

Comprehensive recovery of valuable metals from copper smelting slag using microwave-assisted leaching

Xasanov Shaxzod Rasul ugli

Karshi State Technical University

ORCID: 0009-0001-9533-3603

E-mail: sh.khasanov@gmail.com

Abstract: This study investigates the comprehensive processing of copper-smelting slag as a secondary source of valuable and strategically important metals. The chemical and mineralogical characteristics of the investigated material were determined using instrumental analytical methods, including elemental and X-ray diffraction analyses. The results showed that iron was the dominant component, while copper, zinc, sulfur, lead, antimony, silver, tin, and gold were also present. Fayalite and ferrosilite were identified as the principal mineral phases, together with zinc ferrite, copper sulfide, bornite, and sphalerite. The influence of mechanical grinding and microwave-assisted treatment on the subsequent leaching of valuable components was investigated. Leaching experiments demonstrated that combined microwave activation before and during leaching improved the dissolution of copper and other components. Copper recovery reached approximately 91%, while zinc and iron recoveries were about 87.2% and 90.4%, respectively. The residual material was subsequently treated with thiourea to recover gold. The maximum gold recovery of 88.6% was achieved at 60 °C. The obtained results demonstrate the potential of combining mechanical activation, microwave-assisted leaching, and thiourea treatment for the comprehensive utilization of copper-smelting slag.

Keywords: copper slag; hydrometallurgy; microwave-assisted leaching; copper recovery; gold recovery; thiourea.

INTRODUCTION

The rapid development of industrial production, together with the gradual depletion of high-grade mineral deposits, has increased the need for efficient methods for processing complex ores, industrial residues, and secondary raw materials. Large quantities of valuable metals remain in technogenic wastes because conventional processing technologies often provide incomplete recovery. Therefore, the development of integrated and economically viable approaches for the extraction of valuable components from secondary resources is becoming increasingly important for modern metallurgy [6].

Copper production is associated with the formation of considerable amounts of metallurgical residues, particularly converter slags. These materials may contain significant quantities of copper and other valuable components, making their further processing attractive from both economic and resource-conservation perspectives [4]. Conventional treatment methods do not always ensure sufficiently high recovery, especially when valuable metals are strongly associated with complex mineral phases. Improving the conditions of slag treatment and developing more selective processing routes can therefore contribute to a more complete utilization of metallurgical resources [9].

Selenium-bearing residues generated during copper production also represent an important secondary source of valuable material. Traditional processing of such residues may involve thermal

treatment and subsequent purification stages, which can be accompanied by the formation of gaseous compounds and additional technological difficulties. Alternative approaches based on selective separation and purification can improve the recovery of selenium and reduce the environmental impact of the process [10]. The treatment of selenium-containing residues and associated washing solutions can additionally provide an opportunity to obtain useful products from materials that would otherwise be disposed of.

The recovery efficiency of valuable minerals from complex raw materials depends strongly on their chemical and mineralogical characteristics as well as on the conditions of beneficiation. Flotation processes, for example, are affected by the surface properties of minerals, the type and concentration of reagents, and the interaction between collectors and mineral particles. The use of combined reagent systems can improve selectivity and increase the recovery of valuable components from difficult-to-process ores [4]. Such approaches are particularly relevant for refractory and complex raw materials in which conventional beneficiation methods provide insufficient results.

Technogenic wastes from alumina production constitute another significant source of potentially recoverable components. Red mud and related residues are generated in large quantities and may create serious environmental and storage problems. At the same time, these materials can contain iron, titanium, scandium, rare-earth elements, and other valuable constituents. Their comprehensive processing makes it possible to convert industrial waste into an additional source of mineral resources while simultaneously reducing the volume of accumulated residues [2]. The combination of physical, chemical, and hydrometallurgical methods can provide suitable conditions for the selective recovery of valuable components.

Rare-earth elements are of particular importance because of their application in modern technologies, electronics, energy systems, and advanced materials. However, their recovery from secondary raw materials is complicated by low concentrations, complex mineralogical associations, and the presence of numerous accompanying impurities. Phosphate-processing residues and wastes generated during the production of phosphoric acid may contain recoverable quantities of rare-earth elements [11]. The application of selective extraction and separation techniques can facilitate their concentration and purification and may contribute to the development of alternative sources of these strategically important metals.

Nickel-based heat-resistant alloys also represent a valuable secondary resource because they may contain nickel, cobalt, chromium, rhenium, and other technologically important metals. Conventional recycling approaches can require substantial energy input and may not provide selective recovery of individual components. Hydrometallurgical processing offers the possibility of dissolving valuable metals under controlled conditions followed by their selective separation and purification.

Nevertheless, the use of aggressive chemical reagents can create problems related to corrosion, gas evolution, reagent consumption, and process safety. Consequently, optimization of leaching conditions and the selection of appropriate technological schemes remain important research objectives [1].

The comprehensive processing of mineral resources and technogenic wastes is therefore an important element of sustainable metallurgical development. Efficient recovery of valuable metals from industrial residues can reduce dependence on primary mineral resources, decrease the accumulation of waste, and improve the economic efficiency of production. The development of modern processing technologies should focus not only on increasing metal recovery but also on improving selectivity, reducing energy and reagent consumption, and minimizing environmental impacts.

In this regard, the development of effective technological approaches for the processing of complex ores, metallurgical slags, industrial residues, and secondary raw materials is of considerable scientific and practical significance [5]. Particular attention should be given to technologies that enable the comprehensive extraction of non-ferrous, noble, rare, and rare-earth metals and allow valuable components to be recovered from materials that are currently considered difficult to process or unsuitable for conventional treatment.

RESEARCH METHODOLOGY

The study was carried out using laboratory experimental methods for the processing and analysis of complex and technogenic raw materials. The samples were crushed and ground to obtain a homogeneous material. Their elemental and phase compositions were determined using instrumental analytical methods, including ICP-MS and X-ray diffraction. Leaching experiments were performed under controlled conditions with continuous stirring. After leaching, the solid and liquid phases were separated by filtration and analyzed to determine the distribution and recovery of valuable components. The morphology and elemental distribution of selected samples were also examined by scanning electron microscopy. The obtained results were used to evaluate the efficiency of metal extraction and identify suitable processing conditions.

RESULTS

The chemical composition of the investigated slag mixture was initially determined to evaluate its potential as a secondary source of valuable metals. The analytical results demonstrated that iron was the predominant component of the material, while copper, zinc, sulfur, lead, antimony, silver,

tin, and gold were also detected. The concentration ranges of the principal elements are presented in Table 1.

Table 1. Average concentration of metals in the slag mixture samples (wt. %)

Fe	Cu	Zn	Ag	Sn	Sb	Au	Pb	S
30–31.8	0.3–0.5	1.3–1.4	0.000082– 0.000084	0.00080– 0.00082	0.17–0.19	0.000044– 0.000046	0.08–0.10	1.3–1.5

X-ray diffraction analysis was performed to determine the mineralogical composition of the slag. The results showed that iron-bearing silicate phases constituted the major part of the material. Fayalite and ferrosilite were identified as the dominant phases, while clinoferrite, zinc ferrite, copper sulfide, bornite, and sphalerite were also detected. The identified phases and their approximate contents are summarized in Table 2.

Table 2. Phase composition of the investigated slag (wt. %)

Phase	Fe_2SiO_4	FeSiO_3	CaSiO_3	ZnFe_2O_4	Cu_2S	Cu_5FeS_4	CuFeS_2
Content (%)	30–30.2	24.4–24.6	2.8–2.10	16.1–16.3	0.6–0.8	0.5–0.7	1.0–1.2

The predominance of fayalite and ferrosilite indicates that a substantial proportion of the valuable components is incorporated into a complex silicate matrix. The occurrence of zinc ferrite and copper sulfide phases can also influence the dissolution behavior of the metals during subsequent leaching. Therefore, preliminary mechanical activation and modification of the mineral structure are important for improving the accessibility of the target components.

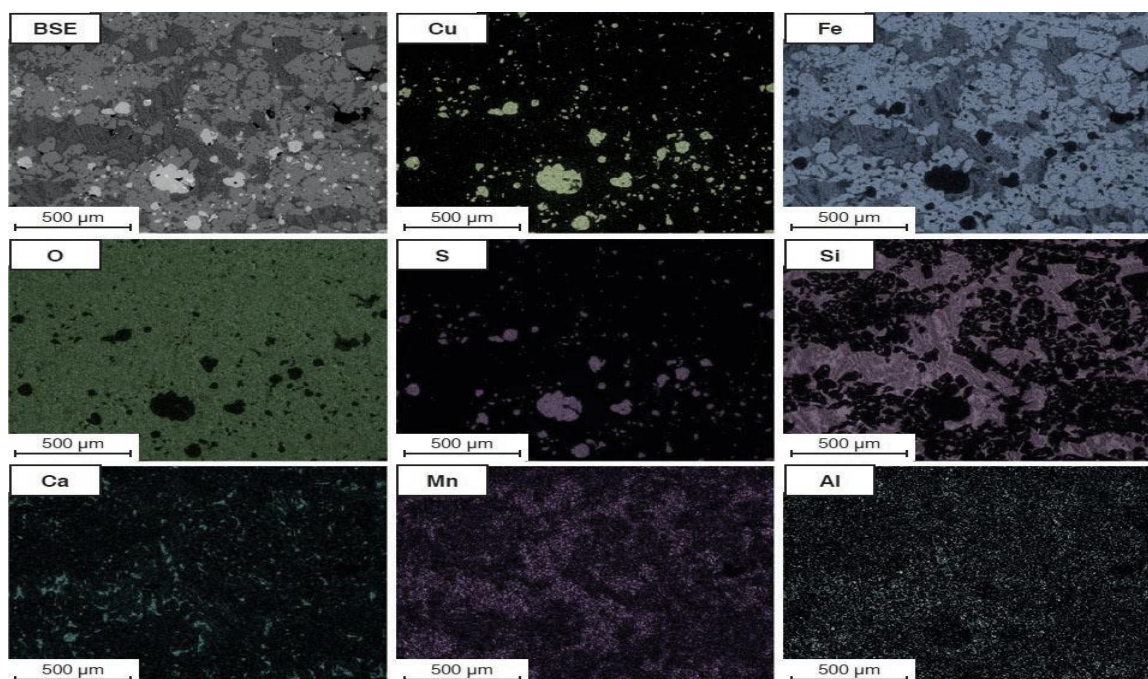


Figure 1. SEM image and EDS spectrum of the investigated slag showing the distribution of elements in the selected area.

The microscopic and elemental analyses demonstrate that sulfur is present in a relatively significant amount in the investigated material. Its occurrence is associated with sulfide-containing

phases and can affect the dissolution behavior of copper and other valuable components during leaching. Consequently, the mineralogical characteristics of the slag must be considered when selecting the leaching conditions.

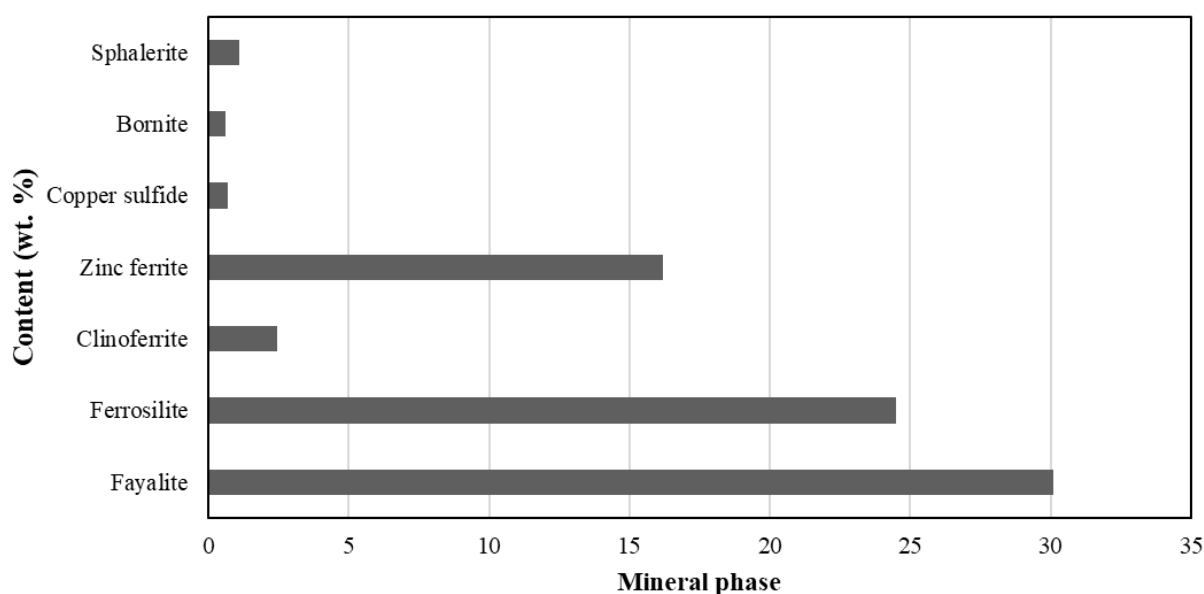


Figure 2. Phase composition of the investigated slag

Leaching of copper

To improve the accessibility of valuable components, the initial slag was mechanically activated by grinding prior to leaching. Four experimental approaches were used to investigate the influence of microwave treatment on copper leaching. In the first experiment, the ground slag was leached without microwave activation in an aqueous solution containing 250 g/L H_2SO_4 and 10 g/L HNO_3 at a solids concentration of 5% for 30 min under magnetic stirring.

In the second experiment, the same leaching conditions were applied, while microwave treatment was introduced during the leaching stage. Microwave exposure was performed for 10 min at 5-min intervals.

In the third experiment, the raw material was first subjected to microwave treatment for different durations of 60, 120, 180, and 240 s at a power of 1 kW. After microwave treatment, the material was ground and leached under the same chemical conditions without additional microwave activation during leaching.

The fourth approach combined preliminary microwave treatment with microwave-assisted leaching. The raw material was subjected to microwave irradiation for different periods, followed by grinding and leaching in a solution containing 250 g/L H_2SO_4 and 10 g/L HNO_3 . Microwave activation was additionally applied during the leaching stage.

After completion of each experiment, the resulting pulp was filtered to separate the productive solution from the solid residue. Both fractions were analyzed to determine the distribution of valuable components. The extraction results demonstrated a clear difference between the applied treatment regimes. The first method resulted in copper, zinc, and iron recoveries of 65.7%, 84.6%, and 93.4%, respectively. The second method increased copper recovery to 79.7%, while zinc and iron recoveries reached 85.3% and 96.4%.

The third experimental regime resulted in copper recovery of 73.2%, zinc recovery of 85.7%, and iron recovery of 94.0%. The combined microwave treatment used in the fourth method produced the highest copper recovery, reaching approximately 91%, while zinc and iron recoveries were 87.2% and 90.4%, respectively. These results indicate that the application of microwave activation both before and during leaching can substantially influence the accessibility of copper-bearing phases.

The results also indicate that the combined treatment is more effective for copper extraction than leaching without microwave activation. This effect is particularly important because copper is one of the principal valuable components of the investigated slag. At the same time, the relatively high extraction of iron should be considered when developing a selective process, since excessive dissolution of iron may increase the consumption of reagents and complicate subsequent purification of the productive solution.

Recovery of gold

Following copper leaching, the residual material was further investigated for gold recovery. Thiourea was selected as the leaching reagent for the subsequent stage. The experiments were performed using a thiourea solution with a concentration of 12 g/L at a solid-to-liquid ratio of 1:10. The process was conducted for 240 min under magnetic stirring at temperatures of 25, 45, and 60 °C, while the pH was maintained at approximately 1.5.

The temperature had a noticeable effect on gold dissolution. The highest gold recovery was obtained at 60 °C, reaching 88.6%. At 25 °C, the recovery was considerably lower, indicating that an increase in temperature enhances the interaction between the reagent and gold-bearing phases. Increasing the temperature above the investigated range did not result in a significant additional improvement in recovery. Overall, the experimental results demonstrate that the investigated slag can be considered a secondary source of copper, zinc, iron, sulfur, and precious metals. Mechanical activation combined with microwave-assisted treatment substantially changes the accessibility of valuable components and improves copper extraction. Subsequent thiourea leaching provides favorable conditions for the recovery of gold from the remaining material. The combination of these stages therefore creates a basis for the comprehensive processing of copper-smelting slag and the recovery of several valuable components from a single technogenic raw material.

CONCLUSION

The study demonstrated that copper-smelting slag represents a promising secondary source of valuable metals due to its complex chemical and mineralogical composition. The investigated material contained mainly iron, together with copper, zinc, sulfur, lead, antimony, silver, tin, and gold. X-ray diffraction analysis showed that fayalite and ferrosilite were the dominant mineral phases, while zinc ferrite, copper sulfide, bornite, and sphalerite were also present. These characteristics confirm the complex structure of the slag and indicate the need for combined processing methods to improve the recovery of valuable components.

The experimental results showed that mechanical grinding combined with microwave treatment can improve the leaching of valuable metals from the slag. The highest copper recovery, approximately 91%, was achieved when microwave treatment was applied before and during the leaching process, while zinc and iron recovery reached about 87.2% and 90.4%, respectively. Subsequent thiourea leaching of the residual material provided a gold recovery of up to 88.6% at 60 °C. Overall, the obtained results demonstrate the potential of combining mechanical activation, microwave-assisted leaching, and subsequent hydrometallurgical treatment for the comprehensive processing of copper-smelting slag and the recovery of valuable metal components.

REFERENCES

1. Agorhom, E. A., Lem, J. P., Skinner, W., & Zanin, M. (2015). Challenges and opportunities in the recovery/rejection of trace elements in copper flotation—A review. *Minerals Engineering*, 78, 45–57. <https://doi.org/10.1016/j.mineng.2015.04.008>
2. Ahmed, I. M., Nayl, A. A., & Daoud, J. A. (2016). Leaching and recovery of zinc and copper from brass slag by sulfuric acid. *Journal of Saudi Chemical Society*, 20, S280–S285. <https://doi.org/10.1016/j.jscs.2012.11.003>
3. Al-Harashseh, M., & Kingman, S. W. (2004). Microwave-assisted leaching—A review. *Hydrometallurgy*, 73(3–4), 189–203. <https://doi.org/10.1016/j.hydromet.2003.10.006>
4. Anand, S., Sarveswara Rao, K., & Jena, P. K. (1983). Pressure leaching of copper converter slag using dilute sulphuric acid for the extraction of cobalt, nickel and copper values. *Hydrometallurgy*, 10(3), 305–312. [https://doi.org/10.1016/0304-386X\(83\)90061-0](https://doi.org/10.1016/0304-386X(83)90061-0)
5. Arslan, C., & Arslan, F. (2002). Recovery of copper, cobalt, and zinc from copper smelter and converter slags. *Hydrometallurgy*, 67(1–3), 1–7. [https://doi.org/10.1016/S0304-386X\(02\)00139-1](https://doi.org/10.1016/S0304-386X(02)00139-1)

6. Borda, J., & Torres, R. (2022). Prospects for thiourea as a leaching agent in Colombian gold small-scale mining: A comprehensive review. *Journal of Sustainable Mining*, 21(4), Article 5. <https://doi.org/10.46873/2300-3960.1364>
7. Chen, Y., & Zhang, W. (2025). Reprocessing of copper by flotation via mineralogical characteristics from a copper slag case study. *RSC Advances*, 15, 34138–34148. <https://doi.org/10.1039/D5RA04963F>
8. Gorai, B., Jana, R. K., & Premchand. (2003). Characteristics and utilisation of copper slag—A review. *Resources, Conservation and Recycling*, 39(4), 299–313. [https://doi.org/10.1016/S0921-3449\(02\)00171-4](https://doi.org/10.1016/S0921-3449(02)00171-4)
9. Kundu, T., Senapati, S., Das, S. K., Angadi, S. I., & Rath, S. S. (2023). A comprehensive review on the recovery of copper values from copper slag. *Powder Technology*, 426, 118693. <https://doi.org/10.1016/j.powtec.2023.118693>
10. Li, J., & Miller, J. D. (2006). A review of gold leaching in acid thiourea solutions. *Mineral Processing and Extractive Metallurgy Review*, 27(3), 177–214. <https://doi.org/10.1080/08827500500339315>
11. Ray, D. A., Baniyadi, M., Graves, J. E., Greenwood, A., & Farnaud, S. (2022). Thiourea leaching: An update on a sustainable approach for gold recovery from e-waste. *Journal of Sustainable Metallurgy*, 8, 597–612. <https://doi.org/10.1007/s40831-022-00499-8>
12. Sasaki, K., Suyama, I., Takimoto, R., Konadu, K. T., Ichinose, H., & Eksteen, J. (2024). Complete gold extraction and recovery from double refractory gold ores by thiourea after bio-oxidation. *Hydrometallurgy*, 227, 106330. <https://doi.org/10.1016/j.hydromet.2024.106330>
13. Sun, J., Dong, L., Zhang, T., Shen, P., & Liu, D. (2024). Efficient recovery of copper from copper smelting slag by gravity separation combined with flotation. *Chemical Engineering Journal*, 494, 153159. <https://doi.org/10.1016/j.cej.2024.153159>
14. Tian, H., Guo, Z., Pan, J., Zhu, D., Yang, C., Xue, Y., Li, S., & Wang, D. (2021). Comprehensive review on metallurgical recycling and cleaning of copper slag. *Resources, Conservation and Recycling*, 168, 105366. <https://doi.org/10.1016/j.resconrec.2020.105366>
15. Zhang, C., Zhang, Y., Zhang, Z., & Zhang, G. (2025). Effective separation and recovery of valuable metals from copper slag: A comprehensive review. *Environmental Research*, 283, 122145. <https://doi.org/10.1016/j.envres.2025.122145>