http://journal.uir.ac.id/index.php/JGEET

E-ISSN : 2541-5794
P-ISSN : 2503-216X

Journal of Geoscience,
Engineering, Environment, and Technology
Vol 9 No 4 2024

REVIEW ARTICLE

Systematic Literature Review about Mineral Resources and Geotechnics Management: Generate Research Trends

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Received: Jul 10, 2024; Accepted: Dec 13, 2024.
DOI: 10.25299/jgeet.2024.9.04.17512

Abstract

The majority of developing nations' mining industries are linked to high waste rates, poor use of resources, and serious ecological and environmental issues. Finding effective ways to use recyclable and clean natural resources through scientific and technological innovation is a key goal for these nations. The goal of this study is to offer a thorough overview of the most significant developments in mineral resource research during the past few decades, along with recommendations for more research. Through the use of a Systematic Literature Review (SLR), this study methodology yields the key conclusion that, in order to minimize risk, stakeholders must appropriately manage mineral resources, which is a necessary basis for social and economic growth. Sustainability and the mining industry are linked by current research trends.

Keywords: Mineral Resource Management, Mineral Resource, Research Trend, Mining Industry, Systematic Literature Review

1. Introduction

Raw materials and mineral resources are the cornerstones of humanity's contemporary life and progress. The principle is particularly demonstrated by the various ways that various raw resources are employed in each nation's economic complex (Sekerin, 2019). Using X-ray diffraction (XRD), the mineral composition of the weathered IBA samples was examined. Blanc et al. (2018), Gori et al. (2011), and Lin et al. (2015) claim that the measurements were taken at angles ranging from 10 to 80°, with a step width of 0.02°. The scanning speed was 4° per minute. According to the study, the main minerals found in the IBA include anhydrite, magnetite, and quartz. The previously published study backs up these findings.

The relationship between economics and geotechnics lies in the crucial role of ensuring the stability and sustainability of infrastructure, which supports economic activities. Effective geotechnical practices enhance infrastructure stability, reduce long-term maintenance costs, and manage risks such as landslides and earthquakes. By utilizing local materials and promoting sustainable approaches, geotechnics conserves natural resources and lowers project expenses. Furthermore, comprehensive geotechnical research informs public policy and planning, supporting long-term economic growth. Overall, geotechnics contributes to economic stability and growth by ensuring that foundational infrastructure is robust, cost-effective, and resilient (Armstrong et al., 2024)

Mineral resources play an important role in economic security, as they provide the basic materials necessary for various industries and infrastructure. The sustainable availability and accessibility of mineral resources can support economic stability, encourage industrial growth, and create jobs. In this context, research by Bansal et al. (2023) focused on the reuse of IBA as a substitute for natural materials in construction, which not only saves mineral resources but also reduces project costs significantly. By reducing dependence on conventional mineral resources and utilizing alternatives such as IBA, we can reduce pressure on limited mineral reserves. This not only supports environmental sustainability but also strengthens economic security through resource diversification. Prudent and innovative management of mineral resources, as suggested in this research, is key to ensuring long-term economic sustainability and mitigating risks related to market fluctuations and resource scarcity.

In December 2019, the European Commission introduced the European Green Deal, a new growth strategy designed for the benefit of the Union's population. The primary goal of the European Green Deal is to transform the EU into a fair and prosperous society with a modern, resource-efficient, and competitive economy. The European Commission aims to reduce the Union's net greenhouse gas emissions to zero by 2050. Given that the European Green Deal emphasizes economic growth independent of resource consumption, special focus is placed on the management of mineral resources (European Commission, 2019).

The European Commission (EC) asserts that the entire industrial sector and its value chains will need to be restructured over the next 25 years, necessitating crucial decisions and plans within the next five years. In March 2020, the EC launched a new Circular Economy (CE) Action Plan to foster a greener and more competitive Europe. The EU is currently transitioning to a CE, as outlined in the European Commission's 2014 communication on the subject. The EC has consistently issued follow-up CE directives, including the 2015 CE Action Plan (European Commission, 2015), the 2018 CE monitoring framework (European Commission, 2018), and the 2019 report on the implementation of the initial CE Action Plan (European Commission, 2019). The CE advocates for a circular economy where waste is converted into valuable resources, replacing the traditional linear "take-make-dispose" model (Smol et al., 2015). It emphasizes the efficient use of mineral resources (raw materials, or RMs), along with their recycling and recovery from various waste streams. The European Community stresses the importance of monitoring changes in each member state's mineral resource management policies and their subsequent impacts.

2. Formulation Of The Problem

Decreased availability of resources for economic activities, climate change, and increased environmental pollution due to human activities contribute to the loss of biodiversity. This pushes societies towards inequality, increases social conflict due to limited access to the main resources of life (such as minerals, energy, and land), and influences the path of world economic development (Koval et al., 2021). Global economic regeneration has encountered difficulties as a result of classical economic relations, which prioritize financial profit accumulation over long-term, sustainable economic growth. Economic entities' irresponsible use of resources causes industrial waste to build up and harm the ecosystem, ultimately depleting natural resources (Akimova et al., 2020). Businesses must navigate these challenges by shifting from traditional practices to more sustainable ones. This often involves significant investments in environmental risk mitigation and waste reduction strategies, which, while costly, can lead to long-term benefits for society and the environment. By embracing these changes, companies can not only help preserve natural resources but also contribute to a more sustainable and equitable economic model, aligning their operations with global sustainability goals and fostering resilience against future environmental and economic disruptions.

The EC intends to put into practice tangible initiatives in a number of industries, including construction, that have the highest resource consumption and the greatest potential for circularity. Regarding this industry, the EC aims to introduce a new Strategy for the Sustainability of the Built Environment (EC 2020).

In the wake of these EC activities, politicians and governmental figures, the media, technologists, and researchers have become accustomed to emphasizing how important it is to make the shift from a linear economy model to a circular economy and implement this change throughout various economic sectors. But improvement in the building sector is still slow, meaning there is still a long way to go. The circular economy in the engineering, architecture, and building industries goes beyond just recovering and reusing construction and demolition (C&D) waste, as is vital to realize. Promoting resource recovery, preserving their presence in the economy for as long as feasible, and reducing the consumption of new materials and energy are all necessary for implementing a circular economy approach in these domains.

The Action Plan and the most recent advancements, scientific and technical research, and outreach programs related to the circular economy in the built environment place a strong emphasis on buildings and construction materials. Notwithstanding this emphasis, geotechnical engineering has the capacity to greatly improve the building sector's sustainability. Thus, the possible contributions of geotechnics to sustainable development and the circular economy are examined in this study. It is crucial to remember that this is merely the author's viewpoint on the matter and is not a comprehensive examination. SDGs of 2030 are the foundation of the circular economy; therefore, the targets where geotechnics may make the most difference are highlighted. A basic explanation of the circular economy is provided, along with an explanation of how it applies to the construction sector. Lastly, potential contributions of geotechnical engineering to sustainability and the circular economy are discussed.

Mineral resources are a vital source of raw materials for social and economic advancement. In the upcoming decades, the demand for natural resources is expected to expand rapidly as global industrialization continues, particularly in developing countries. For example, soil stabilization using chemical agents such as Portland cement, which has a high calcium oxide content, is one vital application in construction, enabling the construction of stronger and longer-lasting infrastructure. Additionally, more environmentally friendly alternatives such as wood ash also show great potential in sustainable construction, reducing environmental impacts and promoting greener building practices (Blayi et al., 2024). Therefore, effective management and utilization of mineral resources is essential to support sustainable infrastructure development and encourage sustainable economic growth, while ensuring that the social and economic benefits of these resources can be felt by the wider community in the future. With global demand for these resources increasing, it is important for governments and industry to collaborate in developing new technologies and better management practices to meet demand while protecting the environment and supporting social well-being. Thus, the international community's primary concern now is meeting the demand for essential resources for sustainable development on a global scale. Numerous western nations have initiated extensive investigations into the effective utilization of sustainable energy and the repurposing of mineral resources. With regard to ecological environments, processing machinery, integrated innovation in technical applications, and the relationship between product quality performance and high-end manufacturing, they have specifically reinforced basic research and improved initial innovation skills.

Information technology and artificial intelligence (AI) are also influencing and linked to the development and use of mineral resources. It is commonly known that useful mineral substances (s.m.u.) are essential to the growth and maintenance of contemporary national economies, especially in the high-tech industry. The wise and sustainable use of resources is required to achieve sustainable economic growth (Arens & Offenberg, 2021). The ongoing demographic surge, exacerbated by the consumption patterns of the middle-class, has resulted in a divergence between resource demand and supply. This surge in consumption, fueled by technological advancements and global population growth, has coincided with the urbanization process and an escalating standard of living, thereby shortening product lifecycles. Despite this, there is a simultaneous increase in product usage and consumption of raw materials, exemplified by the projected tripling of global demand for copper and iron by 2050 (Iliaş et al., 2017). However, such intensive exploitation of resources is expected to deplete accessible mineral reserves, necessitating the exploration of extreme conditions for extraction. As conventional technologies face limitations in accessing s.m.u.-rich regions of the Earth's crust, alternative extraction methods such as micronization, dissolution, liquefaction, gasification, and even exploration of outer space and magma become increasingly viable options.

On the other hand, the majority of developing nations' mining industries are linked to high waste rates, ineffective resource use, and serious ecological and environmental issues. Finding effective ways to employ recyclable and clean mineral resources through scientific and technological innovation is a priority for these countries (Zhai et al., 2021). One of the most vital natural resources for maintaining the Indonesian economy is its mineral wealth. Globally speaking, minerals are strategically important in defining the political landscape of the globe. In the meantime, minerals—such as the valuable metal gold—also play a significant role in the global economy (Hidayat, 2019).

3. Theoritical Review

Metals and non-metals such as iron ore, copper, nickel, bauxite, chromium, tin, titanium, silica, lime, zeolite, bentonite, gold, platinum group metals, rare earth metals, coal, and radioactive elements are all included in mineral resources (Hidayat, 2019). As of the end of 2018, the Russian Federation's Mineral Resources Strategy through 2035 is a critical procedure for planning future improvements in the mining and geological exploration sectors. Furthermore, there is no pressing need to harvest proven, high-quality mineral reserves from a location if they exist. The development of deeper conversion methods for mining wastes is a significant technological advancement in the mining industry. Reducing trash that cannot be recycled, expanding the variety of by-products, and avoiding waste dangers should be the cornerstones of my waste management philosophy. The mining industry's technological advancement trends up to 2025–2030 should be considered when developing mineral resources.

4. Research Method

This study used the systematic literature review process, with data sourced from Scopus-indexed journals. Google Scholar and the Scopus website were utilized to collect information. The research data is compiled from journals that focus on research trends and mineral resource management. A systematic literature review (SLR) is the process of gathering, analyzing, and interpreting all available research data to answer specific research questions (Kitchenham et al., 2007). According to Latifah and Ritonga (2020), this research with the Systematic Literature Review (SLR) proceeded through three stages: planning, implementing, and reporting on the literature review. The first stage involves determining the prerequisites for a systematic review. Then, a systematic review of mineral resource management and future research trends is identified and reviewed. In order to minimize the potential for researcher bias, the review process was created to provide guidance for doing the review. The second step includes research ideas, search strategies, study selection with inclusion and exclusion criteria, quality evaluation, and, finally, data extraction and synthesis. Reporting based on the first and second stages' literature is the third step, which is followed by a conclusion.

5. Result And Discussion

5.1 Mineral Resource Management

A mineral resource is defined as "a concentration of naturally occurring material in or on the Earth's crust in a form and quantity that makes economic extraction of a commodity feasible now or potentially in the future" (USGS, 2018a). Because of the expanding global population and per capita GDP over the last century, mineral resource exploitation has expanded exponentially at a rate of 2–6% each year (USGS, 2017a). The ratio of eventually extractable resources to expected annual extraction rates determines how rapidly a mineral resource is depleted. Despite their abundance, the bulk of elements in the Earth's crust cannot be extracted profitably.

A substance is only considered a mineral resource if its accessibility and concentration allow for both environmentally and commercially viable exploitation. This cutoff point is arbitrary. Lower concentrations have gradually been mined in farther-flung places and at deeper depths. Customers are willing to pay extra for lower concentrations and deeper mining activities. For instance, compared to iron, gold is mined in fewer accessible locations and at considerably lower concentrations. Although it is unrealistic, minerals can be extracted from the Earth's crust in minute quantities. The energy required to extract copper, for example, surpasses the quantity of copper produced, extraction ceases to be economically feasible. Due to economic factors as well as the environmental and climatic effects of extraction—which include high energy needs, massive waste output, and substantial water consumption—this limit is actually reached sooner rather than later. In the end, a mineral resource's extractability is limited more by social, environmental, climatic, and economic variables than by its sheer availability. See Mudd et al.'s publications (2007, 2008, 2009, 2010, 2017a, 2017b) for more information.

Metals and minerals have long served as the cornerstones for the advancement of civilization. In addition to reflecting population growth, economic expansion, and technological advancements, increased demand for metals will place extra strain on ecosystems, water resources, and land use (Wellmer FW and Becker-Platen, 2002). Regarding climate change, metal extraction and processing accounted for 10% of global greenhouse gas emissions in 2018 (UNEP, 2019). The scientific literature and civil society testimonies have clearly demonstrated the negative socioeconomic consequences of poorly managed mining operations (Joyce et al., 2018; Mancini and Sala, 2018; Mines and Communities, 2021; Human Rights Watch, 2021).

According to the previously mentioned concept of social and environmental risk, Over the last decade, the minerals and metals industry, as well as downstream manufacturing industries, have had to fulfill increased client, investor, and business partner expectations for ethical supply chain procedures. The extractive industry is under intense public pressure since it has the highest risk score of any economic sector, with nearly equal shares of environmental and social concerns. (S&P Global, 2019)

Thanks to the application of metallogenic theory and appropriate funding for geological exploration, China has achieved significant strides in the past ten years in its quest for ferrous, nonferrous, precious, rare earth, and radioactive metals (Chang et al., 2019). There are more than 1,000 tons of newly discovered gold reserves, comprising multiple large to medium-sized deposits and two giants.

The local community that lives close to the mine is a cause for concern because it reflects closely related social, socioeconomic, and environmental factors; the latter may be catalysts for conflict between the mining industry and the community, for instance if there are hazards or negative effects on the quantity and quality of water (Mancini & Sala, 2018). In response to this sustainability challenge, a wider range of indirect stakeholders from downstream in the mineral value chain are expected to participate. These parties have varying degrees of involvement in third-party assurance, supply chain due diligence, supplier risk assessment, reporting, and CSR initiatives. This pattern is a result of industry self-regulation throughout the supply chain in addition to pressure from investors, society, and the government.

Global laws, industry-sponsored voluntary programs, and multi-stakeholder campaigns that tackle social and environmental hazards across sectors and in the mining and minerals supply chain are becoming more and more significant. The global minimum standard for mining supply chains now incorporates human rights due diligence rules that apply to both large-scale industrial mining and ASM operations. Building on the basic concept of due diligence, policy measures and non-profit organizations are now widening their reach to embrace a wider range of mineral commodities, as well as new topics such as the consequences of climate change and product recycling rates. This makes it especially important to reflect on past implementation experiences and identify lessons learned for future relevant project, policy, and law design and execution. The development of standards, risk assessment, and reporting have been the foundations of various projects in the mining industry and throughout the mineral supply chain. The sector has made substantial progress in implementation, but site-specific data on sustainability performance and impact is scarce in public business reporting, and current social and environmental risk assessments may be insufficient. However, strong risk management priorities might not sufficiently address long-term development goals and local concerns, which would undermine the social approval of mining operations (Franken & Schütte, 2022).

According to Bringezu et al. (2016), the International Centre of Competence for Mineral Resources Management's primary responsibilities include updating global extractable resource estimates, tracking global resource use, creating a database of global extractable resource estimates and resource use, and developing the Global Mineral Resources Management Program. The International Resource Panel for the Sustainable Use of Natural Resources, which was founded in 2005 at the UNEP and European Commission's request, may serve as the focal point of this competence center (European Commission, 2005). The Center's establishment alone won't have much of an influence until the other instruments listed below are put into practice. However, it is necessary for the Center to prioritize, develop, and create additional policy instruments and ensure their effectiveness.

Modern development policies place a high priority on managing mineral resources, both nationally (Nie´c et al., 2014) and globally (Szamałek and Galos, 2016). This is a result of the realization that, in order to maintain ongoing growth and advance, even the most resilient economies on the planet need reliable and secure access to RMs (Smakowski and Szamałek, 2016). As for the availability of mineral resources, individual countries' economies currently depend more or less on outside sources; this dependency usually increases as economic technology advances (European Commission, 2011). The guarantee of RM security is especially important for European countries since their raw material supply is restricted and they have to import raw materials from countries with different degrees of political and economic stability (Galos et al., 2015). In 2008, the European Commission (EC) created the Raw Materials Initiative (RMI) to address the issue of member states' access to raw materials, emphasizing the importance of responsible natural resource management for the EU economy as well as the necessity to assure supply. The EC's first statement in the text emphasizes how important raw materials are to the long-term viability of modern society. According to the principles of sustainable development, research into novel mining methods, material substitution, resource efficiency, and the provision of secondary RMs via recycling are all critical to the long-term well-being of current and future generations. Recycling materials (RM) are a valuable resource (European Commission, 2018). In 2011, the European Commission announced the Roadmap to a Resource-Efficient Europe, which established a precise framework for future efforts.

The European vision that "raw materials are a major European strength" highlights the vital importance of mineral resources in stimulating economic growth and promoting innovation. This vision is defined by three strategic objectives: ensuring a stable supply of raw materials, developing innovative solutions, and closing material cycles. To achieve these goals, the European Commission established the European Institute of Innovation and Technology on Raw Materials (EIT Raw Materials) in 2014. This institute has since become the world's largest raw materials consortium, with over 120 core and associate partners and 180 project partners. These partners represent the entire knowledge triangle (business, universities, and research units) and include members from more than 20 European and non-European countries.

5.2 Research Trends in Mineral Resources Management

Sekerin et al. (2019) identified key trends in the global mining industry, highlighting several essential developments: 1) creating innovative technologies to predict and assess mineral and raw material potential, thereby reducing time and costs in the geological survey process; 2) developing advanced, efficient technologies for processing medium- and low-grade iron ore and technogenic raw materials; 3) implementing closed, waste-free systems for mineral processing to produce final products; and 4) introducing new technologies for mineral processing.

Gorman and Dzombak (2018) conducted a systematic literature review, using keywords such as "sustainable mining," "sustainable development AND mining," and "sustainability and mining" to search through peer-reviewed journals. Their findings revealed two main themes in sustainable mining. The first theme is centered on improving the long-term sustainability of mining activities, encompassing everything from extraction to processing. This is guided by fundamental environmental principles, established standards, and particular sustainability metrics acknowledged by mining corporations, industry groups, and regulatory authorities. The second theme highlights the life cycle of mined minerals and their circularity, focusing on the extent to which resources are reclaimed from their end-of-life stage and reintroduced into the usage phase within the circular economy.

Mining and sustainability efforts bridge the gap between international standards and national regulations. These initiatives, often seen as a form of industry self-regulation involving multiple stakeholders, address current and anticipated market and regulatory demands for mining and mineral supply chain standards. Numerous projects within the mining industry and across the mineral supply chain have concentrated on creating standards, managing risks, and improving reporting practices. Despite notable progress in implementation, current social and environmental risk assessments might fall short, and public business reports often lack detailed, site-specific data on sustainability performance and impact. Additionally, even robust risk management strategies may not adequately address local issues and long-term development objectives, which can undermine public support for mining operations (Franken & Schütte, 2022).

Zhai et al. (2021) emphasize that present investigations in this domain prioritize the initiation of impactful initiatives and distinctive studies spearheaded by individual researchers. These endeavors strive to foster innovation across diverse realms, such as ore genesis and exploration theory, technological advancements in exploration, ore processing and metallurgy, as well as fundamental theories concerning resource substitution and recycling. This strategy tackles the significant need for mineral resources, while also streamlining the quest for and utilization of these resources, fostering ecological rehabilitation and environmental preservation, and propelling the advancement of mineral resource disciplines.

Trends in mineral resource management reflect a paradox: while the need for mineral resources continues to increase, their management tends towards unrestricted exploitation by businesses, Frequently, these activities result in adverse effects on both deposits and nearby communities. The ongoing depletion of readily accessible mineral reserves stems not solely from escalating demand but also from profit-driven behaviors and inadequate public resource management strategies prevalent in numerous nations. The significance of primary geological data supplied by mining entities is often underestimated, contributing to inaccurate assessments of potential mineral deposits. Lack of understanding of the geological characteristics of an area can result in inaccurate delineation of exploitation area boundaries, rental payments that do not correspond to actual values, and inefficient resource management. However, improving mineral resource management requires collaboration between government and business to be able to conduct objective evaluations of the qualitative and quantitative characteristics of deposits. This makes it possible to establish appropriate boundaries for exploitation areas, determine fair rents, wisely manage natural resource reserves, and minimize environmental impacts. Federal and regional governments, as well as financial and investment organizations, are placing a greater emphasis on the dependability and validity of geological data in decision-making processes. This trend improves the quantity of money for mineral projects, but it also increases investment risks, thereby demanding independent and professional geo-economic evaluations to reduce uncertainty (Litvinenko et al., 2023).

Overall, trends in mineral resource management emphasize the importance of encouraging cooperation between various parties, including governments, businesses, and financial institutions, to achieve more effective, equitable, and sustainable management of mineral resources.

Artificial intelligence (AI) and information technology are also being investigated concerning the advancement and utilization of mineral resources. Critical scientific and technological hurdles in this domain encompass the examination of ore-forming elements on Earth, with a focus on understanding the correlation between mineralization and the diversity of continental constituents, as well as the interactions among the core, mantle, and crust, alongside major geological phenomena. Furthermore, there is interest in comprehending the mechanisms underpinning the aggregation of exceptionally high concentrations of ore-forming components. Efforts in mineral deposit exploration and prospecting models and technologies predominantly revolve around developing ore formation models, refining geophysical and geochemical exploration methodologies, and integrating big data-driven AI for comprehensive prospecting. Additionally, there is a pressing need for theories and techniques facilitating the efficient recycling and sustainable utilization of mineral resources, with specific attention directed towards waste-minimization strategies in mining and metallurgy, environmentally benign metallurgical agents, advanced methodologies for prospecting complex low-grade multimetal deposits, and approaches for repurposing industrial waste streams (Zhai et al., 2022).

Information technologies like artificial intelligence (AI), big data, blockchain, and Internet of Things (IoT) devices have been developed and utilized globally across various technical domains (Li et al., 2023). Modern technologies such as AI, big data, and advanced digital technology (ADT) offer significant potential for managing mineral resources. Artificial intelligence allows us to estimate mineral production, handle market demand more efficiently, detect leaks or theft, and plan maintenance and repair of mining facilities. Big data allows us to organize and analyze data from many sources, allowing us to forecast mineral reserves, market demand, and price trends while optimizing mining operations through the analysis of production and energy usage data. Advanced digital technology also plays an essential role in easing the integration of data from diverse sources and promoting the development of integrated management information systems to better monitor and control mining operations. Mineral resource management may become more efficient, responsive, and sustainable by combining these three technologies, while also reducing environmental and social impacts.

6. Conclusions

This paper provides a comprehensive assessment of significant advancements in mineral resource research over recent decades, along with recommendations. Through an in-depth analysis of literature from various sources, this study underscores the crucial role played by mineral resource management in fostering economic and social progress. With the ongoing surge in global industrialization, particularly noticeable in developing areas, it is expected that the global demand for mineral resources will experience rapid growth in the coming decades. Therefore, effective management of mineral resources is essential to mitigate existing risks. The Social Responsibility (ISO 2010) framework presents a normative structure that addresses this necessity by outlining responsibilities across seven key domains of sustainability challenges.

Acknowledgements

We like to thank Lembaga Penelitian dan Pengabdian Kepada Masyarakat dan Inovasi, Institut Teknologi Nasional Yogyakarta.

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