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MODERN APPROACHES TO METAL RECOVERY: ACID LEACHING AND BIOLEACHING TECHNOLOGIES

Abstract: *With each passing year, the volume of metallurgical waste continues to grow, posing serious environmental and economic challenges. However, metallurgical by-products such as slags and tailings contain numerous valuable metals that can be recovered and reintegrated into production cycles. In this context, hydrometallurgical and bioleaching technologies are gaining particular relevance. These methods enable the efficient extraction of valuable components from waste while simultaneously reducing its volume and minimizing the environmental burden. This article examines how modern techniques, such as acid leaching and bioleaching, can be utilized not only to recover metals but also to address waste disposal issues with minimal ecological impact. Special attention is given to practical examples and research developments that demonstrate the high efficiency and industrial applicability of these technologies. This study highlights the importance of waste recycling not only from an ecological perspective but also as a critical step toward building a more sustainable economy where every resource is used to its fullest potential.*

Key words: *metallurgical waste, hydrometallurgy, bioleaching, recycling, ecology.*

Introduction

Metallurgical waste is becoming an increasingly serious problem for both the environment and the economy every year. Traditional methods of disposal often fail to cope with the growing volumes and specific characteristics of such waste, leading to its accumulation and, consequently, significant environmental pressures. However, this challenge can be turned into an opportunity: slags, beneficiation tailings, and spent catalysts contain numerous valuable metals – copper, zinc, cobalt, and rare earth elements. These are valuable resources that, with proper processing, can be returned to production. Hydrometallurgy and bioleaching are emerging as some of the most effective solutions to this issue. These technologies enable the extraction of metals from waste through chemical reactions or biological processes [6, 7]. For instance, methods such as acid leaching or the use of microorganisms have already proven their effectiveness in both laboratory research and practical applications. These approaches not only reduce the volume of waste but also significantly minimize environmental pollution [2, 3]. This study focuses on examining modern technologies for metallurgical waste processing [9, 4]. Central to the analysis are hydrometallurgical and bioleaching methods, their advantages, and their practical application prospects. Additionally, the study explores the environmental aspects of these technologies and their economic feasibility. Of particular interest are innovations such as acid regeneration, the use of microorganisms, and carbothermal reduction, which enable recycling tasks to be addressed with minimal environmental impact [2,4]. Illustrative examples and research findings emphasize that metallurgical waste recycling is not only a way to address environmental challenges but also an opportunity for economic benefit. The implementation of such methods opens up prospects for more efficient resource utilization, reducing dependence on primary raw material extraction, and transitioning to a circular economy model where waste becomes a new source of raw materials.

Methods

The methodology presented in the article is based on a systematic approach to analyzing metallurgical waste recycling methods, with a focus on hydrometallurgical and bioleaching technologies. The research emphasizes the selection, evaluation, and synthesis of data to assess the efficiency and prospects of these methods.

At the first stage, modern and promising recycling methods were selected based on several key criteria: technical efficiency, expressed as the ability to extract target metals with high purity; environmental sustainability, involving the minimization of negative environmental impacts; economic feasibility, accounting for the costs of implementation and operation at an industrial scale; and versatility, reflecting the adaptability of methods to various types of waste, including slags, tailings, and spent catalysts. Among the reviewed methods were acid leaching, bioleaching with microorganisms, adsorption of rare earth metals on zeolites, and carbothermal reduction [1, 18, 17, 13].

At the second stage, the selected methods were evaluated using experimental data from the literature. Key parameters of evaluation included metal recovery efficiency, expressed as the percentage of extracted metals relative to their total content in the waste; process conditions, such as temperature, reaction time, pH level, reagent concentrations, and other critical factors; selectivity, defined as the ability to extract target metals with minimal dissolution of impurities; and the characterization of by-products in terms of their potential for reuse or safe disposal. Environmental benefits, such as reagent regeneration, waste volume reduction, and toxicity mitigation, were also considered [10].

The third stage involved synthesizing the data. The methods were classified based on their chemical, biological, or thermal nature, and their strengths and weaknesses were identified. For example, acid leaching offers high reaction rates but requires stringent corrosion control for equipment, while bioleaching is environmentally friendly but has slower reaction times. The potential for integrating technologies was also explored to improve overall recycling efficiency. For instance, bioleaching could serve as a preliminary step before hydrometallurgical processes [12, 15, 11].

To ensure the rigor and comprehensiveness of the study, an interdisciplinary approach was adopted. This included a systematic review of the literature on recent advancements in metallurgical waste recycling, a comparative analysis using a unified methodology to standardize data from different sources, and experimental validation of results with a focus on their industrial applicability. This approach ensured the reliability of the findings, emphasizing the scalability and adaptability of the technologies for real-world conditions.

Main part

In modern realities, metallurgical waste is one of the most pressing environmental and economic challenges worldwide. However, it represents not only a challenge but also new opportunities for the development of the industry. Metallurgical slags, beneficiation tailings, and spent catalysts contain valuable metals such as copper, zinc, cobalt, and rare earth elements. These resources, with proper recycling, can be returned to the production cycle, significantly reducing the need for primary raw material extraction.

Modern technologies for processing metallurgical waste, such as hydrometallurgy and bioleaching, allow not only the efficient recovery of metals but also the minimization of waste volumes, thereby reducing the environmental burden. For instance, acid leaching methods have proven highly effective in extracting copper and zinc, while bioleaching, based on the use of microorganisms, provides environmentally friendly processing with minimal use of chemical reagents. Such approaches open up prospects for transitioning to a circular economy in the metallurgical sector, where waste becomes a resource.

Moreover, the implementation of these technologies helps reduce dependency on primary raw material extraction, which is particularly important in the context of growing global demand for rare earth metals and stricter environmental regulations. Economic efficiency also increases through reduced waste disposal costs and the potential for secondary use of recycled materials. For example, by-products such as residual slags after treatment can be used in the construction industry, further reducing the environmental impact.

Thus, the recycling of metallurgical waste is not merely a solution to environmental issues but also a crucial step toward sustainable development. The integration of modern methods, such as the combined use of bioleaching and hydrometallurgy, opens new horizons for improving process efficiency and minimizing environmental impact. In the context of rising costs for natural resources and stricter environmental controls, such approaches become an integral part of the strategy for the development of the metallurgical industry.

Leaching of Copper, Zinc, and Cobalt from Copper Smelting Slag

The acid leaching method described by Yang et al. (2010) [4] is one of the most effective for extracting non-ferrous metals. The process utilizes sulfuric acid (H_2SO_4) and sodium chlorate ($NaClO_3$) as an oxidizer, which minimizes the extraction of undesirable impurities such as iron and silicon. Experiments have shown that optimal conditions include a sulfuric acid concentration of 17.6 g/L, a temperature of 95°C, and a reaction time of 3 hours. Maintaining a pH level of approximately 2.0 using calcium hydroxide ($Ca(OH)_2$) ensures process stability (Figure 1).

The method demonstrates high selectivity and efficiency, with copper extraction reaching 89%, zinc 97%, and cobalt 98%. The resulting solutions are suitable for further metal recovery. However, the technology requires significant energy input due to the high temperature, and the residual slags must be stabilized before disposal. Environmental benefits include the possibility of acid regeneration and waste volume reduction. Nevertheless, corrosion management of equipment remains a critical challenge [10, 14].

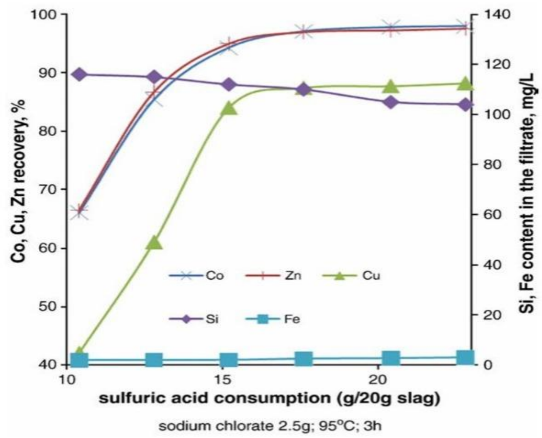

Figure 1 – Effect of sulfuric acid consumption on selective leaching

Leaching of Copper and Zinc from Brass Slag

Ahmed et al. (2016) [9] proposed an acid leaching method for extracting copper and zinc from brass slag. The use of concentrated sulfuric acid (30%) and a high temperature (70°C) significantly accelerates the process. Within just 10 minutes, copper extraction reaches 99%, and zinc extraction reaches 95%. Such rapid results make the method suitable for processing large volumes of waste [16].

An additional advantage is the stability of the residual slag, which can be used in the construction industry. The environmental aspects of the method include the possibility of acid regeneration, reducing the volume of chemical waste. However, the high acid concentration requires strict corrosion control for equipment. Moreover, impurities such as iron can reduce process efficiency (Figure 2). Despite these limitations, the method demonstrates high speed and efficiency, making it attractive for industrial applications [17, 18].

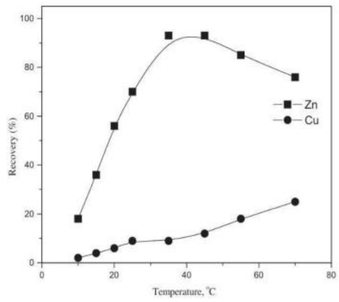

Figure 2 – Effect of temperature on the recovery of zinc and and copper

Bioleaching of Copper from Slag

Bioleaching is an environmentally friendly method for metal extraction. In a study by Carranza et al. (2009) [6], Acidithiobacillus ferrooxidans bacteria were used to treat slags, generating Fe^{3+} as an oxidizer. The process was conducted at a temperature of 60°C and a pH level of 1.8-2.0. Pre-grinding the slags increased the surface area available for microbial activity [19].

The results showed copper extraction reaching 93%. This method minimizes the use of chemical reagents, and the resulting waste is easily stabilized. However, the reaction rate is slower than chemical methods, and microorganisms are sensitive to environmental changes. This method is particularly effective for processing waste with low metal content, where traditional approaches are less efficient (Figure 3).

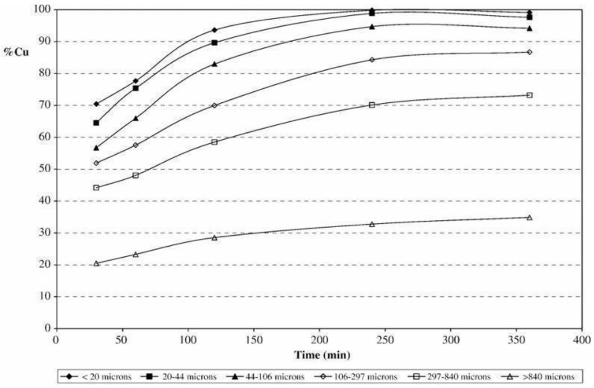

Figure 3 – Copper recovery versus time for different size fractions of sample.

Hydrometallurgical Extraction of Rare Earth Elements from Phosphogypsum

A study by Dotto et al. (2024) [18] proposed an innovative method for extracting rare earth elements (REEs) from phosphogypsum. The process involves acid leaching using citric acid and the adsorption of REEs onto ZSM-5 zeolite. Optimal conditions include a temperature of 25–30°C, pH 6, and a reaction time of 4 hours. Zeolite demonstrates high selectivity, and citric acid serves as a biodegradable leaching agent (Figure 4) [20].

The extraction efficiency reaches 97% for neodymium, and the regeneration of zeolite reduces operational costs. However, contaminant impurities can lower adsorption efficiency, and the process requires prior solution filtration. Advantages include environmental safety and the scalability of the method for industrial applications.

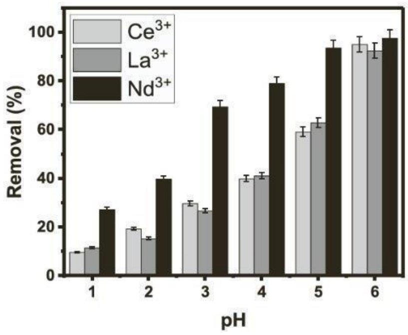

Figure 4 – Effect of the pH on the adsorption of Ce3þ, La3þ, and Nd3þ. Conditions

Carbothermal Reduction of Metals from Slag

The carbothermal reduction method described by Sarfo et al. (2017) [2] uses carbon (graphite) as a reducing agent to extract iron, copper, and molybdenum from copper slag. The process is conducted at a temperature of approximately 1440°C with the addition of fluxes (CaO, Al_2O_3) to improve the properties of the by-product-secondary slag. The resulting slag can be used in the glass and ceramics industries [8].

This method combines high efficiency with the potential use of by-products, making it economically attractive. However, the high temperature increases energy costs, and process parameter management requires advanced equipment (Figure 5).

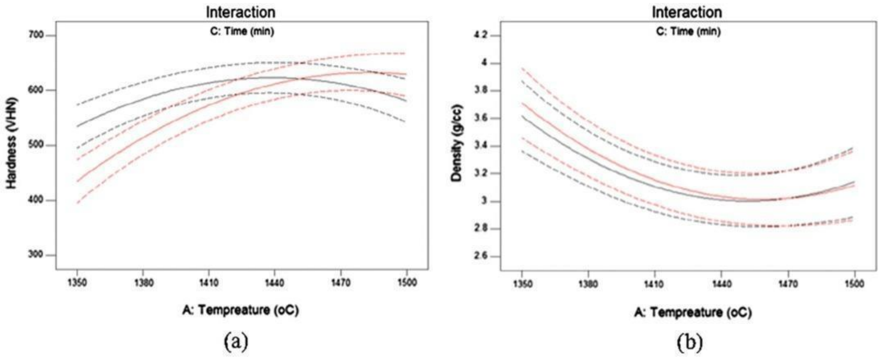

Figure 5 – Interaction plots of secondary slag (a) hardnessand (b) density as a function of reduction time and temperature at the optimum carbon content

Comparison of Methods and Prospects

The reviewed methods demonstrate a wide range of approaches to metallurgical waste recycling, from chemical to biological and thermal processes. Each has its strengths and limitations. Acid leaching methods offer high speed and efficiency but require strict control of corrosion and residue neutralization. Bioleaching represents an environmentally sustainable approach, though it is limited by slow reaction rates and the complexity of maintaining optimal conditions for microorganisms. Carbothermal reduction enables not only metal recovery but also the utilization of by-products, though it requires significant energy input.

The future of metallurgical waste recycling lies in the integration of technologies. Combined approaches, such as preliminary bioleaching followed by chemical processing, can enhance overall process efficiency. Additionally, the development of reagent regeneration methods and the use of renewable energy sources for thermal processes could significantly reduce environmental impacts and costs.

The implementation of such technologies at the industrial level can not only reduce waste volumes but also create a sustainable economy where every resource is used to its fullest potential. This direction requires further research focused on optimizing existing methods and developing new approaches to metallurgical waste recycling.

Discussion conclusion

Based on the main section, four primary methods of metallurgical waste processing can be identified: acid leaching, bioleaching, carbothermal reduction, and rare earth element (REE) extraction.

The acid leaching method is particularly important for metallurgy as it allows for the efficient processing of large volumes of waste, the extraction of valuable metals, and the minimization of environmental risks. This can significantly reduce dependence on primary raw material extraction. However, future efforts should focus on reducing energy consumption and improving the corrosion resistance of equipment.

Bioleaching is a promising solution for processing waste with low metal content that is challenging to recycle using other methods. This approach is vital for metallurgy as it reduces the toxicity of waste and expands the potential for secondary processing. Further research should aim to improve the resilience of microorganisms and accelerate the process.

The carbothermal method is essential for metallurgy as it ensures comprehensive resource utilization and allows recycled products to be integrated into other industrial chains. However, the future of such technologies is tied to the use of renewable energy sources to reduce the carbon footprint and energy costs.

Rare earth element (REE) extraction is critical in light of the global demand for rare earth elements, which are used in high-tech industries such as electronics and battery production. Future research should focus on optimizing the solution purification process and scaling up technologies.

Metallurgical waste is not just a problem but a significant opportunity. Modern waste processing technologies open up prospects for reducing environmental burdens by minimizing waste volumes, extracting valuable metals to decrease dependence on primary extraction, and improving resource efficiency, thereby facilitating the transition to a circular economy. These methods are key to implementing environmentally friendly and economically viable solutions, which are especially important given stricter environmental regulations and rising resource extraction costs.

The prospects for further research and technological development in waste processing include several key areas. Integration of technologies involves developing combined approaches, such as preliminary bioleaching followed by chemical leaching, to improve process efficiency. Process optimization aims to reduce the energy consumption of thermal methods, such as carbothermal reduction, through the introduction of renewable energy sources or lowering operating temperatures. Development of new reagents focuses on using biodegradable and less aggressive substances for leaching processes, making these methods more environmentally friendly. Automation and control will enable the implementation of digital technologies for monitoring and managing complex chemical and biological processes, ensuring their stability and precision. Sustainability and scalability include studying the impact of impurities in waste on method efficiency and developing technologies capable of handling a wide range of materials.

These developmental directions will not only make metallurgical waste processing more efficient but also environmentally sustainable, providing competitive advantages to industry enterprises and marking a significant step toward building an environmentally responsible and economically stable metallurgical industry of the future.

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МЕТАЛДЫ ҚАЛПЫНА КЕЛТІРУДІҢ ЗАМАНАУИ ТӘСІЛДЕРІ: ҚЫШҚЫЛДЫ ШАЙМАЛАУ ЖӘНЕ БИОШАЙМАЛАУ ТЕХНОЛОГИЯЛАРЫ

Жыл сайын металлургиялық қалдықтардың көлемі ұлғайып, экологиялық және экономикалық тұрғыдан елеулі мәселелер туындатады. Алайда металлургиялық өндірістің қосалқы өнімдері – қождар мен үйінділер көптеген бағалы металдарды қамтиды, оларды қалпына келтіріп, өндірістік циклдерге қайта енгізуге болады. Осы тұрғыда гидрометаллургиялық және биошаймалау технологиялары ерекше маңызға ие болуда. Бұл әдістер қалдықтардан бағалы компоненттерді тиімді түрде бөліп алуға мүмкіндік береді, сонымен қатар олардың көлемін азайтып, қоршаған ортаға әсерін төмендетеді. Осы мақалада металдарды ғана емес, сонымен қатар қалдықтарды экологияға ең аз зиян келтіре отырып қайта өңдеу мәселелерін шешу үшін қолдануға болатын заманауи әдістер, соның ішінде қышқылды шаймалау және биошаймалау тәсілдері қарастырылады. Ерекше назар бұл технологиялардың жоғары тиімділігін және өнеркәсіптік қолдануға жарамдылығын көрсететін практикалық мысалдар мен зерттеу нәтижелеріне аударылады. Бұл зерттеу қалдықтарды қайта өңдеудің маңыздылығын тек экологиялық көзқарас тұрғысынан ғана емес, сонымен қатар әрбір ресурсты барынша тиімді пайдалануға бағытталған неғұрлым тұрақты экономиканы қалыптастырудағы маңызды қадам ретінде көрсетеді.

Түйін сөздер: *металлургиялық қалдықтар, гидрометаллургия, биошаймалау, қайта өңдеу, экология.*

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СОВРЕМЕННЫЕ ПОДХОДЫ К ИЗВЛЕЧЕНИЮ МЕТАЛЛОВ: ТЕХНОЛОГИИ КИСЛОТНОГО ВЫЩЕЛАЧИВАНИЯ И БИОВЫЩЕЛАЧИВАНИЯ

С каждым годом объем металлургических отходов продолжает расти, создавая серьезные экологические и экономические проблемы. Однако металлургические побочные продукты, такие как шлаки и хвосты, содержат множество ценных металлов, которые могут быть извлечены и возвращены в производственные циклы. В этом контексте гидрометаллургические и *биовыщелачивающие технологии приобретают особую актуальность. Эти методы позволяют эффективно извлекать ценные компоненты из отходов, одновременно снижая их объем и минимизируя воздействие на окружающую среду. В данной статье рассматриваются современные методы, такие как кислотное выщелачивание и биовыщелачивание, которые могут использоваться не только для извлечения металлов, но и для решения проблем утилизации отходов с минимальным экологическим воздействием. Особое внимание уделяется практическим примерам и исследовательским разработкам, демонстрирующим высокую эффективность и промышленную применимость этих технологий. Исследование подчеркивает важность переработки отходов не только с экологической точки зрения, но и как критически важный шаг на пути к построению более устойчивой экономики, в которой каждый ресурс используется максимально эффективно.*

Ключевые слова: *металлургические отходы, гидрометаллургия, биовыщелачивание, переработка, экология.*

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