

RESEARCH ON THE TECHNOLOGY FOR PRODUCING ZINC SULFATE MONOHYDRATE FROM ZINC-CONTAINING WASTE

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Abstract. Zinc sulfate is an important chemical compound widely used in various industries. It is applied in agriculture to increase crop yields, as well as in the production of paints, pharmaceuticals, beer, and other products. The main element, zinc, promotes the active growth and development of plants. A technology for producing zinc sulfate monohydrate was studied and developed. Powders containing 75-99% zinc and 25% sulfuric acid were used as research materials. In order to increase the interaction rate between the components, the powders were preliminarily mixed with water. The amount of concentrated sulfuric acid added was regulated so that, after addition, a sulfuric acid solution with a concentration of 25% was obtained. Hydrogen peroxide was used to remove impurities such as iron, copper, cadmium, and nickel. According to XRD analysis, the obtained product consisted of single-phase zinc sulfate monohydrate. A laboratory-scale procedure for the production of zinc sulfate monohydrate was developed.

Keywords: zinc sulfate monohydrate, waste, zinc oxide, zinc-containing raw materials, chemical composition, sulfuric acid, hydrogen peroxide, laboratory procedure, filtration, evaporation, drying.

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1. Introduction

Zinc sulfate is widely used in agriculture, pharmaceuticals, chemical production, electroplating, and feed additives [1-4]. Zinc sulfate monohydrate ($\text{ZnSO}_4 \cdot \text{H}_2\text{O}$) is particularly important due to its high zinc content, stability, and favorable storage properties. Growing demand for zinc products has increased interest in recovering zinc from industrial waste for value-added applications [5-7].

Zinc sulfate is mainly produced by hydrometallurgical processing of zinc-containing raw materials and wastes [8-10]. Sulfuric acid leaching enables efficient zinc recovery with relatively low energy consumption and is suitable for low-grade materials [11,12]. Thus, zinc recovery from industrial waste provides both environmental and technological benefits.

Zinc oxide production wastes are promising zinc sources but contain impurities that complicate the production of high-purity zinc sulfate [13,14]. Purification involves methods such as cementation, oxidation, precipitation, filtration, and solvent extraction [15-17]. Hydrogen peroxide enables Fe^{2+} oxidation to Fe^{3+} without introducing additional metal ions, facilitating zinc sulfate purification.

Zinc recovery from zinc-containing waste depends on acid concentration, temperature, particle size, solid-to-liquid ratio, and mixing conditions. Optimizing sulfuric acid concentration and temperature is essential to ensure efficient zinc dissolution and controlled crystallization of zinc sulfate monohydrate.

Limited information is available on the controlled production of phase-pure $\text{ZnSO}_4 \cdot \text{H}_2\text{O}$ from zinc oxide production waste. The effects of sulfuric acid concentration, temperature, and purification conditions on zinc sulfate formation and monohydrate crystallization require further investigation.

The novelty of this study is the development of a laboratory-scale method for producing phase-pure $\text{ZnSO}_4 \cdot \text{H}_2\text{O}$ from zinc-containing waste by optimizing sulfuric acid concentration and thermal conditions. The products were purified and characterized by X-ray diffraction to confirm their phase composition.

The aim of this study was to develop a laboratory-scale method for producing $\text{ZnSO}_4 \cdot \text{H}_2\text{O}$ from zinc-containing waste and optimize the acid concentration and processing conditions.

2. Experimental part

Several zinc-containing waste samples were used in this study. Samples ZO1 and ZO2 were cream-colored powders, whereas samples Z3 and Z4 were silver-colored bars. The zinc content of the investigated materials ranged from 75.35 to 99.13 wt.%, indicating that all samples were characterized by a high zinc content and were therefore considered suitable feedstocks for zinc sulfate production.

Prior to the determination of the major and minor elemental composition, the mercury content of the samples was analyzed separately and was found to be in the range of 0.005-0.016 mg/kg. The concentrations of the remaining elements

were determined by inductively coupled plasma optical emission spectrometry (ICP-OES). The results are presented in Table 1.

Table 1 – Chemical composition of zinc-containing waste samples determined by ICP-OES

Sample	Fe	Si	Al	Ti	Sr	Ba	Mn,	Cu	Cr
	%			mg/kg					
ZO1	0,29	0,26	0,31	42	4	<1	31	292	3
ZO2	0,88	0,72	0,51	162	3	208	101	118	4
Z4	0,05	0,05	0,27	n/o	3	9	12	42	5
Z3	0,18	0,02	0,47	n/o	<1	118	11	32	9
Sample	Zn	K	Pb	Ca	Mg	Na	Ni	Co	Mo
	%						mg/kg		
ZO1	76,00	0,15	0,19	0,11	0,04	0,14	85	2	1
ZO2	75,35	0,13	0,40	0,08	0,01	0,10	26	2	1
Z4	99,13	<0,01	0,03	0,02	0,05	0,12	<1	1	<1
Z3	98,81	<0,01	0,01	0,02	0,04	<0,1	<1	20	7

As shown in Table 1, zinc was the predominant element in all samples. Z3 and Z4 contained 98.81 and 99.13 wt.% Zn, respectively, indicating predominantly metallic zinc, whereas the lower Zn contents in ZO1 and ZO2 (76.00 and 75.35 wt.%) were attributed to its oxidized form. Recalculation of the ZO1 and ZO2 compositions as oxides gave 94.6 and 93.8 wt.% ZnO, respectively, confirming ZnO as the main zinc-containing phase. The major impurities were Al_2O_3 and SiO_2 , with smaller amounts of Fe_2O_3 .

The selection of these materials for subsequent acid treatment was based on their high zinc content and the different chemical forms of zinc represented in the waste: predominantly oxidized zinc in ZO1 and ZO2 and predominantly metallic zinc in Z3 and Z4. This composition enabled the evaluation of sulfuric-acid treatment for zinc-containing wastes with different initial chemical states. In particular, sulfuric acid was selected because it can react with both metallic zinc and zinc oxide to form zinc sulfate, which is the target product of the proposed process.

To increase the contact area between the zinc-containing waste and the sulfuric acid solution and to promote more uniform interaction between the components, the zinc-containing powders were pre-mixed with water before acid treatment. The powder-to-water mass ratio was maintained at 1:1. The resulting slurry was thoroughly homogenized prior to the addition of sulfuric acid. Maintaining a constant powder-to-water ratio ensured reproducible moisture conditions and uniform distribution of the liquid phase throughout the powder, thereby facilitating subsequent acid-solid interaction.

The sulfuric acid solution used for the treatment was prepared by diluting concentrated H_2SO_4 with water to obtain a final concentration of 25 wt.%. When 98 wt.% concentrated H_2SO_4 was used, the required amount of concentrated acid

was calculated according to the mass balance to obtain the target 25 wt.% concentration. The corresponding mass ratio of concentrated H_2SO_4 to water was approximately 1.00:2.92. The concentrated acid was added gradually to water with continuous stirring, and the resulting solution was homogenized before use.

Based on the stoichiometric recalculation, 48.0 g of zinc-containing raw material, expressed as ZnO , was required for the synthesis of zinc sulfate monohydrate ($\text{ZnSO}_4 \cdot \text{H}_2\text{O}$). The required amount of 25 wt.% H_2SO_4 was calculated based on the stoichiometric amount necessary for the conversion of ZnO to ZnSO_4 . The calculated quantities of the starting materials are summarized in Table 2.

Table 2 – Stoichiometric calculation of the starting materials for $\text{ZnSO}_4 \cdot \text{H}_2\text{O}$ synthesis

Parameter	Value
Zinc-containing raw material (as ZnO), g	48.0
ZnO molar mass, g/mol	81.38
Amount of ZnO , mol	0.590
H_2SO_4 molar ratio	1:1
Required H_2SO_4 , mol	0.590
Pure H_2SO_4 required, g	57.78
Concentration of H_2SO_4 solution, wt. %	25
25 wt. % H_2SO_4 solution required, g	231.1
Water in 25 wt. % H_2SO_4 solution, g	173.3
Zinc-containing raw material (as ZnO), g	48.0

The calculated amount of 25 wt.% H_2SO_4 solution was then used for the acid treatment of the zinc-containing raw material. The reaction temperature was maintained above 70 °C to promote the dissolution of the zinc-containing phase and formation of zinc sulfate.

The resulting mixture was stirred for 0.5 h (30 min) to ensure sufficient contact between the zinc-containing solid phase and the sulfuric acid solution and to promote dissolution of the zinc-containing components. Therefore, 30 min was used as the standard mixing time for the subsequent experiments.

Hydrogen peroxide was used as an oxidizing agent during the subsequent purification step to facilitate the removal of impurity elements, particularly iron, copper, cadmium, and nickel. H_2O_2 was selected because of its strong oxidizing properties and its ability to promote the oxidation and subsequent separation of transition-metal impurities under the applied aqueous conditions. In addition, hydrogen peroxide decomposes to water and oxygen, which minimizes the introduction of additional persistent chemical contaminants into the process.

At this concentration, ZnO can be readily converted to soluble ZnSO_4 , while metallic Zn undergoes dissolution according to the following reaction:



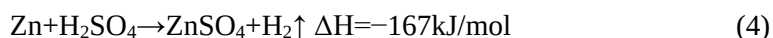
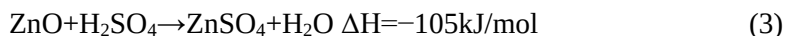
For zinc oxide, the corresponding reaction is:



Thus, the selected acid concentration was intended to provide effective conversion of both oxidized and metallic zinc into zinc sulfate while avoiding unnecessarily high acid concentrations. The use of a common 25 wt.% H_2SO_4 concentration for all samples also ensured comparable experimental conditions and allowed the effect of the initial chemical form of zinc on zinc sulfate formation to be evaluated.

3. Results and discussion

The conducted experiments on the production of zinc sulfate in the form of zinc vitriol ($\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$) and the possibility of converting it into the monohydrate form ($\text{ZnSO}_4 \cdot \text{H}_2\text{O}$) made it possible to determine the stages of this process. The reactions between zinc-containing waste and sulfuric acid proceed according to the following equations:



The reactions are exothermic and proceed easily without additional heating (due to the released heat, the acid is heated to boiling) at temperatures above 70 °C [18].

Zinc sulfate hydrate crystallization depends on temperature: $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ forms at –7–39 °C, $\text{ZnSO}_4 \cdot 6\text{H}_2\text{O}$ at 39–70 °C, and $\text{ZnSO}_4 \cdot \text{H}_2\text{O}$ above 70 °C, with dehydration to anhydrous ZnSO_4 at 238 °C. Therefore, ZO1 and ZO2 wastes were dried at 105 °C, dispersed in water for 10 min, and treated with concentrated H_2SO_4 to obtain a 25 wt.% solution; direct acid treatment was avoided due to poor wetting and vigorous reaction.

In industrial practice, zinc-containing raw materials are added in excess to diluted acid until the acid concentration decreases to 1–2 g/L. Due to the highly exothermic $\text{ZnO} - \text{H}_2\text{SO}_4$ reaction, no preliminary heating is required above 70 °C. Reagent-grade zinc dust dissolved within 5 min at 7–45 wt.% H_2SO_4 , whereas ZO1 and ZO2 required 30 min due to complex zinc compounds. Tin, if present, may hinder filtration; in its absence, the acid can be diluted to 180 g/L and heated to boiling.

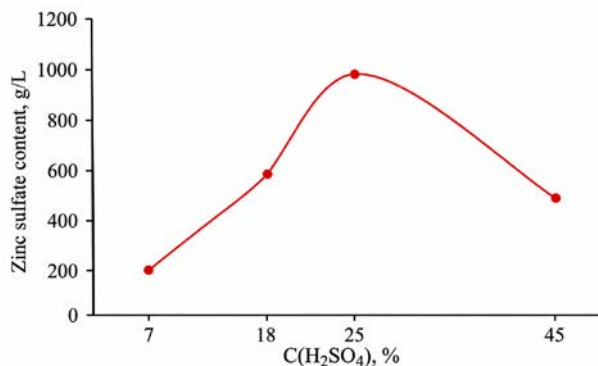
The raw material was pre-ground to increase the reaction rate, while foaming indicated the presence of metallic zinc and hydrogen evolution. The resulting ZnSO_4 solution was purified from Cu, Cd, Ni, and Fe by acid treatment, zinc-dust cementation, Fe^{2+} oxidation, precipitation, and filtration; tin-containing solutions were settled for 10–15 h before purification.

Hydrogen peroxide can also be used as an oxidizing agent.

As a result of the experiments, the zinc sulfate content was determined as a function of sulfuric acid concentration (Table 3, Fig. 1).

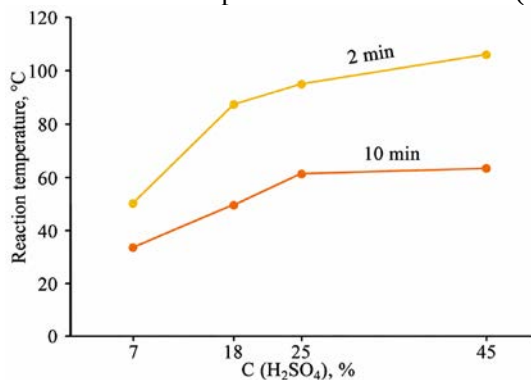
Table 3 – Zinc sulfate content as a function of initial sulfuric acid concentration

H ₂ SO ₄ (% mass.)	T ₀ (°C)	T _i (°C) after 2 min	T _f (°C) (after 10 min)	C _{ZnSO₄} (g/l)	C _{H₂SO₄ free.} (g/l)
45	22,9	107,9	63,1	503	29,4
25	26,5	95,8	61,9	985	24,7
18	23,5	88,3	50,6	589	23,76
7	24,1	50,7	34,6	204	3,43

**Figure 1** – Dependence of zinc sulfate content on the concentration of initial sulfuric acid.

As shown in Figure 1, the maximum zinc sulfate concentration (985 g/l) was achieved at an initial sulfuric acid concentration of 25 wt.%. Both lower and higher acid concentrations resulted in decreased zinc sulfate content. This behavior indicates that the interaction between sulfuric acid and zinc-containing waste is strongly dependent on acid concentration, and that 25 wt.% provides the most favorable conditions for zinc sulfate formation.

A change in the temperature of the products as a function of the initial sulfuric acid concentration in the suspension is also observed (Fig. 2).

**Figure 2** – Dependence of Product Temperature on the Concentration of Initial Sulfuric Acid in the Suspension.

At a high initial sulfuric acid concentration (45 wt.%), the reaction temperature increased rapidly from 22.9 °C to 107.9 °C within the first 2 minutes, indicating an intensive exothermic interaction between sulfuric acid and zinc-containing waste. With decreasing acid concentration, the maximum reaction temperature also decreased, which may be associated with a lower reaction rate and reduced heat release during zinc sulfate formation. The observed temperature changes are influenced not only by sulfuric acid concentration, but also by heat transfer processes, evaporation, and the thermal capacity of the reaction medium.

Temperature gradients for the reaction between sulfuric acid and zinc oxide production waste were also calculated (Fig. 3).

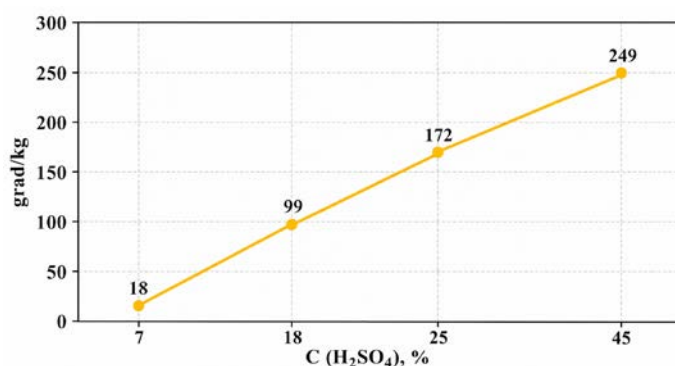


Figure 3 – Temperature gradient of the reaction between H₂SO₄ and zinc oxide production waste.

This curve makes it possible to derive a heat balance equation required for process scaling. Analysis of the curve confirms that the choice of a 25 wt.% acid concentration is appropriate.

Based on the obtained data, the conditions for further application to zinc-containing waste were selected.

It is known that the production of 1 ton of zinc vitriol consumes 0.47 tons of zinc (as metal) and 0.72 tons of sulfuric acid (100%). After recalculation, it was determined that for the synthesis of zinc sulfate monohydrate, 48.0 g of zinc-containing raw material (in terms of oxide) should be used, along with 25% sulfuric acid to maintain the required temperature regime (above 70°C). First, the acid is diluted to 25% by adding 210 g of distilled water to the reaction vessel, followed by 40.74 mL of 95% sulfuric acid.

In all cases, the obtained product consisted of single-phase ZnSO₄·H₂O. Figures 4-5 and Table 4 present the diffraction patterns of the samples, confirming the formation of pure zinc sulfate monohydrate.

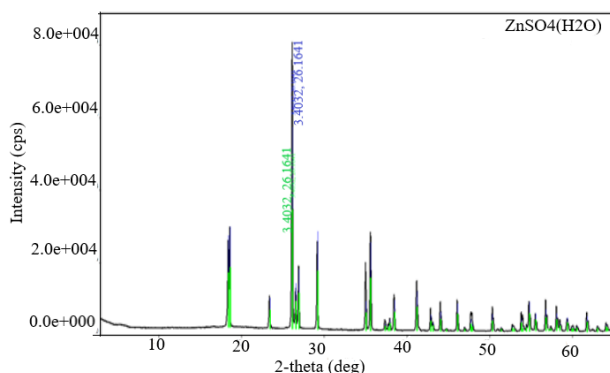


Figure 4 – X-ray diffraction pattern of zinc sulfate monohydrate obtained from sample ZO1.

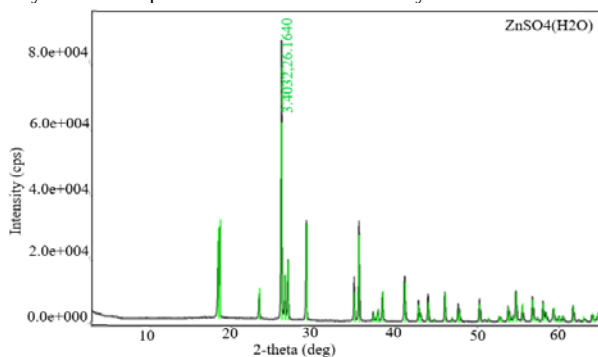


Figure 5 – X-ray diffraction pattern of zinc sulfate monohydrate obtained from sample ZO2.

Table 4 – Phase composition of the samples

Samples	Phase composition	Content, wt. %
ZO1	ZnSO ₄ ·H ₂ O; C2/c (15), ICDD PDF-2; 01-074-1331, RIR = 2.24	100
ZO2	ZnSO ₄ ·H ₂ O C2/c (15), ICDD PDF-2; 01-074-1331, RIR = 2.24	

The mercury content in the obtained samples did not exceed 4 ppm. Lead and cadmium compounds were not detected. The remaining mother liquor is retained and added to subsequent batches of solution for evaporation. If evaporation is carried out at temperatures below 70°C, zinc vitriol crystals are formed.

4. Conclusion

A laboratory-scale technology for the production of zinc sulfate monohydrate from zinc-containing waste was developed. The influence of sulfuric acid concentration on the synthesis process was investigated, and the optimal concentration was determined to be 25 wt.%, which provided the highest zinc sulfate concentration in solution.

The study showed that preliminary mixing of zinc-containing powders with water ensures stable interaction with sulfuric acid and improves the dissolution

process. Hydrogen peroxide was successfully applied for purification of the zinc sulfate solution from iron and other impurity compounds.

XRD analysis confirmed the formation of phase-pure zinc sulfate monohydrate ($\text{ZnSO}_4 \cdot \text{H}_2\text{O}$) in samples obtained from both “ZO1” and “ZO2” wastes. The developed approach demonstrates the possibility of efficient recycling of zinc oxide production waste into a valuable commercial product.

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Conflict of Interest: The authors declare no conflicts of interest that require disclosure in this paper.

МЫРЫШ ҚҰРАМДЫ ҚАЛДЫҚТАРДАН МЫРЫШ СУЛЬФАТЫНЫҢ МОНОГИДРАТЫН АЛУ ТЕХНОЛОГИЯСЫН ЗЕРТТЕУ

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Түйіндемесі. Цинк сульфаты - әртүрлі өнеркәсіп салаларында кеңінен қолданылатын маңызды химиялық қосылыс. Ол ауыл шаруашылығында өнімділікті арттыру үшін, сондай-ақ бояулар, фармацевтикалық препараттар, сыра және басқа да өнімдерді өндіруде қолданылады. Негізгі элемент - мырыш - өсімдіктердің белсенді өсуі мен дамуына ықпал етеді. Цинк сульфаты моногидратын алу технологиясы зерттеліп, әзірленді. Зерттеу материалы ретінде 75-99% мырыштан тұратын ұнтақтар және 25% күкірт қышқылы қолданылды. Компоненттердің өзара әрекеттесу жылдамдығын арттыру үшін ұнтақтар алдын ала сумен араластырылды. Қосылатын концентрлі күкірт қышқылының мөлшері, қосқаннан кейін 25% концентрациялы күкірт қышқылы ерітіндісі алынатындай етіп реттелді. Темір, мыс, кадмий және никель сияқты қоспаларды жою үшін сутек асқын тотығы қолданылды. Осы технология бойынша 100% цинк сульфаты моногидраты алынды. Мырыш сульфатының моногидратын алудың зертханалық регламенті жасалды.

Түйінді сөздер: Цинк сульфаты моногидраты, қалдық, мырыш оксиді, мырышқұрамды шикізат, химиялық құрамы, күкірт қышқылы, сутек асқын тотығы, зертханалық регламент, сүзу, буландыру, кептіру

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ИССЛЕДОВАНИЕ ТЕХНОЛОГИИ ПОЛУЧЕНИЯ МОНОГИДРАТА СУЛЬФАТА ЦИНКА ИЗ ЦИНКСОДЕРЖАЩИХ ОТХОДОВ

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Резюме. Сульфат цинка является важным химическим соединением, широко применяемым в различных отраслях промышленности. Он используется в сельском хозяйстве для повышения урожайности, а также в производстве красок, фармацевтических препаратов, пива и других продуктов. Основным элементом – цинк – способствует активному росту и развитию растений. Была изучена и разработана технология получения моногидрата сульфата цинка. В качестве исследуемых материалов использовали порошки, содержащие 75-99% цинка, и 25% серную кислоту. Для увеличения скорости взаимодействия между компонентами порошки предварительно смешивали с водой. Количество вводимой концентрированной серной кислоты регулировали таким образом, чтобы после добавления получался раствор серной кислоты с концентрацией 25%. Для удаления примесей, таких как железо, медь, кадмий и никель, использовали перекись водорода. По данной технологии был получен 100% моногидрат сульфата цинка. Разработан лабораторный регламент получения моногидрата сульфата цинка.

Ключевые слова: Цинк сульфат моногидрат, отходы, оксид цинка, цинксоодержащее сырьё, химический состав, серная кислота, перекись водорода, лабораторный регламент, фильтрация, выпаривание, сушка

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References

1. Moskalyk, R.R., & Alfantazi, A.M. Review of copper pyrometallurgical practice: today and tomorrow. *Minerals Engineering*, 2003, 16(10), 893–919. DOI: 10.1016/j.mineng.2003.08.002.
2. Gómez, F., Guzmán, J.I., & Tilton, J.E. Copper recycling and slag availability. *Resources Policy*, 2007, 32(4), 183–190. DOI: 10.1016/j.resourpol.2007.08.002.
3. Ghodrat, M., Rhamdhani, M.A., Brooks, G.A., Masood, S., & Corder, G. Techno-economic analysis of electronic bronze production slag processing through black copper smelting route. *Journal of Cleaner Production*, 2016, 126, 178–190. DOI: 10.1016/j.jclepro.2016.03.033.
4. Fu, X., Ueland, S.M., & Olivetti, E. Econometric modeling of recycled copper supply. *Resources, Conservation and Recycling*, 2017, 122, 219–226. DOI: 10.1016/j.resconrec.2017.02.012.
5. Chen, J., Wang, Z., Wu, Y., Li, L., Li, B., Pan, D., & Zuo, T. Environmental benefits of secondary copper from primary copper based on life cycle assessment in China. *Resources, Conservation and Recycling*, 2019, 146, 35–44. DOI: 10.1016/j.resconrec.2019.03.020.
6. Wang, C., Huang, X., Lim, M. K., Tseng, M.-L., & Ghadimi, P. Mapping the structural evolution in the global slag copper trade network. *Journal of Cleaner Production*, 2020, 275, Article 122934. DOI: 10.1016/j.jclepro.2020.122934.
7. Liu, S., Zhang, Y., Su, Z., Lu, M., Gu, F., Liu, J., & Jiang, T. Recycling the domestic copper slag to address China's copper sustainability. *Journal of Materials Research and Technology*, 2020, 9(3), 2846–2855. DOI: 10.1016/j.jmrt.2020.01.019.

8. Apua, M.C., & Madiba, M.S. Leaching kinetics and predictive models for elements extraction from copper oxide ore in sulphuric acid. *Journal of the Taiwan Institute of Chemical Engineers*, 2021, 121, 313–320. DOI: 10.1016/j.jtice.2021.04.005.
9. Tutton, C.G., Young, S.B., & Habib, K. Pre-processing of e-bronze production slag in Canada: Case of a facility responding to changing material composition. *Resources, Environment and Sustainability*, 2022, 9, Article 100069. DOI: 10.1016/j.resenv.2022.100069.
10. Zhou, W., Liu, X., Lyu, X., Gao, W., Su, H., & Li, C. Extraction and separation of copper and iron from copper smelting slag: A review. *Journal of Cleaner Production*, 2022, 368, Article 133095. DOI: 10.1016/j.jclepro.2022.133095.
11. Sadeghian, A., & Iqbal, N. Blue laser welding of low thickness Ni-coated copper and mild steel for electric vehicle (EV) battery manufacturing. *Optics & Laser Technology*, 2022, 155, Article 108415. DOI: 10.1016/j.optlastec.2022.108415.
12. Islam, M.A., Kato, S., Kishi, N., & Soga, T. Enhanced surface morphology and photovoltaic properties of a new class of material copper silver bismuth iodide solar cell. *Journal of Materials Research and Technology*, 2023, 25, 4171–4186. DOI: 10.1016/j.jmrt.2023.06.182.
13. Ndiribe, C.C. The nature fit concept of bronze production slag reduction: Prospects for engineering a clean future. *Resources, Environment and Sustainability*, 2023, 14, Article 100127. DOI: 10.1016/j.resenv.2023.100127.
14. Wei, H., Feng, G., Li, X., Zhan, W., Li, F., Dai, Y., & Zou, J. Copper–graphite–TiC composites: Synthesis and microstructure investigation. *Materials Letters*, 2023, 351, Article 135005. DOI: 10.1016/j.matlet.2023.135005.
15. Li, X., Ma, B., Wang, C., & Chen, Y. Sustainable recovery and recycling of slag copper and alloy resources: A review. *Sustainable Materials and Technologies*, 2024, 41, Article e01026. DOI: 10.1016/j.susmat.2024.e01026.
16. Cañadilla, A., Rodríguez, G., Romero, A., Caminero, M. A., & Dura, O. J. Sustainable production of copper components using concentrated solar energy in material extrusion additive manufacturing (MEX-CSE). *Sustainable Materials and Technologies*, 2024, 39, Article e00799. DOI: 10.1016/j.susmat.2023.e00799.
17. Abd El Aal, E. E., Abd El Wanees, S., Farouk, A., & Abd El Haleem, S. M. Factors affecting the corrosion behaviour of aluminium in acid solutions. II. Inorganic additives as corrosion inhibitors for Al in HCl solutions. *Corrosion Science*, 2013, 68, 14–24. DOI: 10.1016/j.corsci.2012.09.038.
18. Abkhoshk, E., Jorjani, E., Al-Harahsheh, M. S., Rashchi, F., & Naazeri, M. Review of the hydrometallurgical processing of non-sulfide zinc ores. *Hydrometallurgy*, 2014, 149, 153–167. DOI: 10.1016/j.hydromet.2014.08.001.