Article

Copper and Zinc Recovery from Sulfide Concentrate by Novel Artificial Microbial Community

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Abstract: Exploring efficient methods to enhance leaching efficiency is critical for bioleaching technology to deal with sulfide concentrate. In our study, a novel artificial microbial community was established to augment the bioleaching efficiency and recovery of copper (Cu) and zinc (Zn). The optimum parameters in bioleaching experiments were explored according to compare a series of conditions from gradient experiments: the pH value was 1.2, temperature was 45 °C, and rotation speed was 160 r/min, which were different with pure microorganism growth conditions. Under optimal conditions, the result of recovery for Cu and Zn indicated that the average leaching rate reached to 80% and 100% respectively, which almost increased 1.8 times and 1.2 times more than control (aseptic condition) group. Therefore, this method of Cu and Zn recovery using a new-type artificial microbial community is expected to be an environmentally-friendly and efficient bioleaching technology solution, which has the potential of large-field engineering application in the future.

Keywords: copper; zinc; recovery; sulfide concentrate; artificial microbial community

Citation: Cui, X.; Yuan, X.; Li, H.; Che, X.; Zhong, J.; Wang, L.; Liu, Y.; Hu, X.; Zhang, Q.; Jin, R.; et al. Copper and Zinc Recovery from Sulfide Concentrate by Novel Artificial Microbial Community. *Metals* **2022**, *12*, 45. <https://doi.org/10.3390/met12010045>

Academic Editor: Antoni Roca

Received: 7 October 2021

Accepted: 22 December 2021

Published: 25 December 2021

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1. Introduction

Mineral resources are the economic and material basis of human society. In recent years, with the proposal of green mine development concept, efficient exploitation of mineral resources and reduction of ecological environmental impact have been important principles for future exploitation and utilization of mineral resources [1]. However, most mines in China have backward mining technology, enormous destruction and waste, too low recycling proportion, and low management efficiency [2]. As is known to us, with continuous decline in copper rich ore reserves, reprocessing of low-grade copper-bearing sulfide ores, accounting for >70% of the global copper reserves, has become inevitable [3–5]. Unfortunately, metal extraction from these low-grade ores using traditional smelting techniques is uneconomical. Therefore, most low-grade ores have been discarded [6–8].

In the last two decades, extensive efforts have been made to apply microbes to sulfides leaching due to demand of ores and low costs [9,10]. Biological processes are effective methods and the interaction between microorganisms and minerals has been a hot topic to reveal the transformation of key elements affecting bioleaching efficiency [11,12]. Moreover, bioleaching attracts increasingly more attention for its simplified operation, low cost, and

environmentally friendly benefits [13,14]. In the bioleaching process, structural metals in solid materials are transformed into soluble and extractable ones by microorganisms through biological oxidation or complexation processes for easy recovery [15]. Bioleaching has been actively studied for years to deal with metal-contaminated sludge and environments, such as sediment and soil, and the removal efficiency of most heavy metals is usually higher than 85% [16–19]. Bioleaching facilitates metal mobilization from solid sources via different biologically catalyzed reactions mediated by different microbial leaching agents such as (in)organic acids. A wide range of microorganisms such as chemolithoautotrophic bacteria, archaea, and fungi have been applied for bioleaching of metals from different solid materials [20–23].

In the bioleaching technology, microorganisms, such as *Acidithiobacillus ferrooxidans*, *Acidithiobacillus thiooxidans*, *Acidithiobacillus caldus*, *Leptospirillum ferrooxidans*, and *Ferropasma* spp., are often employed to enhance the dissolution process of copper sulfide ores [24]. The detailed bioleaching efficiency for metals of several microbes is listed in Table 1. Obviously, the community which consists of *Acidithiobacillus thiooxidans*, *Acidithiobacillus ferrooxidans*, and *Leptospirillum ferriphilum* had lower leaching efficiency for Cu and Zn and pH value was 2.0–2.2 in 25 days, which only reached 69–83% and 4.1–14% respectively [25]. Further research used two bacteria including *Acidithiobacillus thiooxidans* and *Acidithiobacillus ferrooxidans*. The leaching efficiency of Cu and Zn reached 38% and Zn 67% [26]. Furthermore, another previous study showed that *Bacillus megaterium* QM B1551 can extract valuable metals such as Co, Ni, and Cu from a complex sulfide flotation concentrate, but the Cu only leached 39.8% [27]. Meanwhile, the bioleaching potential of indigenous *Aspergillus fumigatus* to remove metals was evidenced and the leaching efficiency reached 100%, 62%, 58%, 56%, and 54% for Mn, As, Fe, Pb, and Zn, respectively [28]. Moreover, *Aspergillus niger* was used to treated waste LCD panels, and the indium bioleaching efficiency could be improved from 12.3% to 100% by fermentation method optimization [29], but the method process speed time was more than 15 h. Additionally, the microbial leaching of heavy metal from municipal sludge was studied in a continuously stirred tank reactor, and about 62% of Cu and about 77% of Zn were dissolved [30]. Above all, the majority of bioleaching experiments employed single wild microorganisms, which means that the leaching efficiency was relatively limited. Some researchers improved the experimental system with microbes used as the target and adopted the mixed community system, which greatly improved the leaching efficiency [26,29,31,32]. However, to our knowledge, there is little research focus on exploring the simultaneous improvement of Cu and Zn leaching efficiency in polymetallic ore remains.

Table 1. The advance in leaching metals technological scheme.

Microbe or Method	Result (Leaching Efficiency)	Reference
<i>Aspergillus fumigatus</i>	As (62%), Fe (58%), Mn (100%), Zn (54%)	Bahi Jalili Seh-Bardan et al., 2012 [28]
<i>Acidithiobacillus thiooxidans</i> ; <i>Acidithiobacillus ferrooxidans</i> ; <i>Leptospirillum ferriphilum</i>	Cu (69~83%); Zn (4.1~14%)	Olli H. Tuovinen et al., 2015 [25]
<i>Acidithiobacillus thiooxidans</i> ; <i>Acidithiobacillus ferrooxidans</i>	Cu (38%); Zn (67%)	Van Khanh Nguyen and Jong-Un Lee., 2015 [26]
<i>Bacillus megaterium</i> QM B1551	Co (60.7%); Ni (76.3%); Cu (39.8%)	Xinlan Cui et al., 2016 [27]
<i>Acidithiobacillus</i> sp., <i>Leptospirillum</i> sp., <i>Ferropasma</i> sp.	Pyrite (69.29%); Chalcocite (65.02%); Covellite (84.97%)	Shang He et al., 2021 [24]
<i>Aspergillus niger</i>	Indium (100%)	Jiaying Cui et al., 2021 [29]
Chemical leaching	Zn (85%); Cu and Fe (10%)	Jia Li et al., 2021 [33]
<i>Acidithiobacillus ferrooxidans</i>	Cu (54%); Ni (75%), Fe (55%)	Mahdokht Arshadi et al., 2021 [34]

In our study, we aim to adopt a new microbial culture method to cultivate a new-type artificial microbial community to leach Cu and Zn from sulfide concentrate, and explore the influence of different conditions (temperature, pH value, and rotation speed)

on metal recovery, to further research and development of environmentally friendly and efficient bioleaching technology. An artificial microbial community consisting of *Sulfobacillus thermotolerans* 6Y-1, *Leptosirillum ferriphilum* MJ-CL, and *Acidithiobacillus caldus* OY (the concentration ratio is 1:1:1) was established for targeted and efficient recovering of copper and zinc from sulfide concentrate. Furthermore, different pH value, temperature, and rotation speed gradient were determined for the optimal conditions by the artificial microbial community. Then, the preferred conditions were chosen for bioleaching efficiency of Cu and Zn, using this novel artificial microbial community, which provided a new-type and high-efficiency method for recovering of copper and zinc from low-grade ores.

2. Materials and Methods

2.1. Sample Source and Mineral Component Analysis

The sulfide concentrate used in our study was from Qinghai Derni flotation sulfide concentrate. The mineral component was characterized by X-ray diffraction (XRD) on a Philips Diffractometer (model: X'Pert-Pro MPD; Philips, Eindhoven, The Netherlands) using CuK α radiation ($\lambda = 0.15418$ nm, 45 kV, 200 mA). Diffraction patterns covering a 2θ range of 10° – 90° were measured at a step size of 0.02° . The scanning speed was $8^\circ/\text{min}$ and all the tests were carried out at room temperature.

The chemical and elemental composition of the sulfide concentrate sample was characterized by X-ray fluorescence spectrometer (XRF) (Model: ARL Advant XP, Thermo Electron Corporation, Berne, Switzerland). All measurements have been done with the excitation power of 4.2 kW, 50 kV excitation voltage and 55 mA excitation current.

The chemical analyses of the screened samples and mineralogical data were obtained from mineral liberation analyses (MLA, 650 F) equipped with a Bruker EDX (energy dispersive X-ray) system and MLA suite 3.1 for data acquisition.

2.2. Culture for the Artificial Microbial Community

Bacteria of the genus *Sulfobacillus* are successfully used in biotechnologies of treatment of sulfide ore materials [32]. Cultures deposited in China Center for Type Culture Collection (CCTCC) were used in the study. The artificial microbial community was constituted by *Sulfobacillus thermotolerans* 6Y-1 (CCTCC No. M2010279), *Leptosirillum ferriphilum* MJ-CL (CCTCC No. M2011019), and *Acidithiobacillus caldus* OY (CCTCC No. M2010356) (with a concentration ratio for 1:1:1). The artificial microbial community was cultured with a medium containing: 44.7 g/L of $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, 3 g/L of $(\text{NH}_4)_2\text{SO}_4$, 0.1 g/L of KCl, 0.5 g/L of K_2HPO_4 , 0.5 g/L of $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, 0.01 g/L of $\text{Ca}(\text{NO}_3)_2$. The value of the medium was adjusted by using 1 mol/L sulfuric acid. The artificial microbial community was aerobically inoculated in 100 mL medium at 45°C condition with shaking speed of 160 r/min for 3 days. Then it was inoculated with 5 mL microbial suspension into 100 mL medium and reactivated two times until the optical density at 600 nm (OD_{600}) reached about 1.5. The number of bacteria in bacterial liquid was directly counted by blood counting plate under light microscope (Nikon ECL IPSE 50I). The pH value of the solution was measured by using a pH meter (Orion 868A, ThermoFisher, Waltham, MA, USA).

2.3. Chemical Analysis Procedure of Leached Elements

As for leaching process experiment, 20 g sulfide concentrate sample, 90 mL medium, and 10 mL logarithmic phase microbial community solution were placed into 250 mL conical flask. The initial pH and different temperature conditions were controlled. During leaching process, 5 mL samples of suspension were aseptically removed at 24 h intervals. The distilled water was added to replenish the evaporated solution before sampling. After the leaching finished, the residual ore concentrate was separated into solids. The supernatant immediately by centrifugation (Eppendorf Centrifuge 5804R, Hamburg, Germany) with 11,000 r/min for 10 min to obtain the supernatant and sediment. The quantitative analysis of the main elements was carried out by ICP-OES (Inductively coupled plasma emission Spectrometer, Agilent 725-ES, Santa Clara, CA, USA).

3. Results and Discussion

3.1. Mineral Composition for Sulfide Concentrate

With the aim of understanding the chemical constituents of sulfide concentrate, XRF was employed in the study. As shown in Table 2, the sulfide concentrate contained large amounts of SO_3 (47.6%), Fe_2O_3 (37.6%), SiO_2 (5.94%), MgO (4.24%), and CaO (2.27%). In addition, there were several limited content chemical compounds, which including ZnO (0.730%), CuO (0.540%), Al_2O_3 (0.380%), and other oxides content was less than 0.100%. Therefore, there were minute amount of oxides content of Cu and Zn in the sulfide concentrate.

Table 2. XRF Results for sulfide concentrate (wt%).

Oxides	Fe_2O_3	SiO_2	MgO	CaO	Na_2O	ZnO	CuO
Content	37.6	5.94	4.24	2.27	0.540	0.730	0.540
Oxides	Cr_2O_3	TiO_2	MnO	K_2O	NiO	Al_2O_3	SO_3
Content	0.0100	0.0100	0.0500	0.0100	0.0400	0.380	47.6

Furthermore, chemical elements in the sulfide concentrate were determined by ICP-OES. As shown in Table 3, the main elements in the sulfide concentrate were Fe (48.5%), S (32.3%), Ca (1.41%), Mg (1.32%), Zn (0.890%), Cu (0.600%), and other lower content (less than 0.1%) elements, such as Al, Mn, Ni, Na, Ti, Cr, Pb, and K.

Table 3. Main chemical constituents of sulfide concentrate (wt%).

Elements	Fe	S	Si	Ca	Mg	Zn	Cu	Al
Content	48.5	32.3	2.61	1.41	1.32	0.890	0.600	0.0600
Elements	Mn	Ni	Ti	Cr	Pb	K	Na	
Content	0.0400	0.0300	0.0100	0.0100	0.0100	0.0100	0.0100	

The powder X-ray diffraction (XRD) patterns for sulfide concentrate are shown in Figure 1. As can be seen, the main minerals of the sample are pyrite, pyrrhotite, chalcopyrite, sphalerite, and magnetite, similar to previous research [33]. In detail, the diffraction peaks were observed at 28.5° , 33.0° , 37.0° , 40.7° , 47.4° , 56.3° , 61.7° , 64.3° , 83.6° , and 88.3° corresponding to the lattice planes of pyrite (111), (200), (210), (211), (220), (311), (023), (321), (332), and (422), respectively (PCPDF: 99-0087). Meanwhile, diffraction peaks appeared at 29.9° , 33.8° , 43.8° , 53.1° , 62.2° , and 71.2° corresponding to the lattice planes of pyrrhotite (200), (205), (2010), (220), (400), and (1120), respectively (PCPDF: 29-0724). In addition, 29.4° , 48.6° , and 81.6° were assigned to three characteristic diffraction planes of chalcopyrite (112), (220), and (404) (PCPDF: 26-1116), and 47.5° , 59.1° , 76.8° corresponding to planes of sphalerite (220), (222), and (331) (PCPDF: 05-0566). The XRD data revealed that pyrite and pyrrhotite have perfect crystallinity, but chalcopyrite and sphalerite are imperfect according to the sharpness differentiation of the peak shape.

Figure 1. Powder XRD pattern for sulfide concentrate.

3.2. MLA and Liberation Classes for Sulfide Concentrate

Mineral Liberation Analysis (MLA) is the effective modern method to analyze mineral properties, especially the liberation of minerals which is very important to the separation of different minerals. The chemical analyses and main mineral constituent data obtained from MLA are presented in Table 4 and the minerals in sulfide concentrate could be divided into five categories as sulfide, oxide, carbonate minerals, sulfate minerals, and silicate minerals. Analyzing their particle size distribution in Figure 2a, the sulfide minerals including pyrite, pyrrhotite, chalcopyrite, sphalerite, and galena as a group and their particle size distribution is mainly between 10 μm and 100 μm (13–93%). The particle size distribution of oxide minerals such as magnetite, hematite, chromite, and ilmenite with the percent of 26.5% lower than 10 μm and all of them were lower than 125 μm . Moreover, the size distribution property of carbonate minerals (dolomite and calcite) and silicate minerals (enstatite, quartz, biotite, hornblende, and pyroxene) was similar to the oxide minerals. As far as sulfate minerals (anhydrite and FeCaMgSO_4) are concerned, their size was lower than 99 μm and most of them were lower than 10 μm (60%). The size distribution results indicated that the sulfide concentrate was suitable for bioleaching [24].

Table 4. MLA results for main mineral constituents in sulfide concentrate (wt%).

Mineral	Content	Mineral	Content
Pyrite	40.0	Quartz	0.720
Pyrrhotite	31.0	Albite	0.0600
Chalcopyrite	1.77	Hornblende	0.360
Sphalerite	1.31	Pyroxene	0.0300
Galena	0.0100	Muscovite	0.0300
Magnetite, Hematite	13.5	Biotite	0.610
Chromite	0.0100	Enstatite	3.86
Ilmenite	0.0100	Calcite	0.0400
Anhydrite	0.0800	Dolomite	4.07
FeCaMgSO_4	2.50	-	-

Figure 2. (a) Sieve size distribution for different minerals in sulfide concentrate; (b) liberation classes results for sulfide concentrate.

Analyzing the mineral liberation classes results in Figure 2b, the liberation characteristic of five categories was ordered: sulfide minerals > silicate minerals > carbonate minerals > oxide minerals > sulfate minerals. Most importantly, the sulfide minerals present the best liberation characteristic and 57.3% of them had 100% liberation degree, which was higher than the rest of the other four type minerals. Because the Cu and Zn were mainly abundant in chalcopyrite and sphalerite, the suitable size and great liberation provide possibilities for recovery from sulfide concentrate by the artificial microbial community.

3.3. Artificial Microbial Community Growth Characteristic Analysis

It is widely known that microbial community composition mainly depended on environmental factors, such as pH, temperature, and oxygen content. In order to better understand growth condition of the artificial microbial community, different pH, temperature, and cultural revolving speed were determined, respectively. As shown in Figure 3a, the growth rate of microbial significantly changed with pH ranging from 1.0 to 1.8. After 5 days, the artificial microbial community was in logarithmic phase. Moreover, better growth rates were observed with pH values of 1.8 and 1.5, the average logarithmic cell concentration was 8.3×10^7 cell/mL and 7.7×10^7 cell/mL respectively. A lower growth rate was observed when pH value was 1.2 with average logarithmic cell concentration was 6.5×10^7 cell/mL. The lowest growth rate was observed at pH = 1.0 and the cell concentration was only 2.4×10^7 cell/mL. We could conclude that the most suitable pH value should be 1.8, which was similar to previous study (optimal pH value was 1.5) [35].

Figure 3. Culture condition results of (a) pH, (b) temperature, and revolving speed for artificial microbial community.

Furthermore, another two environmental factors of temperature and revolving speed were studied as well [28,29]. As shown in Figure 3b (Red Lines), the microorganism is significantly affected by culture temperature. The best growth rate presented under 30 °C, and the number of microbials continued increasing within 1–10 days, which reached the maximum value about 6.1×10^7 cell/mL. When the temperature was 45 °C, the growth rate was the fastest in the first three days, and the number of microorganisms attaining the maximum was about 4.7×10^7 cell/mL on the fifth day. However, the number of microorganisms decreased rapidly five days later, which reached to 2.2×10^7 cell/mL. When the temperature was 55 °C, an unsatisfactory growth curve was performed and the cell concentration did not exceed 1.5×10^7 cell/mL in the whole culture process.

As far as rotation speed is concerned, the growth of microorganisms should be influenced notably. As shown in Figure 3b (Blue Lines), the fastest growth rate was observed with 160 r/min condition, and the number of microorganisms which reached the maximum value about 6.3×10^7 cell/mL on the fifth day. However, when the rotation speed was adjusted to 120 r/min or 190 r/min, the average cell concentration was 2.8×10^7 cell/mL and 1.2×10^7 cell/mL respectively. Based on the above results, we conclude that the artificial microbial community preferred values of pH, temperature, and cultural revolving speed of 1.8, 30 °C, and 160 r/min respectively.

3.4. Reaction Condition Exploration for Leaching Process

Based on the artificial microbial community growth characteristic analysis results, the leaching efficiency of Cu and Zn was studied under different pH (pH = 1.0, 1.2, 1.5, 1.8) and different temperature (35 °C, 45 °C, 55 °C) conditions. As shown in Figure 4 (left part), the highest leaching efficiency of Cu and Zn were observed when pH value was 1.2, and the value attained was 80% and 100% respectively. In addition, the leaching efficiency of Cu is similar when pH value was 1.0, 1.5, and 1.8, only reached to 65%, 62%, 61%, respectively. Meanwhile, the leaching efficiency of Zn is similar when pH value was 1.5 and 1.8, which reached to 95% and 94.5% respectively. However, the lowest leaching efficiency of Zn only came up to 85% when pH value was 1.0. Therefore, the optimal pH value was 1.2, which was different with the cell-culture value (1.8).

Figure 4. Leaching efficiency for Cu and Zn under (a) different pH and (b) different temperature conditions by the artificial microbial community.

Furthermore, the Figure 4 (right part) presented the highest leaching efficiency of Cu and Zn under 45 °C, which reached to 84% and 98% respectively. However, when temperature value reduced to 35 °C, the leaching efficiency of Cu was 58%, and the value of Zn was 81%. Meanwhile, when temperature raised to 55 °C, the leaching efficiency of Cu

Zn reached to 51% and 97%, respectively. Therefore, the preferred value of temperature was also changed from 35 °C to 45 °C in the experiments, compared with cell-culture process. We could conclude that the artificial microbial community has positive effect on the leaching efficiency of Cu and Zn. However, the conditions of microbial growth and degradation need to be further corrected in practical engineering applications. Compared with the previous microorganism growth conditions, the preferred values of pH and temperature were changed in the experiments, the highest leaching efficiency of Cu and Zn which occurred in the value of pH and temperature was 1.2 and 45 °C respectively, and the conditions have a slight difference with regard to previous related study [29].

In order to further improve the leaching efficiency of Cu and Zn, the study of essential factors for ore pulp density and inoculation quantity was necessary [29]. The leaching efficiency of Cu and Zn in various of ore pulp density (5%, 10%, 15%, 20%, 25%) were explored, while the pH value was 1.2, temperature was 45 °C, and rotation speed was 160 r/min. For the ore pulp density result presented in Figure 5 (red lines), the leaching efficiency of Cu and Zn increased at first and then decreased rapidly with the increasing of ore pulp density. The highest leaching efficiency of Cu and Zn reached to 100% and 79% on 20% ore pulp density. Meanwhile, when the ore pulp density was lower than 20%, the leaching efficiency of Cu and Zn only attained to 74% and 84% respectively. Moreover, with 25% ore pulp density, the leaching efficiency of Cu and Zn decreased rapidly as well, which reached to 53% and 55% respectively.

Figure 5. Leaching efficiency curves determined by ore pulp density and inoculation quantity.

In addition, the inoculation quantity of microbial community is another essential factor for the leaching efficiency of Cu and Zn. In this part, different inoculation quantity (5%, 8%, 10%, 12%, and 15%) were explored in the same conditions, with the value of ore pulp density is 20%. Figure 5 (blue lines) shows the inoculation quantity results: with increasing inoculation quantity, the leaching efficiency of Cu and Zn increased at first and then decreased. The highest value occurred on 10% inoculation quantity, which reached to 82% and 100%, present a non-linear relationship. At the same time, if the inoculation quantity (8%) was smaller than 10%, the leaching efficiency of Cu and Zn decreased to 77%

and 85% respectively, and further reduced to 68% and 72% with the inoculation quantity of 5%, when the inoculation quantity (12%) was higher than 10%, the leaching efficiency of Cu and Zn reduced to 78% and 87% respectively, and further reduced to 72% and 82% with the inoculation quantity of 15%.

The trend of the leaching efficiency is inseparable with ore pulp density and inoculation quantity. We speculate that there are two reasons. Firstly, lower concentration of ore pulp density will not be enough to satisfy the adherent area of microorganisms, but higher concentration will hinder the exchange of microorganisms and ore pulp. As far as inoculation quantity is concerned, limited microorganisms result in lower leaching efficiency of Cu and Zn, but the dissolved oxygen could not support superfluous microorganisms to maintain optimal activity. Based on the above results, we could conclude that ore pulp density and inoculation quantity were key factors affecting the leaching efficiency of Cu and Zn from sulfide concentrate. Therefore, 20% ore pulp density and the inoculation quantity of 10% are optimal conditions for engineering application in system.

3.5. Efficient Performance for Novel Artificial Microbial Community

Based on above experiment results, when the leaching efficiency of Cu and Zn have reached maximum, the optimal conditions were: pH was 1.2, temperature was 45 °C, artificial microbial community inoculation quantity was 10%, and ore pulp density was 20%. In order to explore the leaching efficiency performance by the novel artificial microbial community, control groups (leaching under aseptic conditions) without microbial were set up in the same time, which was used to compare with the experimental group.

As shown in Figure 6, the artificial microbial community had a significant effect on the leaching of Cu and Zn. The points were as follows. For Cu, the leaching rate of the control group increased steadily in the first eight days, and reached the maximum on the eighth day, with the average leaching rate of 45%. Compared to control group, in the experimental group, the leaching rate increased steadily in the first ten days, and the growth rate was greater than the control group. The leaching rate of Cu reached the maximum on the tenth day, with an average leaching rate of 80%. The increase of artificial microbial community lengthened the leaching cycle of Cu, but the leaching rate of Cu was significantly increased, and the leaching rate of Cu in the experimental group was 1.8 times that of the control group. For Zn, the leaching rate of control group and experimental group was higher than the Cu. In the control group of Zn, the leaching rate reached the maximum on the eighth day, with an average leaching rate of 80%. However, after the addition of artificial microbial community, all Zn leaching on the sixth day and leaching rate was 100%. The addition of artificial microbial community not only shortened the leaching cycle of Zn, but also increased the leaching rate by 1.2 times. In a single microbial reaction system, the leaching rates of Cu and Zn by microorganisms were up to 62% and 77% [30]. Compared with the single microbial system, the novel artificial microorganism improves the leaching rate of Cu and Zn effectively, and the leaching efficiency is increased by 30% and 29%.

All in all, comprehensive analysis shows that the artificial microbial community can significantly enhance the leaching rate of Cu and Zn from mine tailings, and the leaching rate of Zn was significantly higher than of Cu. In addition, an artificial microbial community has the advantage of high efficiency and no pollution in leaching Cu and Zn, which has important research significance in improving mineral recovery and degrading heavy metal pollution in the future.

Figure 6. Copper and zinc recovery by the novel artificial microbial community.

4. Conclusions

As an environmentally friendly and high-efficiency bioleaching technologies scheme, the artificial microbial community's enhancement of the recovery of Cu and Zn was studied for the first time. The optimal experimental parameters (pH value, temperature, and rotation speed) are unlike those between microorganism growth conditions and bioleaching experiments. Under the optimal conditions, the average recovery rate of Cu and Zn reached to 80% and 100% respectively, which almost increased 180% and 120% more than the control group. Further studies plan to optimize the novel artificial microbial community to leach more kinds of metal ions and provide different solutions for various kinds of low-grade ore.

Author Contributions: Conceptualization, X.C. (Xinglan Cui) and X.Y.; methodology, X.C. (Xiaokui Cui); software, H.L. and Q.Z. (Qidong Zhang); validation, J.Z., L.W. and X.H.; formal analysis, Q.Z. (Qi Zheng); investigation, R.J.; resources, Y.L.; data curation, X.C. (Xinglan Cui); writing—original draft preparation, X.C. (Xinglan Cui) and X.Y.; writing—review and editing, Y.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Project (No. 2019YFC1805900), the National Key Research and Development Project (No. 2020YFC1807700), the Open Foundation of State Key Laboratory of Vanadium and Titanium Resources Comprehensive Utilization (No. 2021P4FZG13A), the Youth Fund Project of GRINM (No. 12008, No12119 and No12120), National Natural Science Foundation of China (No. 51704028), and the Open Foundation of State Key Laboratory of Mineral Processing (No. BGRIMM-KJSKL-2020-07).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

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