Metalurgi (2024) 1: 37 – 48

METALURGI
Majalah Ilmu dan Teknologi
p-ISSN 0126-3188 | e-ISSN 2443-3926
ejurnalmaterialmetalurgi.lipi.go.id

GREEN APPROACHES TO EXTRACTIVE METALLURGY: A NOVEL SYNTHESIS OF SUSTAINABLE PRACTICES

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Received: 27-02-2024, Revised: 14-05-2024, Accepted: 22-05-2024

Abstract

The realm of extractive metallurgy, a cornerstone for diverse industrial applications, has traditionally grappled with environmental challenges stemming from conventional extraction methods. This thorough literature review delves into the realm of innovative green approaches within extractive metallurgy, with the overarching goal of synthesizing sustainable practices. The introduction casts a spotlight on the environmental quandaries associated with traditional metallurgical practices, underscoring the imperative for ecologically friendly alternatives. The research methodology meticulously entails a comprehensive review of peer-reviewed literature, applying stringent criteria to handpick studies that delve into sustainable metallurgical practices. The results and discussion section intricately categorizes and dissects an array of green approaches in metal extraction, including bioleaching, ionic liquids, supercritical fluid extraction, green hydrometallurgy, electrochemical methods, and hybrid processes, providing nuanced insights into their efficacy and sustainability. Through the lens of case studies, the study sheds light on recent strides made by industries that have wholeheartedly embraced these sustainable practices, with a keen focus on unraveling their consequential environmental and economic impacts. Moreover, the study conscientiously addresses the challenges encountered in the adoption of green metallurgy and adeptly identifies latent opportunities for further development in this transformative field. The findings resonate with a resounding call for the widespread adoption of sustainable practices within extractive metallurgy, emphasizing their profound implications for both industrial application and the trajectory of future research endeavors. This expanded exploration underscores the pivotal role of environmentally conscious approaches in reshaping the landscape of extractive metallurgy, paving the way for a more sustainable and responsible future.

***Keywords:** Green, extraction, metallurgy, eco-friendly, sustainability*

1. INTRODUCTION

The extraction of metals, a crucial process in various industries, has historically relied on methods with significant environmental challenges. Conventional techniques like pyrometallurgy and hydrometallurgy involve hazardous chemicals, high energy consumption, and substantial waste generation, contributing to environmental degradation. The escalating concerns about the ecological footprint of extractive metallurgy have led to a paradigm shift towards green approaches. Green metallurgy, integrating sustainable practices, aims to minimize the environmental impact of metal extraction while remaining economically viable [1].

The primary objective of this study is to systematically explore and evaluate innovative green approaches within the domain of extractive metallurgy. The specific aims are as follows: To assess and delineate the environmental challenges associated with conventional methods of metal extraction, including the ecological impact on soil, water, and air quality. To conduct a comprehensive review of peer-reviewed literature, focusing on recent advancements and emerging practices in green metallurgy. To categorize and analyze various green approaches

DOI : 10.55981/metalurgi.2024.748

Metalurgi is Sinta 2 Journal (https://sinta.kemdikbud.go.id/journals/profile/3708) accredited by Ministry of Education, Culture, Research, and Technology, Republic Indonesia

in metal extraction, evaluating their effectiveness in terms of metal recovery and sustainability in mitigating environmental impact. To present and analyze case studies of industries that have successfully adopted green metallurgical practices, emphasizing both environmental and economic outcomes. To identify and discuss challenges encountered in implementing green approaches and to explore opportunities for further development and optimization of sustainable metallurgical practices. To contribute insights to the academic and industrial communities by synthesizing current knowledge on green approaches in extractive metallurgy, and to propose avenues for future research and innovation in the field. By achieving these objectives, this research aims to provide a comprehensive understanding of the current state of green metallurgy, emphasizing its potential to revolutionize extractive metallurgical practices toward sustainability.

The literature review addresses the environmental drawbacks of traditional extractive metallurgy methods, emphasizing the need for sustainable practices aligned with green energy and thermal engineering principles [2]. It aims to provide valuable insights to both academic and industrial communities by reviewing recent advancements, exploring environmentally friendly approaches, and suggesting future research and innovation opportunities in the field. The conceptual framework is grounded in dimensions such as understanding environmental challenges, embracing green principles, exploring alternative solvents, assessing energy efficiency, considering economic viability, examining case studies, and addressing implementation challenges. Through these dimensions, the study seeks to provide a comprehensive understanding of the current state of green metallurgy and contribute to the development of novel, sustainable practices in extractive metallurgy [3].

2. MATERIALS AND METHODS

The research design involves a systematic literature review to investigate and synthesize green approaches in extractive metallurgy. Key components include a thorough search of databases, inclusion criteria focusing on sustainability, data extraction, quality evaluation, categorization based on themes, and thematic synthesis. The design also includes an in-depth analysis of case studies, considering both environmental and economic perspectives. The findings will be comprehensively discussed, leading to conclusions and implications for industry and future research. The research design prioritizes recent, peer-reviewed literature, diverse methodologies, innovative practices, and a global perspective to compile a reliable body of knowledge on sustainable practices in extractive metallurgy.

A comprehensive discussion of the findings, including the effectiveness and challenges of green approaches in extractive metallurgy. Formulation of conclusions based on the synthesized knowledge, highlighting implications for industry and future research directions. The research design is structured to provide a robust foundation for understanding and evaluating the current landscape of sustainable practices in extractive metallurgy, with a focus on innovative and green methodologies. Inclusion of literature directly related to green approaches in extractive metallurgy, focusing on sustainable practices, environmentally friendly methodologies, and innovations aimed at reducing the ecological footprint of metal extraction.

3. RESULTS AND DISCUSSION

3.1 Eco-Friendly Metal Extraction Methods

The exploration of eco-friendly metal extraction methods represents a pivotal shift in the field of extractive metallurgy, addressing the ecological concerns associated with conventional techniques. Several innovative approaches have emerged, each aiming to minimize environmental impact while ensuring efficient metal recovery.

Bioleaching involves the use of microorganisms to extract metals from ores [4]-[7]. The flow diagrams for bioleaching as shown in Fig. 1, is environmentally friendly as it eliminates the need for harsh chemicals traditionally used in metallurgical processes. Microorganisms, such as bacteria and fungi, catalyze the dissolution of metals, offering a sustainable alternative with lower energy requirements. Bioleaching has proven effective in extracting metals from various ores, especially for low-grade deposits. The use of microbial activity reduces the need for harsh chemicals, making it an eco-friendly alternative. The bioleaching reactors use acidophilic bacteria or fungi that oxidize the mineral sulfides and help solubilize the metals into the leaching solution. This is an environmentally friendly alternative to conventional acid leaching. Bioleaching demonstrates sustainability by promoting the use of natural processes and minimizing the environmental impact associated with traditional leaching methods. However, challenges include the specificity of microbial strains and the need for optimization in large-scale applications.

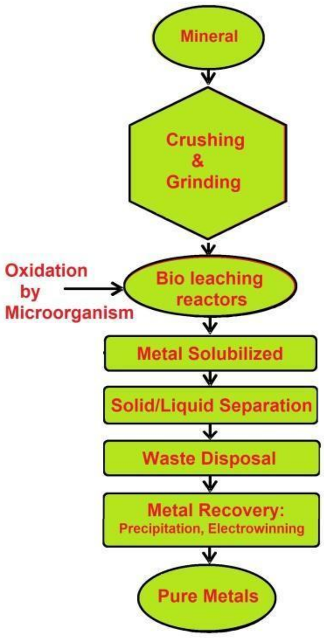

Figure 1. Bioleaching flow diagrams

The use of ionic liquids as alternative solvents in metal extraction has gained prominence [8]-[11], as shown in Fig. 2. Ionic liquids are molten salts at low temperatures and exhibit unique properties, including low volatility and high thermal stability.

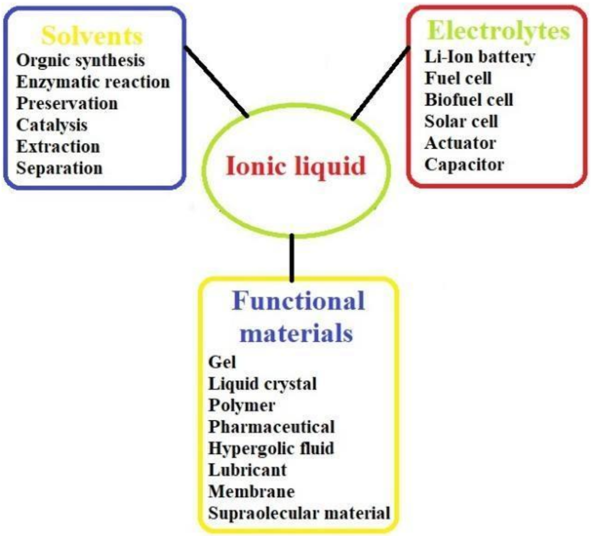

Figure 2. Ionic liquids in metal extraction

Their application in metal extraction reduces the environmental impact associated with conventional solvents, contributing to a greener approach. Ionic liquids exhibit high metal solubility and selectivity, making them effective in extracting metals. Their unique properties contribute to improved efficiency compared to conventional solvents. While ionic liquids offer a greener alternative to traditional solvents, concerns related to toxicity and recyclability need to be addressed. Ongoing research focuses on developing more sustainable ionic liquid formulations.

Supercritical fluid extraction, as shown in Fig. 3, involves the use of supercritical fluids to extract metals from ores. Operating under specific temperature and pressure conditions, supercritical fluids offer enhanced metal selectivity and reduced environmental footprint compared to conventional extraction methods that use organic solvents [12]-[16]. Supercritical fluid extraction enhances metal selectivity and offers advantages in terms of reduced solvent usage. The method is effective for certain metal types and is especially promising for applications requiring high purity. The use of supercritical fluids aligns with green principles, but challenges include high operating pressures and the energy-intensive nature of the process. Continued research aims to improve energy efficiency and reduce environmental impact.

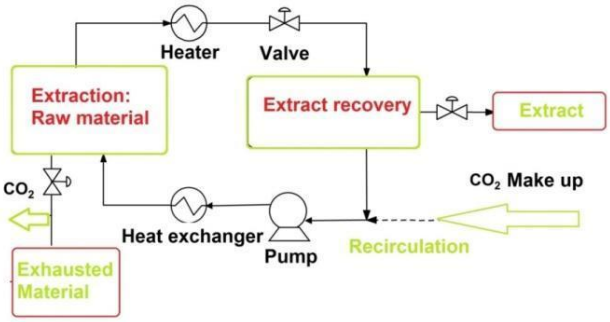

Figure 3. Supercritical extraction

Green hydrometallurgical processes as shown in Fig. 4, utilize environmentally benign leaching agents, such as water and organic acids, to extract metals [17]-[20]. These processes avoid the use of toxic reagents, minimizing environmental contamination in the leaching process uses H_2SO_4 (sulfuric acid) and HCl (hydrochloric acid) as reagents, resulting in the formation of sulfate and chloride salts as separation products. The separation products from using organic acid leachants would typically be metal salts of those organic acids, such as metal citrates or oxalates, rather than metal sulfates or chlorides produced from mineral acids. Additionally, the recovery of valuable metals from electronic waste through hydrometallurgical routes contributes to sustainable resource management. Green hydrometallurgical processes, utilizing benign leaching agents, effectively extract metals from ores and electronic waste. These processes often achieve comparable or improved metal recovery rates. By avoiding toxic reagents, hydrometallurgical processes contribute to sustainability. However, considerations include the need for process optimization, water usage, and the management of leachate solutions to minimize environmental impact.

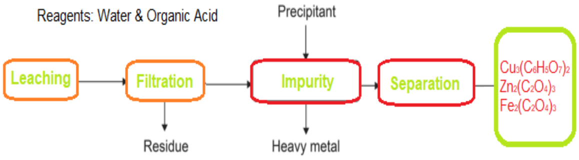

Figure 4. Green hydrometallurgical processes

Electrochemical methods as shown in Fig. 5, such as electro-winning and electro-deposition, provide energy-efficient alternatives for metal recovery [21]-[24]. The electrowinning process involves feeding a metal-bearing solution into an electrowinning cell, where an inert anode and an electrolyte solution facilitate the flow of ions. At the cathode, metal ions from the solution are reduced and plated onto the cathode surface. The plated metal is then periodically stripped from the cathode, yielding pure metal products.

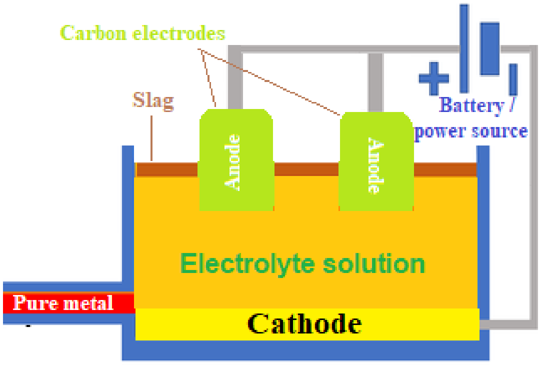

Figure 5. Electrochemical method

These processes often require lower temperatures and can be powered by renewable energy sources, aligning with the principles of green chemistry and reducing the overall carbon footprint of metallurgical operations. Electrochemical methods provide energy-efficient metal recovery with high purity. These methods are effective for certain metals and can be integrated into existing processes. The energy efficiency of electrochemical methods aligns with sustainability goals. However, challenges include the selection of suitable electrode materials and addressing the environmental impact of electrode position waste.

Hybrid processes as shown in Fig. 6 combine multiple environmentally friendly techniques to optimize metal extraction [25]-[28]. For example, integrating bioleaching with ion exchange or coupling ionic liquids with supercritical fluid extraction can enhance metal recovery rates and reduce the overall environmental impact. While these methods exhibit promise in terms of environmental sustainability, their practical implementation faces challenges. Issues such as scalability, economic feasibility, and process optimization need further exploration. However, the reviewed methods collectively represent a paradigm shift toward greener practices in extractive metallurgy, providing a foundation for more sustainable and responsible metal production. Hybrid processes that combine multiple green approaches often lead to improved metal recovery rates and process efficiency. Synergies between different methods contribute to improved overall effectiveness. The sustainability of hybrid processes depends on the specific combination of methods employed. Challenges include optimizing the integration of different processes and addressing potential trade-offs in terms of environmental impact.

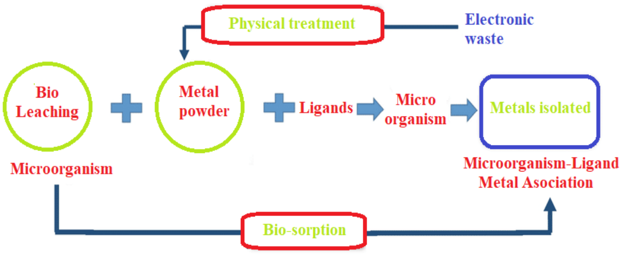

Figure 6. Hybrid processes

Each green metallurgical approach demonstrates varying degrees of effectiveness and sustainability. The choice of method should consider factors such as metal type, ore characteristics, and process scalability. Further research and innovation are essential to address challenges and enhance the overall sustainability of these green approaches in extractive metallurgy.

3.2 Conventional Extraction Processes and Transitioning to Green Extraction Processes

Multitudes of different traditional metal extraction processes have been implemented on an industrial scale. Pyrometallurgy and hydrometallurgy have been most commonly used in industrial-scale metal recovery due to them being effective and well-established. However, these methods are often associated with the use of hazardous reagents, substantial energy consumption and waste generation, and other significant environmental issues.

Pyrometallurgical processes, which involve high-temperature treatment of ores or ore concentrations, are high-energy-consuming and produce large amounts of greenhouse gases. In addition, significant amounts of sulfur dioxide and particulate matter can be emitted into the atmosphere.

While hydrometallurgical processes work with lower temperatures, they often include harmful chemicals such as cyanide, acids, and organic solvents. If not properly managed, such chemicals get into water bodies, negatively impacting human health and the environments. The application of conventional extraction processes also has a detrimental impact on the environment outside the operational stages. The disposal of tailings and waste streams results in soil and water pollution, destruction of habitats, and loss of biodiversity.

To mitigate the environmental impact of metal extraction, a paradigm shift towards green approaches is essential. Green extraction processes prioritize the principles of green chemistry, such as atom economy, waste minimization, and the use of environmentally benign substances. The following sections will discuss various green approaches in metal extraction, highlighting their advantages over conventional processes and providing data to support their environmental and economic benefits.

Energy Efficiency Comparison

One of the key advantages of green extraction processes is their potential for energy savings compared to conventional methods. Figure 7 illustrates a comparison of energy requirements between a conventional pyrometallurgical process and a green bioleaching process for copper extraction. As shown in the figure, the green bioleaching process exhibits significantly lower energy requirements compared to the conventional pyrometallurgical process across various levels of copper extraction [29]. This energy efficiency can translate into reduced greenhouse gas emissions and operational costs, contributing to environmental sustainability and economic viability. It is important to note that the energy savings and environmental benefits of green extraction processes may vary depending on the specific metal, ore characteristics, and process parameters. However, the general trend suggests that green approaches offer a promising avenue for mitigating the environmental impact of metal extraction while maintaining economic feasibility.

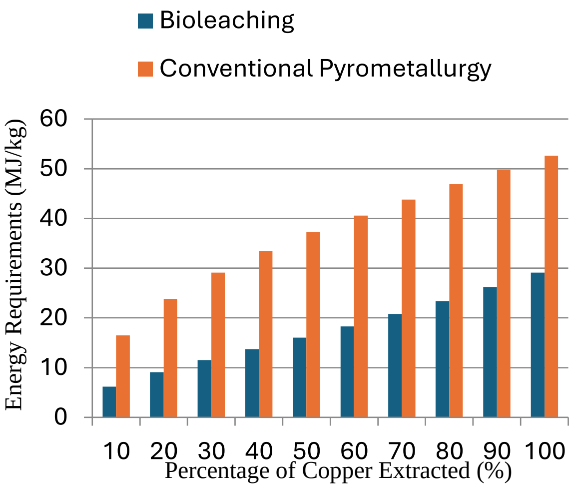

Figure 7. Energy requirements efficiency comparison

In addition to energy efficiency, green extraction processes often involve the use of environmentally benign substances and generate less hazardous waste compared to conventional methods. Table 1 provides a comparison of chemical usage and waste generation between a conventional hydrometallurgical process and a green ionic liquid-based extraction process for the REEs (recovery of rare earth elements). As shown in the table, the green ionic liquid-based extraction process avoids the use of hazardous acids and organic solvents, instead utilizing ionic liquids, which are generally less toxic and can be recycled [30]. Consequently, this green approach generates significantly less hazardous waste compared to the conventional hydrometallurgical process. These examples illustrate the potential advantages of green extraction processes in terms of energy efficiency, chemical usage, and waste minimization. However, it is crucial to conduct comprehensive life cycle assessments and techno-economic analyses to evaluate the overall sustainability and economic viability of these approaches for specific applications.

Table 1. Comparison of chemical usage and waste generation

Process	**Chemical usage**	**Hazardous waste generated**
Conventional hydrometallurgy	Acids, organic solvents	High (acidic and organic waste streams)
Green ionic liquid extraction	Ionic liquids	Low (ionic liquids can be recycled)

3.3 Research and Innovation Findings

Recent research in extractive metallurgy emphasizes green approaches for sustainable metal extraction [31], including innovations in alloy production to reduce carbon emissions and closed-loop recycling systems [32]-[33] for efficient metal recovery. Biomimicry-inspired metallurgical processes [34]-[35] and the adoption of circular economy models are gaining traction, emphasizing resource efficiency, waste reduction, and energy-efficient smelting technologies. Urban mining initiatives focus on recovering valuable metals from electronic waste, utilizing advanced separation and extraction technologies to contribute to resource conservation and waste reduction. The development and application of green solvents, such as ionic liquids and bio-based alternatives [36]-[37], mark a significant innovation in replacing environmentally harmful chemicals in metallurgical processes. A holistic approach to sustainability involves engaging with local communities, collaborative efforts, and transparent metallurgical practices [38], [39], demonstrating a paradigm shift towards greener practices. Green metallurgical practices substantially reduce the environmental footprint of metal extraction, contributing to a sustainable resource management model. These practices also lead to cost savings, market competitiveness, and positive stakeholder relations [40]. Implementing green approaches demonstrates social responsibility, positively impacting stakeholder relations, enhancing industry reputation, and fostering long-term partnerships. Green practices contribute to both environmental preservation and economic viability, establishing a resilient foundation for the metallurgical industry.

Advanced research explores nanotechnology applications for more efficient and selective metal extraction, minimizing the need for harmful reagents [41]-[42]. Integration of machine learning algorithms optimizes extractive processes, enhancing efficiency, reducing energy consumption, and improving overall performance. The implementation of sensor technologies enables real-time monitoring, allowing for immediate adjustments to minimize environmental incidents or suboptimal performance. The development of hybrid extraction systems synergistically combines multiple green approaches [43], enhancing metal recovery rates and overall process efficiency. The adoption of cradle-to-cradle design principles focuses on designing fully recyclable products and processes, contributing to a circular economy. Advanced alloy design using 3D printing technologies enables precise control of alloy composition, optimizing mechanical properties with reduced environmental impact. Electrochemical recovery from industrial effluents minimizes waste and efficiently extracts trace metals from dilute solutions.

The application of blockchain technology enhances supply chain transparency, tracking metal sources and providing verifiable information about origin and environmental footprint. Future research may explore advanced nanomaterials, AI and big data analytics for process optimization, closed-loop systems, novel green solvents, expanded electrochemical technologies, enhanced life cycle assessment methodologies, green additives in metallurgical processes, collaborative initiatives for supportive policies, and integration of smart manufacturing principles and Industry 4.0 technologies [44]-[48]. The evolving landscape of extractive metallurgy offers exciting opportunities for future research and technological advancements, aiming for a more sustainable, efficient, and environmentally friendly metallurgical sector.

3.4 Impact, Challenges and Opportunities

The adoption of green approaches in extractive metallurgy positively impacts customer perception, brand differentiation, and market share [49]. Environmentally conscious consumers increasingly value and prefer companies committed to sustainability. Green practices contribute to brand differentiation, providing a competitive edge in a market where sustainability is a key differentiator [50]. Metallurgical companies prioritizing green initiatives stand out, attracting environmentally aware consumers and securing loyalty. Embracing green approaches opens avenues for market expansion and diversification. Companies positioning themselves as leaders in sustainable metallurgy attract a broader consumer base and gain access to markets prioritizing eco-friendly practices.

Adhering to green practices aligns with regulatory standards and certifications, enhancing credibility and consumer trust [51]. Compliance with environmental regulations not only meets legal requirements but also resonates positively with environmentally conscious customers. Green approaches provide opportunities for consumer education and engagement. Transparent communication fosters a sense of shared values, increasing customer loyalty. Ethical and sustainable practices attract socially responsible investors, improving access to capital for expansion and innovation. Strong sustainability profiles enhance investor confidence. Sustainable marketing involves transparent communication, leveraging certifications, crafting compelling narratives, transparent product labeling, collaborations with environmental organizations, and creating avenues for consumer engagement. Positioning products as premium offerings with enhanced environmental credentials and regularly sharing updates on environmental impact metrics contribute to a transparent marketing strategy. Sustainable practices lead to increased customer trust, loyalty, and advocacy. Customers prefer products or services aligned with their environmental values, contributing to a positive brand perception.

The journey towards green approaches in extractive metallurgy faces challenges such as initial costs, resistance to change, and evolving regulations [52]-[54]. Reliable sourcing of green materials is crucial, and advancements in energy-efficient technologies present significant potential [55]-[57]. Smart sensor networks, biomimicry, sustainable alloy design, and circular economy principles offer opportunities for further development. Overcoming challenges requires collaborative efforts, proactive adaptation to regulations, and addressing uncertainties. Challenges include technological gaps, initial costs, resistance to change, evolving regulations, and sourcing green materials. Scaling up sustainable practices, providing adequate training, managing public perception, and optimizing infrastructure are additional challenges. Overcoming limitations requires collaborative efforts, addressing uncertainties, and aligning with sustainable practices. A successful shift to cyanide-free extraction methods reduced environmental impact and operational costs [58]-[62]. Transition to energy-efficient smelting technologies led to reduced emissions, improved resource efficiency, and economic benefit [63]-[64]. Implementation of closed-loop systems reduced water consumption, minimized environmental impact, and resulted in cost savings. Adoption of sustainable alloy design contributed to market differentiation, premium positioning, increased market share, and brand loyalty. Urban mining initiatives: Recovery of precious metals from electronic waste minimized environmental impact and demonstrated economic viability. These case studies showcase the successful adoption of green metallurgical practices, emphasizing environmental benefits alongside substantial economic gains, providing valuable models for other sectors in the industry.

3.5 Contribution and Future Research Directions

The synthesis of current knowledge on green approaches in extractive metallurgy is valuable for academic and industrial communities, offering insights for widespread implementation. Key contributions include a systematic review that facilitates the identification and adoption of best practices in green metallurgy for academic and industrial stakeholders. Synthesizing knowledge enables a comprehensive environmental impact assessment of green metallurgical practices, influencing policy formulation and corporate strategies [65]-[67]. The nuanced understanding of the economic viability of green practices aids industrial stakeholders and policymakers in making informed decisions and conducting cost-benefit analyses. The synthesis serves as a platform for technology transfer and collaboration between academia and industry, fostering a smoother transition toward green approaches. Consolidated knowledge forms the foundation for developing educational resources and training programs, enriching curricula, and preparing future metallurgists for sustainable practices.

Looking ahead, future research and innovation should concentrate on developing eco-friendly alternatives to improve extraction efficiency while minimizing the environmental impact. Researching ways to further minimize waste, promote recycling, and extend the life cycle of materials for improved resource efficiency [68]-[69]. Exploring how artificial intelligence and machine learning can enhance process control, predictive maintenance, and overall operational efficiency. Delving into biomimicry to develop sustainable extraction methods, materials, and processes inspired by the efficiency of ecosystems. Conducting comprehensive assessments to understand the full environmental impact of metallurgical processes and improve supply chain resilience. Prioritizing research on efficient and scalable methods for extracting valuable metals from electronic devices, reducing the demand for traditional mining [70]-[72]. Encouraging collaboration between metallurgy, chemistry, environmental science, and engineering for holistic solutions. Investigating the social impact of green metallurgical practices on local communities, including community perceptions and engagement strategies. The synthesis provides a foundation for future advancements, allowing academic and industrial communities to collectively contribute to the evolution of sustainable practices in the metallurgical industry.

Future research could explore collaborative initiatives between industries and governments to create supportive policies for sustainable practices. This involves establishing frameworks for incentive programs, regulatory standards, and industry certifications that promote and reward environmentally responsible metallurgical practices. Integration of smart manufacturing principles and Industry 4.0 technologies can further optimize the efficiency of metallurgical operations. IoT (Internet of Things) devices, sensors, and real-time data analytics can be employed to enhance process monitoring, control, and overall resource management. Conducting comprehensive techno-economic analyses can provide valuable insights into the economic feasibility of green practices. Future research may refine and expand these analyses to include a broader range of factors, such as market dynamics, policy impacts, and societal benefits. These potential future research directions and technological developments hold the promise of advancing the field of green approaches in extractive metallurgy. By exploring these avenues, researchers and industry stakeholders can contribute to the ongoing transformation of metallurgical practices toward greater sustainability.

4. CONCLUSION

The exploration of green approaches in extractive metallurgy signifies a transformative shift towards sustainability and environmental responsibility. The synthesis of current knowledge and case studies highlights progress, challenges, and innovation within the metallurgical industry, leading to several key conclusions. The review shows a notable industry shift towards sustainability, with practices evolving to minimize environmental impact and promote responsible resource management, including eco-friendly extraction methods and circular economy integration. Successful case studies demonstrate the feasibility of balancing environmental stewardship with economic viability. Industries adopting green practices achieve cost savings, improved efficiency, and enhanced market competitiveness. The synthesis emphasizes the importance of integrating both environmental and economic considerations in the pursuit of sustainability. Challenges in implementing green approaches, such as technological barriers and resistance to change, are acknowledged as catalysts for innovation. Collaboration, technological advancements, and strategic management are identified as means to overcome these challenges. The synthesis highlights the resilience of the metallurgical sector in navigating obstacles and driving positive change.

While significant strides have been made, the synthesis underscores the need for continued research and collaboration. Future exploration areas include advanced green solvents, digital technologies, and nature-inspired design. Cross-disciplinary collaboration, community engagement, and a focus on social impact emerge as crucial elements in steering the metallurgical industry towards a sustainable future. The progress, challenges, and untapped potential in green extractive metallurgy contribute to academic understanding and offer actionable insights for industry stakeholders. As the metallurgical sector embraces green approaches, the synthesis serves as a call to action for ongoing research, innovation, and collaborative efforts to ensure a harmonious coexistence between industrial processes and environmental preservation.

ACKNOWLEDGMENT

The author would like to express gratitude to the family and institutions for supporting this work.

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