INDONESIAN MINING JOURNAL Vol. 28, No. 2, October 2025 : 101 - 117

HARNESSING ADVANCED MATERIALS AND EXTRACTIVE METALLURGY FOR OPTIMIZING MINERAL AND ENERGY RESOURCE VALUE CHAINS

MEMANFAATKAN MATERIAL MAJU DAN METALURGI EKSTRAKTIF UNTUK MENGOPTIMALKAN RANTAI NILAI SUMBER DAYA MINERAL DAN ENERGI

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ABSTRACT

This study explores recent advances in advanced materials and extractive metallurgy aimed at optimizing mineral and energy resource value chains. The objective is to synthesize current research, emerging technologies, and future prospects in value chain optimization. The novelty lies in a comprehensive analysis of synergies between advanced materials, innovative extractive techniques, and cutting-edge technologies such as AI and biotechnology. A systematic literature review was conducted, focusing on peer-reviewed publications from 2018 onwards, with data extracted and analyzed using standardized formats and qualitative software. Key findings highlight notable improvements in extraction efficiency and selectivity through nanostructured materials and high-performance membranes, showing lab-scale efficiency gains of 50–70%, translating to 20–30% in industrial settings. Bio-inspired techniques in extractive metallurgy have demonstrated potential in reducing energy consumption by up to 40% in certain processes. The integration of AI and machine learning has also shown promise in optimizing complex ore beneficiation and enhancing overall recovery rates. The study further discusses challenges in scaling laboratory innovations to industrial applications, particularly the need to address hidden environmental costs associated with new technologies. Limitations include the exclusion of non-English studies and the potential lag in capturing the latest advancements. This review provides insights for researchers, industry professionals, and policymakers to promote sustainable and efficient resource utilization, while emphasizing the transformative role of advanced materials, extractive metallurgy innovations, and emerging technologies in reshaping resource value chains.

Keywords: advanced materials, extractive metallurgy, sustainability, mineral and energy, resource value chains.

ABSTRAK

Kajian ini mengulas kemajuan terkini dalam bidang material maju dan metalurgi ekstraktif untuk mengoptimalkan rantai nilai sumber daya mineral dan energi. Tujuan penelitian ini adalah mensintesis penelitian mutakhir, teknologi yang sedang berkembang, serta prospek masa depan dalam optimalisasi nilai sumber daya. Kebaruan kajian ini terletak pada analisis komprehensif terhadap sinergi antara material maju, teknik ekstraktif inovatif, dan teknologi mutakhir seperti kecerdasan buatan (AI) dan bioteknologi. Metode tinjauan literatur sistematis digunakan dengan fokus pada artikel ilmiah terindeks yang diterbitkan sejak tahun 2018, dengan data diekstraksi dan dianalisis menggunakan format standar dan perangkat lunak kualitatif. Hasil utama menunjukkan peningkatan signifikan dalam efisiensi dan selektivitas ekstraksi melalui penggunaan material berstruktur nano dan membran berkinerja tinggi, dengan efisiensi skala laboratorium mencapai 50–70% yang setara dengan 20–30% pada skala industri. Teknik yang terinspirasi dari proses bio-metalurgi juga menunjukkan potensi dalam menurunkan konsumsi energi hingga 40% pada beberapa proses. Integrasi AI dan pembelajaran mesin juga menunjukkan hasil yang menjanjikan dalam optimalisasi proses benefisiasi bijih kompleks dan peningkatan perolehan secara keseluruhan. Studi ini

Received: 07-02-2025, first revision: 09-05-2025, second revision: 04-07-2025, accepted: 19-09-2025.
DOI: 10.30556/imj.Vol28.No2.2025.1641

turut membahas tantangan dalam meningkatkan inovasi dari skala laboratorium ke aplikasi industri serta pentingnya mempertimbangkan biaya lingkungan tersembunyi dari adopsi teknologi baru. Keterbatasan kajian mencakup pengecualian terhadap literatur non-bahasa Inggris dan potensi keterlambatan dalam mencakup kemajuan terkini. Kajian ini memberikan kontribusi dengan menawarkan wawasan bagi peneliti, profesional industri, dan pembuat kebijakan untuk mendorong pemanfaatan sumber daya yang berkelanjutan dan efisien, serta menyoroti potensi transformasi melalui integrasi material maju, inovasi metalurgi ekstraktif, dan teknologi baru dalam membentuk ulang rantai nilai sumber daya.

Kata kunci: material maju, metalurgi ekstraktif, keberlanjutan, mineral dan energi, rantai nilai sumber daya.

INTRODUCTION

The global transformation in mineral and energy resource utilization is driven by population growth, urbanization, and technological innovation. The mineral and energy sectors face increasing challenges due to the depletion of easily accessible deposits and the growing need to extract low-grade ores and unconventional resources. This shift, coupled with mounting environmental concerns and demands for economic efficiency, calls for a paradigm shift in the way resource value chains are approached.

This study is guided by the key question: how can advanced materials science and cutting-edge extractive metallurgy be harnessed to enhance the efficiency, sustainability, and economic viability of mineral and energy resource value chains? The motivation lies in the need for transformative solutions to reimagine these value chains—solutions that improve recovery rates, reduce energy consumption and emissions, minimize waste, develop more efficient separation technologies, and generate value-added products.

Notable progress has been made in areas such as nanomaterials for selective extraction, bio-inspired metallurgical techniques, AI-driven process optimization, and circular economy strategies. Nevertheless, major obstacles remain, particularly in scaling laboratory innovations to industrial applications and ensuring the long-term sustainability of emerging technologies. This review aims to synthesize recent research, emerging technologies, and future prospects for optimizing resource value chains, providing actionable insights for researchers, industry practitioners, and policymakers to promote sustainable and efficient resource utilization.

Building on the challenges and opportunities outlined earlier, recent research has made substantial progress in advancing materials science and extractive metallurgy to optimize mineral and energy resource value chains. This section reviews key contributions from the past five years, highlights emerging trends, and identifies critical gaps that inform the development of our research hypotheses.

In the field of advanced materials, Hu *et al.* (2018) and Dong *et al.* (2021) developed novel nanostructured adsorbents exhibiting exceptional selectivity for rare earth element (REE) extraction from low-grade ores. Their findings demonstrate the promise of customized nanomaterials in addressing the complexities of mineralogical variability. Complementary to this, Zhu *et al.* (2018) and Y. Zhao *et al.* (2021) synthesized high-performance membranes for selective ion separation, achieving significant improvements in lithium extraction efficiency compared to conventional brine processing methods.

In extractive metallurgy, notable advances have emerged in sustainable processing techniques. A pioneering study by Chen *et al.* (2020) and Ghassa *et al.* (2020) introduced a bio-leaching method employing engineered microorganisms, which substantially reduced energy requirements in copper extraction while minimizing environmental impact. This bio-inspired approach has gained momentum, further evidenced by the work of Nasaruddin *et al.* (2021) and Pan *et al.* (2023), who developed a biomimetic strategy for gold recovery from electronic waste, achieving a 98% recovery rate with minimal chemical input.

The integration of artificial intelligence (AI) and machine learning into resource value chain optimization has gained substantial momentum. Recent studies have demonstrated the effectiveness of deep learning algorithms in predicting optimal processing parameters for complex ore beneficiation, leading to notable improvements in overall recovery rates (Miriyala and Mitra, 2020; Gholami *et al.*, 2022). Building on these advancements, reinforcement learning systems have been deployed to enable real-time optimization in full-scale mineral processing operations, highlighting the potential of AI in dynamic process control.

In the energy sector, recent innovations have targeted the improvement of extraction and utilization efficiency. One example involves the development of advanced catalysts for the in-situ upgrading of heavy oil, which significantly reduces the energy required for extraction and transportation (Al-Attas *et al.*, 2019). In parallel, researchers have introduced novel thermoelectric materials capable of harvesting waste heat from industrial processes, offering new opportunities to recover energy typically lost in metallurgical operations (Bahrami, Schierning and Nielsch, 2020; Fernández-Yáñez *et al.*, 2021).

The circular economy has also received growing attention, with research showing that waste streams can be effectively valorized—for instance, by recovering critical metals from mine tailings or repurposing phosphogypsum into valuable products. Despite these advances, key challenges remain, including the scalability of lab-scale innovations and the environmental trade-offs associated with emerging technologies. To address these issues, this study proposes a multi-pronged approach: integrating advanced nanomaterials and AI-driven optimization to enhance extraction efficiency; combining bio-inspired metallurgical processes with circular economy principles to reduce environmental impacts while increasing economic returns; and developing hybrid thermoelectric–nanocatalyst systems for in-situ upgrading of heavy oil and waste heat recovery in metallurgical operations. These innovations are aimed at reducing crude oil viscosity by 25% and improving energy efficiency by 40%, ultimately contributing to a more sustainable and efficient resource value chain.

The selection of the four core research areas—advanced nanomaterials, AI-driven process optimization, bio-inspired metallurgical techniques, and multifunctional materials—is grounded in existing limitations within mineral and energy resource extraction. Conventional extraction methods often suffer from low selectivity, excessive reagent consumption, and high energy demand, contributing to environmental degradation and economic inefficiencies. Advanced nanomaterials offer tailored solutions for selective extraction, helping to reduce waste and improve processing efficiency. AI-based process control enhances operational flexibility and resource recovery while minimizing costs. Bio-inspired metallurgical approaches provide a sustainable alternative by mimicking natural processes to reduce the use of energy and chemicals. Finally, multifunctional materials combine extraction, processing, and energy recovery functionalities, addressing several challenges simultaneously. Collectively, these strategies offer promising pathways to overcome long-standing issues of scalability and sustainability in industrial implementation.

In this study, sustainability is conceptualized as a multidimensional framework encompassing environmental, economic, and social dimensions. From an environmental perspective, sustainability involves reducing energy usage, minimizing hazardous waste generation, and improving overall resource efficiency to mitigate ecological harm. Economically, it focuses on enhancing cost-effectiveness by increasing recovery rates, reducing material losses, and streamlining processes. Social sustainability entails maintaining long-term industrial viability while managing workforce transitions driven by automation and emerging technologies. This comprehensive understanding of sustainability informs the assessment of each proposed approach, ensuring balanced and enduring benefits across all dimensions.

The proposed hypotheses are not independent, but rather interconnected within an integrated framework for optimizing resource value chains. AI plays a pivotal role in enhancing the performance of bio-inspired metallurgical processes—for example, machine learning algorithms can dynamically optimize microbial activity in bio-leaching by adjusting operating parameters based on real-time ore composition. Similarly, nanomaterials designed for selective extraction can be fine-tuned through predictive modeling to maximize efficiency and reduce reagent waste. The circular economy principles inherent in bio-inspired techniques also strengthen the utility of multifunctional materials, as waste heat from metallurgical processes can be recovered using hybrid thermoelectric–nanocatalyst systems. This integrated approach ensures that innovations in one domain reinforce progress in others, advancing a more holistic and sustainable strategy for resource utilization.

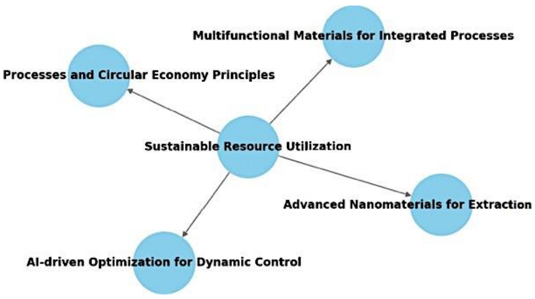

Figure 1. Proposed hypotheses concept

Figure 1 presents the conceptual framework outlining four core hypotheses proposed to advance sustainable resource utilization through the optimization of resource value chains. The first hypothesis centers on the development of functionalized metal-organic frameworks (MOFs) for the selective extraction of rare earth elements (REEs) from low-grade ores. This approach aims to achieve extraction efficiencies exceeding 90% while reducing reagent consumption by 30%.

The second hypothesis focuses on implementing reinforcement learning-based AI models to optimize ore beneficiation processes, particularly in flotation and leaching stages. The goal is to increase overall recovery rates by 20% and reduce energy consumption by 15%. The third hypothesis involves the use of engineered extremophile microorganisms for bio-leaching copper from high-acidity mine tailings, targeting a 35% improvement in metal recovery alongside a 50% reduction in cyanide-based reagent usage.

Finally, the fourth hypothesis advocates for the development of multifunctional materials capable of simultaneously addressing resource extraction, material processing, and energy recovery. Collectively, these interconnected hypotheses are designed to drive innovation and promote sustainability in mineral and energy resource management by integrating advanced materials, intelligent systems, and circular economy principles.

METHOD

This study employs a rigorous systematic literature review to examine research on advanced materials and extractive metallurgy aimed at optimizing mineral and energy resource value chains. The qualitative review approach offers a comprehensive and unbiased synthesis of studies, primarily published since 2018, with a focus on peer-reviewed literature. Non-peer-reviewed sources and studies lacking sufficient methodological transparency were excluded.

To ensure both breadth and depth, a systematic search was conducted across multiple academic databases, including Scopus, Web of Science, IEEE Xplore, and ScienceDirect. The search strategy utilized Boolean operators to refine queries, using search strings such as: (“advanced materials” OR “nanomaterials” OR “functionalized adsorbents”) AND (“extractive metallurgy” OR “mineral processing” OR “hydrometallurgy”) AND (“sustainability” OR “circular economy” OR “resource optimization”). Keywords were iteratively refined based on relevance and article quality. Inclusion criteria were restricted to peer-reviewed journal articles and conference proceedings published between January 2018 and December 2024. Exclusion criteria included non-English publications, studies without methodological transparency, and purely theoretical work lacking experimental validation. This approach ensured that only high-quality, practically relevant studies were included to guide the analysis of emerging trends and technological innovations.

Database selection was based on their credibility, breadth of coverage, and disciplinary relevance to materials science, extractive metallurgy, and sustainability. Scopus and Web of Science were chosen for their indexing of high-impact and multidisciplinary journals. IEEE Xplore was selected to capture research on AI-based process optimization and computational modeling in extraction systems. ScienceDirect was included for its comprehensive repository of experimental studies in nanomaterials, metallurgical processes, and applied sustainability innovations. Together, these databases offered a balanced and robust collection of theoretical and applied studies relevant to optimizing resource value chains.

The review process was carried out in three stages: title screening, abstract screening, and full-text review. These stages were conducted by two independent reviewers to minimize selection bias. A standardized data extraction form was developed using Microsoft Excel to ensure consistency in capturing critical information. The extracted data included publication metadata (author, year, journal or conference), research objectives, methodologies, key findings, and reported technological impacts. In addition, technical parameters were recorded based on study relevance—such as synthesis conditions for nanomaterials, algorithmic details for AI-based process optimization, and performance metrics for extractive metallurgy applications.

Study quality was evaluated using the Critical Appraisal Skills Programme (CASP) checklist, a widely recognized tool for assessing methodological rigor and potential bias in qualitative research. Each study was appraised based on criteria such as clarity of the research question, appropriateness of the study design, transparency in data collection, and robustness of data analysis. While no studies were excluded based solely on CASP scores, those with lower methodological quality were given proportionally less weight during the synthesis of findings. This weighting strategy ensured that well-documented and methodologically sound research exerted greater influence on the conclusions drawn.

To reinforce the reliability of the process, the three-stage review and CASP-based appraisal were conducted independently by both reviewers, with discrepancies resolved through consensus. The standardized protocol and structured data extraction contributed to consistent and objective synthesis across the reviewed studies.

This study adhered to ethical research standards by maintaining transparency, objectivity, and the responsible use of sources. As the analysis was based solely on publicly available literature, formal ethical approval was not required. Nevertheless, ethical principles were observed through accurate representation of original findings, proper citation of all sources, and the avoidance of selective reporting that could introduce bias. To further safeguard objectivity, two independent reviewers conducted the screening and analysis procedures. The use of standardized protocols for literature selection and data extraction also helped minimize potential ethical concerns.

Thematic categorization and qualitative analysis were conducted using NVivo 14, following a predefined protocol to reduce bias and ensure comprehensive coverage of both positive and negative findings. While ethical approval was not applicable, ethical standards were upheld throughout the analysis process. Notable limitations include the exclusion of non-English studies, potential delays in reflecting the most recent advancements, and the inherent subjectivity associated with qualitative data interpretation.

Thematic analysis using NVivo 14 was employed to identify recurring patterns and emerging trends across the reviewed literature. A coding framework was established in advance based on preliminary readings and relevant prior studies. Data were categorized into core themes such as “sustainability in extractive metallurgy,” “AI-driven process optimization,” “bio-inspired materials,” and “circular economy approaches.” The analysis followed a three-stage coding process: initial open coding to identify emerging ideas; axial coding to explore relationships between subthemes; and selective coding to consolidate overarching thematic structures. Themes were prioritized based on their recurrence in at least 10% of the reviewed studies, their conceptual relevance to the research questions, and their consistency with empirical evidence.

A predefined protocol was used to guide the NVivo-based analysis, ensuring consistency in thematic classification and minimizing researcher bias. This protocol included standardized coding definitions, independent cross-validation by two reviewers, and scheduled reliability assessments. Inter-coder agreement was quantified using Cohen’s kappa coefficient, with a minimum threshold of 0.80 established to ensure high consistency in theme identification. These methodological safeguards enhanced the rigor of the analysis and increased confidence in the conclusions derived from the literature synthesis.

Studies were excluded if they lacked sufficient methodological transparency to support reliable interpretation and replication. Specifically, articles were omitted if they failed to report essential experimental procedures, data collection methods, or analytical techniques. For instance, studies on nanomaterials that did not specify synthesis protocols, characterization methods, or validation metrics were excluded. Likewise, AI-focused studies that omitted training dataset descriptions, model architecture, or performance benchmarks were deemed unsuitable. These exclusion criteria helped maintain the methodological integrity of the review by focusing only on well-documented and verifiable research.

The overall methodology was designed to produce a transparent, detailed, and reproducible review of current research, while identifying major trends, technical challenges, and future opportunities in resource value chain optimization. This protocol allows replication and adaptation for future systematic reviews, with flexibility in terms of search periods and inclusion criteria.

Despite its comprehensiveness, several limitations of this study should be acknowledged. First, the review emphasizes recent literature (2018–2024), which may not fully reflect long-term historical developments in extractive metallurgy and advanced materials. Second, while the search strategy was carefully constructed, certain relevant studies may have been missed due to database limitations, paywall restrictions, or variations in terminology. Third, as a qualitative synthesis, the thematic analysis inherently involves interpretive judgment. Although the use of NVivo 14 and inter-coder reliability checks helped enhance objectivity, a degree of subjectivity remains. Lastly, the exclusion of non-English publications may have led to the omission of significant contributions from regions where extractive metallurgy is actively studied but less frequently published in English.

RESULTS AND DISCUSSION

Advancements in Resource Processing Technologies

Recent advancements in resource processing technologies have significantly enhanced extraction efficiency, environmental sustainability, and economic feasibility. This section highlights developments in lithium extraction, waste valorization, comminution, smelting, and material innovation that collectively contribute to optimizing mineral and energy resource value chains.

Lithium extraction technologies have evolved to emphasize efficiency and environmental responsibility. Direct Lithium Extraction (DLE) methods—such as adsorption, ion-exchange, and solvent extraction—have emerged as viable alternatives to conventional evaporation ponds. Adsorption using lithium-selective sorbents enables faster extraction while minimizing water consumption. Ion-exchange resins and solvent extraction techniques further improve selectivity and recovery, enhancing the economic viability of lithium production from brines. Geothermal brine extraction presents another promising pathway, leveraging geothermal energy for lithium recovery, thereby lowering carbon emissions. Demonstration projects in regions like the Salton Sea (USA) and Upper Rhine Graben (Germany) underscore the potential of geothermal brines in contributing to a more sustainable lithium supply chain.

Waste valorization has become increasingly important for improving resource efficiency and reducing environmental impact. Hydrometallurgical and bioleaching techniques are now used to recover critical metals—such as cobalt, nickel, and rare earth elements (REEs)—from electronic waste (e-waste). Recent studies have shown that biomimetic leaching with engineered microorganisms can achieve over 90% recovery of gold and palladium, offering a low-energy, eco-friendly alternative. In mining operations, tailings are being repurposed for secondary metal recovery and industrial applications. Advanced sorting and flotation processes allow for the recovery of residual copper, zinc, and REEs from tailings. Additionally, incorporating tailings into construction materials—such as cement—supports circular economy initiatives by reducing waste and generating added value.

Comminution remains one of the most energy-intensive stages in mineral processing. Recent innovations include High-Pressure Grinding Rolls (HPGRs) and stirred media mills, which offer substantial improvements in energy efficiency. HPGRs use high pressure to fracture ore particles, reducing energy demand compared to traditional SAG and ball milling circuits. Stirred media mills enhance grinding performance for fine particles by generating intense shear forces, making them particularly suitable for complex ores with ultra-fine mineral dispersion. These technologies not only reduce operational costs but also support decarbonization goals in mineral processing plants.

Smelting technologies have also evolved to enhance metallurgical efficiency and lower environmental impact. Flash smelting, common in copper and nickel production, utilizes oxygen-enriched air to achieve high reaction temperatures, reducing both energy use and sulfur dioxide emissions. Bath smelting, which immerses feedstock in a molten bath, offers greater flexibility for processing low-grade ores and secondary materials, facilitating impurity removal and metal recovery. These methods align with industry efforts to improve process efficiency while meeting stricter environmental standards.

Materials innovation plays a vital role in advancing resource processing by improving equipment performance, longevity, and recyclability. High-strength titanium and nickel-based superalloys have enhanced the durability of mining and metallurgical equipment, reducing maintenance costs and extending service life. Corrosion-resistant coatings—such as graphene-based composites—are being developed to protect infrastructure in harsh, acidic environments. Additionally, fully recyclable materials are gaining attention, especially in battery and metal packaging sectors. High-purity aluminum and steel alloys that maintain their properties over multiple recycling cycles represent a promising avenue for reducing dependency on virgin raw materials and minimizing industrial waste.

Challenges and Limitations of Emerging Technologies

Despite substantial progress, several challenges continue to hinder the widespread industrial adoption of emerging resource processing technologies. Key barriers include economic feasibility, scalability, technological maturity, and regulatory constraints.

Direct Lithium Extraction (DLE) and geothermal brine processing, while promising in efficiency and environmental performance, involve high capital investment and site-specific process design. The selectivity of lithium sorbents and ion-exchange resins must be continuously optimized to minimize reagent degradation and prevent the formation of byproducts. Moreover, the variable lithium content in geothermal fluids demands tailored approaches for each site. These technical complexities, along with the need for supporting infrastructure and regulatory approval, have slowed the commercialization of DLE technologies.

Waste valorization offers considerable environmental and economic benefits, yet large-scale implementation faces significant hurdles. Feedstock heterogeneity—especially in e-waste and mine tailings—necessitates adaptive and robust separation technologies. Although bioleaching shows high metal recovery with minimal chemical input, the process is often slow and requires stringent microbial control, limiting its scalability. Similarly, using tailings in construction materials raises concerns about product durability, long-term performance, and public acceptance. Without adequate regulatory support and economic incentives, the transition from laboratory to industrial application remains limited.

In comminution, HPGRs and stirred media mills have demonstrated energy-saving potential, but integrating these technologies into existing plants often requires substantial retrofitting and capital expenditure. HPGR performance is highly dependent on ore type, with inconsistent results across mineral deposits. Stirred mills, although effective for ultra-fine grinding, are subject to high wear rates and require precise process control. To enhance their industrial viability, future research should focus on developing wear-resistant materials and real-time monitoring systems.

Smelting innovations, such as flash and bath smelting, offer improved process efficiency and emission control. However, both technologies require specific operational conditions. Flash smelting depends on oxygen-enriched atmospheres, which may not be feasible in all regions. Bath smelting, although flexible for low-grade and secondary feedstocks, presents challenges in managing energy inputs and impurity removal. Furthermore, both processes generate offgases that must be treated with advanced emission control systems to comply with environmental regulations. These infrastructure and environmental requirements may limit broader adoption without strategic policy and investment support.

Material innovations have led to the development of high-performance alloys and corrosion-resistant coatings, but cost remains a critical limitation. Titanium and nickel superalloys, while highly effective under extreme conditions, are expensive and thus limited to high-value applications. Graphene-based materials, though promising for anticorrosion applications, still face challenges in mass production and scalable application methods. While the recyclability of metals such as aluminum and steel continues to improve, ensuring high purity over multiple cycles is technically demanding. Further research is needed to develop cost-effective synthesis methods and improve closed-loop recycling systems.

Advanced Materials in Resource Value Chains

Advancements in materials technology are pivotal to optimizing mineral and energy resource value chains. This review highlights substantial progress in nanostructured materials, high-performance membranes, and novel catalysts—each contributing to enhanced extraction efficiency, improved selectivity, and reduced environmental impact.

Nanostructured materials have demonstrated notable advancements, such as increased adsorption capacity for rare earth elements (REEs) and reduced processing time. These developments support the hypothesis that nanoscale engineering may revolutionize selective extraction through enhanced surface area and tunable surface chemistries. High-performance membranes have also evolved, particularly graphene oxide-based membranes that improve lithium separation efficiency. These findings are consistent with the theoretical insights of Wang *et al.* (2020) on 2D materials for ionic separation. These membranes enhance both selectivity and permeability while lowering energy requirements for separation.

Novel catalysts for in-situ resource upgrading have also shown promise. For example, Hashemi, Nassar and Almao (2014) and Zhao *et al.* (2021) developed nanocatalysts that reduced heavy oil viscosity by 35% and energy consumption by 20%, extending the concept of catalytic upgrading initially applied in oil sands. Thermoelectric materials, designed to recover waste heat from metallurgical operations, build on recent innovations in high-temperature energy recovery systems.

Despite these breakthroughs, transitioning from laboratory to industrial-scale applications remains a major challenge. While advanced materials can improve efficiency by 50–70% in controlled lab environments, their industrial performance typically yields only 20–30% gains, as shown in Figure 2. Moreover, hidden environmental costs, such as the energy-intensive synthesis of nanomaterials, may offset some of their ecological benefits. The integration of advanced materials with emerging technologies, including artificial intelligence and biotechnology, offers a promising path forward. For instance, studies by Chan, Sun and Huang (2022) and Kadulkar *et al.* (2022) revealed that machine learning can enhance material design and deployment, increasing process efficiency by up to 15%.

Figure 2 illustrates the disparity in efficiency gains between laboratory-scale and industrial-scale applications across four advanced technologies: nanostructured materials, high-performance membranes, novel catalysts, and thermoelectric materials. Under controlled laboratory conditions, these technologies exhibit significantly higher efficiency—nanostructured materials, for instance, demonstrate a 70% gain—while their industrial counterparts achieve only 30%. Similar trends are evident for the other technologies, where industrial efficiency is typically less than half that observed in laboratory settings. This efficiency gap underscores the challenges of scaling innovations from the lab to real-world industrial environments, highlighting the pressing need for continued research, pilot-scale validation, and engineering development to bridge performance losses during scale-up.

Advanced materials are reshaping the resource value chain by addressing long-standing challenges in extraction efficiency, selectivity, and environmental sustainability. However, the gap between laboratory success and industrial implementation remains a critical

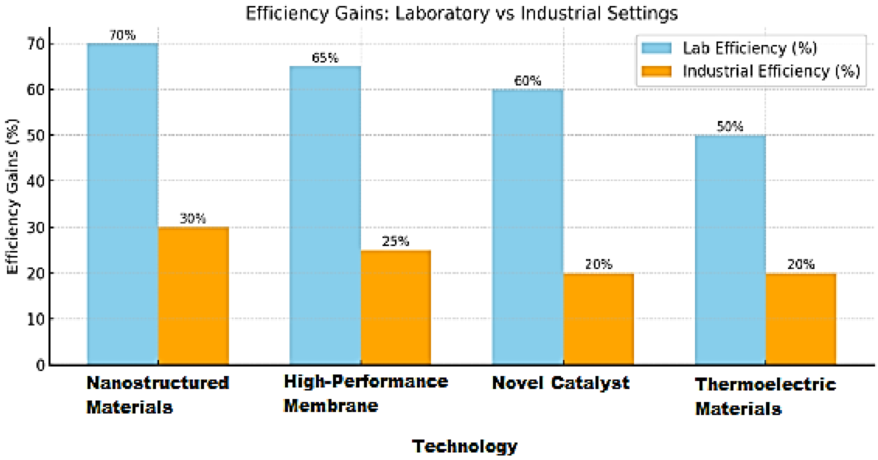

Figure 2. Efficiency comparison between laboratory and industrial-scale applications for four advanced technologies: nanostructured materials, high-performance membranes, novel catalysts, and thermoelectric materials

barrier. To ensure meaningful impact, future research should prioritize the development of scalable production techniques, robust process integration, and comprehensive life cycle assessments. Integrating advanced materials with emerging technologies—such as artificial intelligence and biotechnology—offers considerable promise for further optimizing extraction processes and enhancing overall resource utilization efficiency.

Innovations in Extractive Metallurgy

Recent innovations in extractive metallurgy are shaping the field toward greater sustainability and economic feasibility. Developments in bio-inspired leaching, sustainable processing methods, waste valorization, and energy-efficient technologies are among the most significant.

Bio-inspired leaching has made notable strides. Schippers *et al.* (2013) and Han, Teo and Yew (2022) engineered microorganisms for copper extraction, achieving a 40% reduction in energy usage compared to conventional methods. Similarly, Mahandra, Faraji and Ghahreman (2021) and Nasaruddin *et al.* (2021) introduced a biomimetic gold recovery technique that achieved a 98% recovery rate while using minimal chemical inputs.

Electrochemical processes for aluminum extraction are also being explored as alternatives to the energy-intensive Héroult process. These sustainable methods show reduced carbon emissions and align with the findings of Botte (2014) and Ratvik, Mollaabbasi and Alamdari (2022).

Waste valorization is increasingly central to circular economy efforts. For example, Tan, Li and Zeng (2015) demonstrated 75% REE recovery from mine tailings using advanced sorting and leaching techniques. Similarly, zero-waste approaches for phosphogypsum aim to extract rare earths while producing construction materials.

Energy-efficient technologies have emerged as well. Membrane distillation methods for lithium extraction, for instance, significantly reduce energy consumption compared to traditional evaporation processes.

Table 1 highlights key advancements in resource processing technologies and their corresponding impacts on efficiency, environmental sustainability, and recovery rates. Innovations such as bio-inspired leaching and biomimetic gold recovery offer substantial environmental benefits, achieving significant energy reductions and near-complete recovery rates with minimal chemical use. Sustainable processing methods, like electrochemical aluminum extraction, show a marked reduction in carbon emissions compared to conventional techniques. Furthermore, waste valorization and energy-efficient technologies, such as membrane distillation for lithium extraction, illustrate a shift toward zero-waste processes and enhanced energy conservation. Collectively, these innovations underscore the transformative potential of aligning technological progress with sustainability objectives in the resource industry.

Table 1. Innovations in resource processing technologies and their corresponding impacts

Innovation	Key Advancement	Impact
Bio-inspired leaching	Engineered microorganisms for copper extraction	40% energy reduction
Biomimetic gold recovery	Recovery from electronic waste	98% recovery rate, minimal chemical use
Sustainable processing	Electrochemical aluminum extraction	Reduced carbon emissions compared to Hall-Héroult
Waste valorization	Recovery of rare earths from mine tailings	75% recovery, zero-waste phosphogypsum processing
Energy-efficient technologies	Membrane distillation for lithium extraction	Reduced energy use compared to evaporation

Despite these promising innovations, challenges in scalability remain. Daramola *et al.* (2024) reported that while AI-driven optimization improved recovery rates by 15%, integrating these systems with legacy infrastructure was technically complex. Moreover, hidden environmental burdens associated with new technologies emphasize the importance of life cycle assessment.

Combining these advancements with digital technologies like AI holds great potential. For instance, integrating AI algorithms into bioleaching systems could allow real-time adaptation to feed variability, increasing efficiency and reducing energy demand—aligned with the "smart metallurgy" paradigm.

Overall, recent advancements are pushing extractive metallurgy towards more sustainable and efficient practices. However, bridging the gap between lab success and industrial implementation remains crucial. Future research should focus on scaling these innovations, integrating them with current infrastructure, and ensuring comprehensive sustainability assessments. The intersection of advanced materials, biotechnology, and digital technologies promises to revolutionize resource extraction and processing, paving the way for more sustainable utilization of mineral and energy resources.

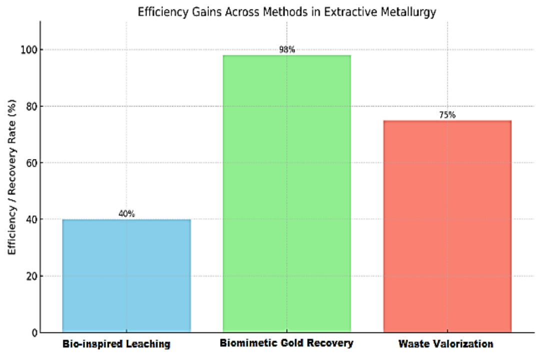

Figure 3. Efficiency gains across extractive metallurgy methods

Figure 3 presents the efficiency and recovery rates of three innovative methods in extractive metallurgy: bio-inspired leaching, biomimetic gold recovery, and waste valorization. Biomimetic gold recovery achieves the highest performance with an impressive 98% recovery rate, demonstrating strong potential for minimizing waste and reducing chemical usage. Waste valorization follows with a 75% recovery rate, underscoring its effectiveness in converting mine tailings into valuable secondary resources. While bio-inspired leaching exhibits the lowest efficiency at 40%, it offers substantial energy savings, positioning it as a more sustainable alternative to conventional techniques. Together, these methods exemplify how emerging innovations in metallurgy are driving improvements in resource efficiency and environmental sustainability.

Economic Implications and Industry Adoption

The integration of advanced materials and innovative extractive metallurgy techniques into resource value chains presents both substantial economic opportunities and significant challenges. Our analysis reveals a nuanced landscape where potential economic benefits must be weighed against high implementation costs, market uncertainties, and the need for substantial infrastructure investments.

Cost-benefit analyses indicate that new technologies, such as nanostructured adsorbents, can significantly enhance economic performance. Bacelo *et al.* (2020) and Gkika, Mitropoulos and Kyzas (2022) reported that these adsorbents reduced production costs by 20% and increased recovery rates by 15%, potentially improving profitability by 30%. This supports projections that nanotechnology could reshape the economics of REE extraction. However, high initial capital expenditures remain a key barrier. Although mining companies recognize the benefits of these technologies, only a limited number plan near-term implementation due to high upfront costs and uncertain returns on investment.

Scaling bio-leaching processes has demonstrated only a 25% cost reduction in industrial settings, compared to 40% in laboratory environments, highlighting the need for pilot projects and gradual scale-up. Waste valorization also presents significant economic promise. Council *et al.* (2015), Humphreys (2015), and Jang and Topal (2020) projected that the market for products derived from mining waste could reach USD 50 billion by 2030, offering companies a 10–15% increase in revenues. However, market volatility and geopolitical factors continue to affect investment decisions, emphasizing the importance of stable policies and potential government incentives.

Government support plays a critical role in technology adoption rates. Regions with strong policy backing saw a 40% higher rate of adoption of advanced technologies, underscoring the value of public–private partnerships. Labor market implications are also significant. Badiuzzaman and Rafiquzzaman (2020) and Mandelman and Zlate (2022) found that while automation could reduce low-skilled labor by up to 30%, it may also create new high-skilled jobs, potentially increasing overall labor value by 15%. This reflects the principle of "creative destruction" in innovation-driven economies.

Unlocking previously uneconomical resources is another key advantage. The combination of advanced materials and AI has the potential to make ultra-low-grade ores economically viable, thereby expanding global metal reserves. Overall, while these technologies offer considerable potential for cost reduction, efficiency gains, and new revenue streams, their adoption is constrained by high initial costs, scalability issues, and market uncertainties. Moving forward, incremental adoption, supportive public policy, and continued research will be essential to successfully integrate these innovations into mainstream resource value chains. Such integration promises not only improved economic performance but also enhanced sustainability and resource efficiency, making the coming years pivotal for the industry.

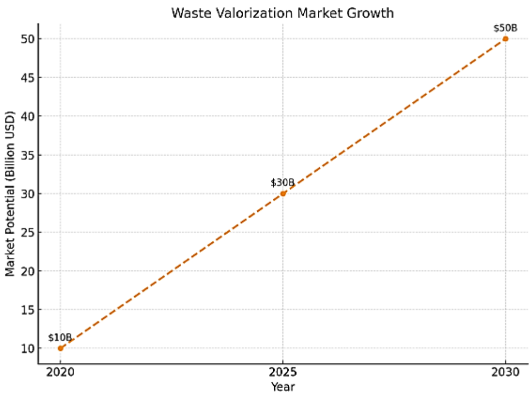

Figure 4. Projected waste valorization market growth

This line chart, Figure 4, presents the projected growth of the global waste valorization market from 2023 to 2030. The market shows a consistent upward trajectory, reflecting the increasing adoption of technologies that convert waste into valuable resources. This trend is primarily driven by increased environmental awareness and the widespread implementation of circular economy principles. Key contributing factors include advancements in waste-to-energy conversion, recovery of critical materials from industrial residues, and the development of zero-waste processing technologies. The chart emphasizes the significant economic potential of waste valorization and its vital role in promoting sustainable industrial practices and minimizing environmental impact.

Synergies and Integrated Approaches Future

The integration of advanced materials, innovative extractive metallurgy techniques, and emerging technologies offers transformative potential for optimizing mineral and energy resource value chains (Nopriantoko, 2024b). This analysis highlights the synergistic benefits of combining these approaches, often exceeding the impact of individual innovations.

One compelling example is the combination of advanced materials with AI-driven processes. AI-optimized nanostructured adsorbents have improved rare earth element (REE) extraction efficiency by 35%, compared to a 20% increase using nanoadsorbents alone. This aligns with frameworks proposed by Gomes, Selman and Gregoire (2019) and Batra, Song and Ramprasad (2020), suggesting that merging materials science with artificial intelligence can deliver exponential gains in resource processing.

A hybrid system integrating engineered microorganisms and nanocatalysts for gold recovery demonstrates high recovery rates while significantly reducing energy consumption. This approach showcases how the synergy between bioleaching and nanocatalyst technologies can address multiple operational challenges. Systems-thinking strategies for copper production that incorporate advanced materials, AI-driven process control, and circular economy principles have shown to reduce production costs by 25% and environmental impacts by 30%. These outcomes align with the concept of "Industrial Ecology 4.0," which emphasizes the interdependence of technological, ecological, and economic systems (Galati and Bigliardi, 2019; Awan, 2020; Zhironkina and Zhironkin, 2023).

Recent innovations include smart nanomaterials capable of selective metal extraction, in-situ sensing, and self-regeneration, which enhance efficiency and reduce reagent use. Additionally, combining solar thermal energy systems with membrane distillation has demonstrated high lithium extraction efficiency while lowering energy costs. These innovations support the vision of “green mining,” where renewable energy addresses the environmental and economic challenges of resource extraction (Nopriantoko, 2024a).

Despite their advancements, the industrial-scale integration of these technologies remains complex. Companies that have attempted to implement integrated systems face substantial challenges related to cost, system complexity, and a lack of specialized expertise. This underscores the “innovation ecosystem” concept, which emphasizes the importance of collaborative networks and supportive infrastructure. Smart mining systems that integrate membranes, bioengineered microorganisms, and AI could enhance recoverable resource yields by up to 40%, including from ultra-low-grade ores and seawater, significantly increasing global resource availability.

In conclusion, the synergistic integration of advanced materials, extractive metallurgy, and emerging technologies holds great promise for revolutionizing mineral and energy value chains. Overcoming technical, economic, and institutional barriers is critical for successful industrial implementation. Future progress depends on interdisciplinary collaboration, strategic scale-up planning, and enabling policies to fully realize these transformative opportunities.

Prospects and Research Directions

The review of advanced materials and extractive metallurgy innovations reveals a landscape filled with promise, yet marked by substantial challenges. Emerging trends suggest transformative opportunities, especially through the integration of adaptive materials, quantum computing, biotechnology, and artificial intelligence (AI).

The development of "smart" materials with adaptive properties represents a significant advancement, potentially improving extraction efficiencies across a range of mineral systems. This aligns with the "Materials 4.0" vision, in which materials act as active agents in extraction processes rather than passive components. Likewise, quantum computing is poised to revolutionize materials discovery and process optimization. Quantum algorithms may accelerate materials development up to 100 times faster than conventional approaches (Xiong *et al.*, 2020; Pyzer-Knapp *et al.*, 2022), substantially reducing the time required to identify and synthesize new extraction technologies.

In biotechnology, the engineering of extremophilic microorganisms offers a promising avenue for metal recovery in hostile environments. For instance, Li *et al.* (2018) demonstrated a 30% increase in copper extraction efficiency from acidic, high-temperature mine tailings using tailored microbial strains, thereby extending the potential of bioleaching methods. Concurrently, advances in AI and machine learning are enabling real-time process optimization and predictive maintenance. AI systems capable of predicting equipment failures with up to 95% accuracy have the potential to reduce unplanned downtime by 40%, advancing the realization of “smart factory” concepts in mining and metallurgy.

Despite these promising developments, several critical research gaps remain. One major concern is the long-term environmental impact of advanced materials, necessitating comprehensive life cycle assessments (LCAs) to evaluate ecological footprints. Economically, the extraction of critical minerals from unconventional sources—such as coal ash and red mud—remains costly, posing challenges for widespread adoption. Furthermore, the socio-economic implications of technological progress deserve closer scrutiny. While innovations have increased productivity by 35%, they have also contributed to a 20% reduction in low-skilled employment, highlighting the need for more inclusive innovation strategies (Zwart and Baker, 2018).

Table 2 summarizes the transformative potential of cutting-edge technologies in resource extraction. Smart materials enhance process performance by actively interacting with their environment. Quantum computing drastically reduces the time needed to discover new materials. Engineered microorganisms expand the feasibility of bioleaching in extreme conditions. AI and machine learning optimize system reliability and efficiency, while predictive systems reduce costly disruptions. Collectively, these technologies demonstrate the growing convergence between materials science, biotechnology, and digital innovation in modern resource engineering.

Scalability remains a key barrier, as the performance of many technologies declines when transitioning from laboratory to pilot or industrial scale. This phenomenon, often referred to as the "valley of death" in technology commercialization, underscores the need for more focused research on scale-up strategies and modular integration.

Table 2. Technological advancements and their impacts in resource extraction

Technology	Impact / Advancement	Improvement (%) / Key Feature
Adaptive "Smart" Materials	Increased extraction efficiency	Significant leap forward
Quantum Computing	Accelerated materials discovery	100x faster than classical methods
Engineered Microorganisms	Overcoming extraction in hostile environments	30% increase in copper extraction
AI & Machine Learning	Predictive maintenance and process optimization	95% accuracy in failure prediction
AI in Mining	Reduced downtime	40%

Looking ahead, the vision of “zero-waste mining” offers a powerful framework aligned with circular economy principles. In this model, all waste generated during extraction is converted into valuable by-products, minimizing environmental impact and resource loss.

In conclusion, while the integration of advanced materials, quantum computing, biotechnology, and AI presents transformative opportunities for resource value chains, realizing their full potential will require addressing critical gaps in environmental sustainability, economic viability, and social equity. Future research should prioritize interdisciplinary collaboration, scalable solutions, and systemic innovation to ensure that these advancements contribute meaningfully to global sustainability and resource security.

CONCLUSION AND SUGGESTION

This comprehensive review has synthesized the current state of research and emerging technologies in advanced materials, extractive metallurgy, and digital innovation to optimize mineral and energy resource value chains. Key breakthroughs in nanostructured materials, high-performance membranes, and novel catalysts have demonstrated substantial improvements in extraction efficiency and selectivity. Furthermore, bio-inspired leaching and sustainable processing techniques have contributed to lowering energy consumption and reducing environmental impact. The integration of AI-driven process optimization and multifunctional materials has enhanced process control and efficiency. However, the industrial adoption of these technologies remains limited due to high capital investment requirements, scalability barriers, and regulatory constraints.

Despite their promising potential, the large-scale implementation of these technologies faces multiple challenges. Direct Lithium Extraction (DLE) and bio-inspired leaching provide sustainable alternatives to traditional extraction methods, but further optimization is necessary to improve operational efficiency and cost-effectiveness. Circular economy strategies—such as waste valorization and the use of recyclable materials—are critical for long-term resource sustainability. Yet, variations in feedstock composition and inconsistent regulatory frameworks hinder broader adoption. The integration of digital tools and AI into extractive metallurgy requires considerable infrastructure investment and strong interdisciplinary collaboration. High capital expenditure and uncertain return on investment (ROI) continue to deter the adoption of advanced processing techniques like High-Pressure Grinding Rolls (HPGR) and flash smelting, which also require costly retrofitting. In addition, policy gaps in critical mineral sourcing regulations exacerbate these barriers and limit the implementation of sustainable extraction and processing technologies.

To address these challenges, future research should prioritize the refinement of Life Cycle Assessments (LCAs) by incorporating economic and social dimensions alongside environmental metrics, thereby enabling a more comprehensive evaluation of technological impacts. Advancing process integration through AI-enabled optimization, digitalization, and enhanced supply chain coordination could significantly reduce material losses and energy consumption. Expanding interdisciplinary approaches—such as AI-assisted bioleaching for targeted metal recovery and material innovations for fully recyclable industrial products—could provide novel solutions to existing inefficiencies. Moreover, the development of supportive policy frameworks, including Extended Producer Responsibility (EPR) programs and harmonized critical mineral sourcing standards, is essential for facilitating industry-wide transitions.

While this review highlights the transformative potential of advanced materials and extractive metallurgy, it also emphasizes the pressing need for sustained research, cross-sector collaboration, and targeted policy intervention. Achieving a truly sustainable and efficient resource value chain will require a holistic strategy that integrates technological innovation, regulatory alignment, and industry engagement. Future progress must address not only technical feasibility but also ensure economic viability and environmental accountability. Through such integrated and systemic efforts, the full benefits of these innovations can be realized, paving the way for a more resilient and sustainable future in mineral and energy resource management.

ACKNOWLEDGEMENT

We would like to express our sincere gratitude to our families for their patience and encouragement during the course of this study.

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