; Ruan, R. Correlation of surface oxidation with xanthate adsorption and pyrite flotation. *Appl. Surf. Sci.* **2019**, *495*, 143411. [[CrossRef](#)]
33. Nesbitt, H.W.; Muir, I.J. X-ray photoelectron spectroscopic study of a pristine pyrite surface reacted with water vapour and air. *Geochim. Cosmochim. Acta* **1994**, *58*, 4667–4679. [[CrossRef](#)]
34. Nesbitt, H.W.; Muir, I.J.; Prarr, A.R. Oxidation of arsenopyrite by air and air-saturated, distilled water, and implications for mechanism of oxidation. *Geochim. Cosmochim. Acta* **1995**, *59*, 1773–1786. [[CrossRef](#)]
35. Bonnissel-Gissinger, P.; Alnot, M.; Ehrhardt, J.J.; Behra, P. Surface oxidation of pyrite as a function of pH. *Environ. Sci. Technol.* **1998**, *32*, 2839–2845. [[CrossRef](#)]
36. Chiriță, P.; Schlegel, M.L. Pyrite oxidation in air-equilibrated solutions: An electrochemical study. *Chem. Geol.* **2017**, *470*, 67–74. [[CrossRef](#)]
37. Cai, Y.; Pan, Y.; Xue, J.; Sun, Q.; Su, G.; Li, X. Comparative XPS study between experimentally and naturally weathered pyrites. *Appl. Surf. Sci.* **2009**, *255*, 8750–8760. [[CrossRef](#)]

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