M|T|J MINING TECHNOLOGY JOURNAL

E-ISSN: 2460 - 8386

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MINING TECHNOLOGY JOURNAL

E-ISSN: 2460 - 8386
http://jurnal.upnyk.ac.id/index.php/mtj

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Mining Technology Journal
Vol.(2), No.(2), 2024
E-ISSN: 2460 - 8386
http://jurnal.upnyk.ac.id/index.php/mtj

Phytoremediation Methods for Managing Lead (Pb) Contaminated Soil: A Literature Review

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ARTICLE INFO

Keywords:
phytoremediation, Pb, Plants.

ABSTRACT

In addressing the issue of heavy metal contamination, current reviews mainly focus on remediation through plants. Phytoremediation, a promising technology involving the use of plants to absorb heavy metals from the soil and eliminate contaminants by harvesting the plant parts above ground, has garnered significant attention due to its cost-effectiveness and environmental friendliness. The objective of this research, based on a literature review, is to determine whether there is a reduction in lead (Pb) concentration in the soil using phytoremediation methods and to assess the efficiency of plants in absorbing lead (Pb) from the soil. Based on the review of 5 plants from previous studies, some plants have shown significant and efficient effects in assisting the absorption of lead (Pb) content in the soil. Calotropis gigantea (95.88%) and Sphenoclea zeylanica Gaertn (92.43%) are identified as suitable plants for applying the phytoremediation method due to their fast absorption processes, ease of application, and availability

INTRODUCTION

The concentration of lead (Pb) in soil has nearly tripled due to human activities such as mining, smelting, manufacturing, waste disposal, and the increasing urbanization and industrialization. Pb primarily accumulates in the topsoil (Kumar et al., 2022). The resulting soil Pb pollution poses significant risks to human health, agricultural product safety, and the environment. Conventional remediation techniques for addressing Pb contamination in soil, such as excavation, electrokinetic remediation, soil leaching, and stabilization, can be costly or ineffective, making them unsuitable for large-scale applications (Rehman et al., 2023).

Lead (Pb), a common contaminant, can have negative impacts on both the environment and human health (García-Delgado et al., 2015b; Rigas et al., 2009; Sehube et al., 2017). Due to the challenges posed by the simultaneous presence of chemicals with disparate properties, this type of contamination, often

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referred to as mixed contamination, frequently hinders remediation efforts (Cameselle and Gouveia, 2019; Polti et al., 2014). Anthropogenic activities, such as mining, increase the bioavailability of lead (Pb) and human exposure to it. Pb is naturally found in various geological processes, including hydrothermal vents, volcanic activity, atmospheric convection, and river erosion (Zhang et al., 2023). Mining, smelting, production and reuse processes, oil refineries, paints, pigments, electroplating, finishing, glassmaking, ceramics, the steel industry, coal, and power generation are just a few of the industries that release lead into the environment (Sevak et al., 2021; von Voithenberg et al., 2019). Pb contamination of the environment is a serious issue, and it is important to note that Pb waste does not only come from these industries. Pb-containing paints and lead-acid batteries used in the automotive sector also contribute to environmental pollution.

The remediation of contamination through plants is the primary focus of current research aimed at addressing the issue of heavy metal contamination. Phytoremediation, a promising method that uses plants to remove pollutants and absorb heavy metals from the soil by harvesting aboveground plant parts, has garnered significant attention due to its affordability and environmental friendliness (Dou et al., 2022). This method is appealing for controlling soil contamination because it not only utilizes natural plant processes but also contributes to environmental detoxification. However, the use of this technique is limited by factors such as the low bioavailability of lead in soil and the lack of Pb hyperaccumulator species (Shen et al., 2022; Egendorf et al., 2020). Therefore, selecting non-hyperaccumulator plants and implementing appropriate support measures could be a potential way to enhance the effectiveness of phytoremediation.

Hyperaccumulators are currently regarded as the optimal plants for phytoremediation; however, species classified as hyperaccumulators are limited in number and exhibit certain limitations, including reduced biomass and slow growth rates. As a result, researchers worldwide are exploring novel plant species suitable for the remediation of heavy metals through phytoremediation (Guo et al., 2018; Mahar et al., 2016; Cao et al., 2019; Willscher et al., 2017). Aquatic plants are an integral component of a complex ecosystem, capable of functioning as hyperaccumulators of heavy metals, thereby facilitating the remediation of heavy metal contaminants along with various other pollutants through the process of phytoremediation (Ali et al., 2020). Methodologies that employ plants to mitigate metallic concentrations rely on the absorption of these contaminants through the root systems, foliar structures, and aerial shoots of the plants. Aquatic plants play a crucial role in an intricate ecological framework, with the potential to serve as hyperaccumulators of heavy metals, thus aiding in the elimination of these contaminants as well as other pollutants through phytoremediation (Hu et al., 2015). The careful selection of appropriate plant species is the most critical factor for the successful implementation of phytoremediation strategies (Bali and Sidhu, 2021; Zhu et al., 2018).

METHODOLOGY

The procedure of this study begins with a comprehensive literature review on the types of plants that are effective in absorbing lead (Pb) through phytoremediation methods, with a focus on analyzing the characteristics of plants that have been proven in previous studies. Following this, an assessment of plant effectiveness is conducted based on criteria such as lead reduction efficiency, the time required for the phytoremediation process, and the sustainability of plant growth despite exposure to lead contamination. Based on the results of these studies and comparisons, researchers will draw conclusions about the most suitable plants to be used for lead removal in soil.

The stages of the research conducted are shown in **Figure 1.** below. This study is based on a literature review summarized from several scientific papers, both from national and international journals. A literature review is the process of in-depth analysis and evaluation of similar research conducted previously (Shuttleworth, 2009). The purpose of this research is to serve as a reference in examining the types of plants that are efficient in absorbing lead (Pb) from the soil using the phytoremediation method. The phases of the research conducted are as follows:

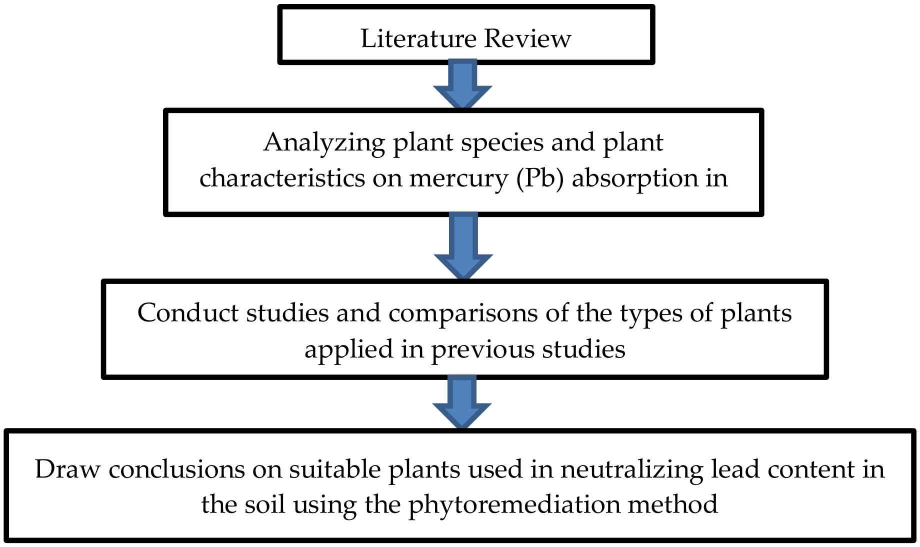

Figure 1. Research Stages

RESULT

Research has explained the need for plants in eliminating soil contaminated with heavy metal substances. Lead (Pb) is one of the heavy metal pollutants and is a naturally occurring element that frequently contaminates the environment and is highly toxic. Efforts to remove lead from contaminated soil have been conducted in various locations using the phytoremediation technique. Phytoremediation is one of the bioremediation methods that can be used as an alternative solution for the heavy metal remediation process. Phytoremediation is a practical, efficient, and environmentally friendly green technology that involves the use of metal-accumulating plants to remove toxic metals, including radionuclides and organic contaminants, from polluted soil and water (Raskin et al., 1997). Plants play a crucial role in eliminating contaminants from the environment, achieving their detoxification effect. Three main phytoremediation processes can be identified based on the different properties of the plants: phytoaccumulation, phytostabilization, and phytovolatilization (Marques et al., 2009). The following plants can be used to remove lead content from soil, based on previous research, among others:

Table 1. Phytoremediation Plant Species

Researcher Name	**Plant Type**	**Absorption Time (Day)**	**Treatment**	**Decrease in Lead Level**
Rony Irawanto , Anjar Aris Munandar	*Ceratophyllum demersum*	14	83 gr	85,1%
L. Indah Murwani Yulianti	*Calotropis gigantean*	28	700 mg/l	95,88%
Rhenny Ratnawati , Risna Dwi Fatmasari	*Sansevieria trifasciata*	30	200 mg	81,08%
Juhriah, Nur Fadila, Mutmainnah dan Dian Islamiah	*Zinnia elegans (Jacq.) Kuntze*	84	100 gr	50%
Ninik Triayu Susparini , Fathur Rohman , Heny Hindriani	*Sphenoclea zeylanica Gaertn*	6	150 gr	92,43%

The research presented in this table examines the effectiveness of several plant species in reducing lead (Pb) levels from contaminated media. Each plant has different uptake times as well as varying treatment dosages, which affect their efficiency in absorbing lead.

The plant successfully reduced lead levels by 85.1% within 14 days with 83 grams of treatment. The effectiveness was quite high, which shows that aquatic plants such as Ceratophyllum demersum can be a good choice for lead remediation in aquatic environments. Although the reduction in lead levels did not reach 100%, this result was very significant in a relatively short time.

With a sorption time of 28 days and 700 mg/l treatment, Calotropis gigantea showed a very high lead reduction of 95.88%. This plant has a remarkable ability to absorb lead, making it a potential candidate for use in bioremediation of heavy metal-contaminated soil. Its advantage is its ability to survive in less than ideal environmental conditions, such as dry and nutrient-poor soils.

Sansevieria trifasciata, also known as tongue-in-law, successfully reduced lead levels by 81.08% after 30 days with 200 mg treatment. Although the lead reduction was not as great as the other plants in this study, Sansevieria trifasciata has other advantages such as ease of maintenance and the ability to survive in water shortage and poor soil conditions. Therefore, it also has the potential to be used in more extreme conditions.

The reduction in lead levels recorded in Zinnia elegans was 50% after 84 days with 100 grams of treatment. Although this reduction rate is lower than the other plants, Zinnia elegans shows that flowering plants can also have potential in remediation, although the results are slower and less efficient. The long time (84 days) may have contributed to the non-optimal lead reduction.

In this study, Sphenoclea zeylanica showed an excellent lead reduction ability of 92.43% in just 6 days with 150 grams of treatment. The high rate of lead reduction made this plant one of the most effective in this study. This shows the potential of this plant in rapid remediation of heavily polluted environments in a short time.

Overall, the main recommendation is to select plant species that best suit the specific environmental conditions and the level of lead contamination in the area. Plants with fast and efficient lead reduction, such as Sphenoclea zeylanica and Calotropis gigantea, are more suitable for remediation in heavily contaminated areas, while plants that are more resistant to extreme conditions, such as Sansevieria trifasciata, can be used in areas with limited resources. Ceratophyllum demersum is excellent for aquatic environments, and Zinnia elegans can be selected for long-term remediation projects in combination with other plants.

The following is a table of the advantages and disadvantages of plant species in the absorption of lead metal in the soil.

Table 2. Excess and Shortage of Plants

Type of Plant	Excess	Shortage
Ceratophyllum demersum	1. Effective in absorbing various heavy metals from soil, including lead. 2. These plants can absorb heavy metals relatively quickly, helping to reduce metal pollution in a short period of time. 3. This plant helps in the absorption of excess nutrients.	1. Limited capability compared to some other crops 2. These plants may not be able to effectively remove all types of heavy metals or other contaminants, depending on the concentration and type of pollutants.

Calotropis gigantean	1. These plants can help reduce lead concentrations in contaminated environments. 2. These plants have relatively fast growth, which can help the soil remediation process in a short time compared to some other plants. 3. The plant is drought-resistant and can grow in a wide range of soil conditions, including contaminated or infertile soils	1. Calotropis gigantea plants contain toxic compounds that can be harmful if ingested by humans or animals. This can be a problem in the context of using the plant for soil rehabilitation near residential areas 2. It may not grow well in very high humidity conditions or waterlogged soils, which may limit its application in some environments.
Sansevieria trifasciata	1. Sansevieria trifasciata is known to absorb several types of air pollutants such as formaldehyde, benzene, and trichloroethylene. While its ability to absorb heavy metals such as lead from the soil is not well known, its ability to improve air quality in enclosed spaces is a plus. 2. It can survive low lighting and drought conditions, which makes it easy to maintain in a variety of indoor environments, including spaces with potential contamination. 3. It can survive low lighting and drought conditions, which makes it easy to maintain in a variety of indoor environments, including spaces with potential contamination 4. Sansevieria trifasciata is easy to grow and maintain, requires no special care, and can grow well in a wide range of soil conditions, including poor or contaminated soil. It does not require a rich substrate to grow and can function in a wide range of soil conditions.	1. Its ability to absorb lead from the soil is not as strong as some other plants. 2. Sorption of heavy metals such as lead by Sansevieria trifasciata may be less significant
Zinnia elegans (Jacq.) Kuntze	1. It grows quickly, which means it can start absorbing heavy metals immediately after planting, providing faster results than some other crops. 2. The plant can grow in a wide range of soil conditions, including soils that may be contaminated with heavy metals, making it flexible in use	Zinnia elegans may not be as effective as some hyperaccumulator plants in absorbing heavy metals. Its ability to lower lead concentrations in soil may not be as strong as plants specifically designed for soil remediation.
Sphenoclea zeylanica Gaertn	1. Sphenoclea zeylanica has the ability to absorb heavy metals from the soil. 2. This plant has relatively fast growth. 3. Sphenoclea zeylanica can grow in a variety of soil conditions, including soils that may be contaminated with heavy metals.	1. Although Sphenoclea zeylanica can absorb heavy metals, its ability may not be as strong as some other hyperaccumulator plants. 2. This plant requires wet or humid conditions to grow well. In a dry or less humid environment, plant growth and metal uptake effectiveness may be affected.

CONCLUSION

Based on the results, the two plants with the highest lead (Pb) reduction were *Calotropis gigantea* and *Sphenoclea zeylanica*. *Calotropis gigantea* showed a 95.88% decrease in lead levels within 28 days with a 700 mg/l treatment, making it highly effective for the bioremediation of heavy metal-contaminated soil, particularly in less-than-ideal conditions such as dry and nutrient-poor soils. Meanwhile, *Sphenoclea zeylanica* demonstrated an impressive 92.43% reduction in just 6 days with a 150-gram treatment, making it an excellent choice for rapid remediation of heavily contaminated soils. Both plants were highly effective in reducing lead levels in a short period, with *Sphenoclea zeylanica* being more suitable for emergency remediation and *Calotropis gigantea* being better for more challenging soil conditions.

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M|T|J

Mining Technology Journal
Vol.(2), No.(2), 2024
E-ISSN: 2460 - 8386
http://jurnal.upnyk.ac.id/index.php/mtj

Combustion Efficiency Analysis of Lignite and Anthracite Coal in Co-firing Technology with Biomass: A Literature Review

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ARTICLE INFO

ABSTRACT

Keywords: combustion efficiency, lignite, anthracite, biomass

Coal is a non-renewable natural resource widely utilized as the main fuel for power generation, contributing approximately 80% of energy demand. However, dependence on coal presents significant challenges, such as future supply limitations, negative environmental impacts, and the need for diversification of energy sources. Co-firing technology, which involves the joint combustion of coal and biomass, is emerging as an alternative solution to improve combustion efficiency while reducing environmental impacts. This study aims to analyze the combustion efficiency of two types of coal, namely lignite and anthracite, combined with various types of biomass, such as sawdust, rice husk, wheat straw, tobacco, sawdust, and sunflower seed shells. Based on a literature review of previous studies, the analysis shows that lignite coal has higher combustion efficiency than anthracite when blended with biomass. The highest efficiency was recorded at 92% in the mixture of lignite with sunflower seed shells, supported by the reactive nature of lignite and the characteristics of biomass with high volatility and low ash content. In contrast, anthracite coal recorded its highest combustion efficiency of 85.5% when combined with sawdust biomass, attributed to the less reactive nature of anthracite and the high temperature required for complete combustion. Overall, co-firing technology has proven effective in improving combustion efficiency and utilizing biomass as a sustainable alternative fuel. The successful implementation of this technology highly depends on proper biomass selection, optimization of mixture proportions, and control of operating conditions. With a well-planned approach, co-firing can be a strategic solution to reduce greenhouse gas emissions while supporting the transition to a more efficient and environmentally friendly energy system.

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INTRODUCTION

Economic development and the growing global population have resulted in a substantial increase in the demand for electrical energy. Currently, the majority of the world's electricity is produced by burning fossil fuels, with coal being the predominant source (Zaman & Suedy, 2020). Coal is finite natural resource that is extensively used as the main fuel in thermal power plants, particularly in highly industrialized nations (Mohamed, 2024).

In Indonesia, coal plays a critical role in the electricity sector and serves as one of the main sources of state revenue. Approximately 80% of domestic coal consumption is used to meet the needs of electricity generation (Haq et al., 2022). However, reliance on coal as the primary energy source presents significant challenges, including the limited future energy supply, negative environmental impacts, and the need for energy diversification.

The combustion of coal produces greenhouse gas emissions, including carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen oxides (NO_x), all of which contribute to environmental degradation (Ding et al., 2024). To address these challenges, cofiring coal with biomass is emerging as a promising alternative. This technology not only reduces the environmental impact of coal combustion but also helps decrease greenhouse gas emissions (Nainggolan et al., 2023; Matei et al., 2010; Aufi et al., 2023). Biomass, as a renewable energy source, is abundantly available in forms such as sawdust, corn cobs, bagasse, palm empty fruit bunches, rice husks, and wheat straw (Basar et al., 2022). The types of coal analyzed in this study include lignite and anthracite. Both types of coal have distinct characteristics. Lignite is a low-rank coal with relatively low energy content but is considered more environmentally friendly due to its low sulfur content (Samudro, 2016). In contrast, anthracite is a high-rank coal with higher energy content but also higher sulfur content (Yunianto & Septiani, 2015). Based on previous relevant studies that have been conducted, the biomass used in coal blends is sunflower seed shells, sawdust, sawdust, tobacco, sawdust and wheat straw. This study aims to evaluate the combustion efficiency of previous studies based on the biomass used.

METHODOLOGY

The literature review is the process of compiling and analyzing literature relevant to the research topic. Summaries of scientific papers from national and international journals were used to conduct this research. The reason of the writing survey is to provide a comprehensive summary of existing research, which underlies the formation of theoretical and methodological frameworks in new research (Creswell, 2014). The following are the stages of the research conducted as shown in **Figure 1.**

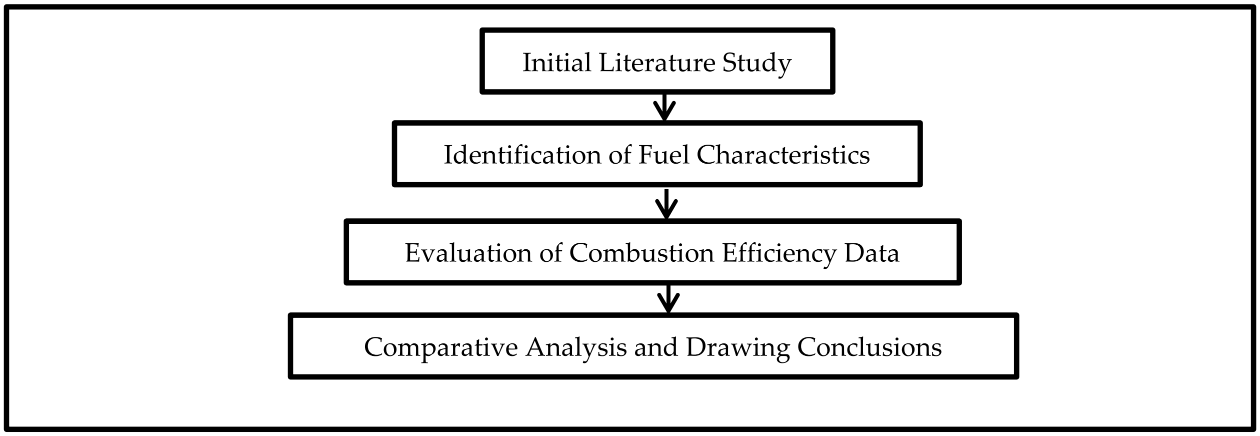

Figure 1. Research Stages

The research phase began with an initial literature study, which included collecting and analyzing literature related to co-firing technology, characteristics of lignite and anthracite coal, and various types of biomass that have been used in previous studies. The next stage is fuel identification, which is carried out by assessing the physical and chemical characteristics of coal and biomass-based on available data. This analysis includes important parameters such as heating value, ash content, volatility and combustion reactivity. Next, the combustion efficiency data was evaluated by comparing the combustion efficiency results of various types of coal and biomass through a review of previous research data, including an analysis of the factors that affect combustion efficiency. The last stage is a comparative analysis and conclusion drawing, which is carried out by analyzing the combination of coal and biomass to determine the pair that produces the highest combustion efficiency. The results of this analysis are then used to develop practical recommendations that can be applied to power plants to improve energy efficiency and reduce environmental impacts. Similar studies related to the combustion of mixtures between lignite coal and several biomasses are listed in **Table 1**.

Table 1. Similar Research on Combustion of Lignite Coal with Biomass

Research Name	Year	Research Results
Haykiri & Yaman	2009	Recommendations using the Co-firing Method Using Sunflower Seed Shells
Varol, et. al.	2010	Recommendations Using the Co-firing Method Using Wood Powder
Liu, et. al.	2023	Recommendation using the Co-firing Method Using Sawdust

Similar studies related to the combustion of anthracite coal blends with several biomasses are listed in **Table 2**.

Table 2. Similar Research on Combustion of Anthracite Coal with Biomass

Research Name	Year	Research Results
Li, et. al.	2011	Recommendation using the Co-firing Method Using Tobacco
Hao, et. al.	2018	Recommendation using the Co-firing Method Using Sawdust
Ye, et. al.	2022	Recommendations using the Co-firing Method Using Wheat Straw

RESULT

Co-firing technology has proven to be an effective solution to improve coal combustion efficiency, especially when combined with biomass. Based on previous studies, the combination of lignite and anthracite coal with various types of biomass shows mixed results in terms of combustion efficiency, depending on the nature of the fuels used. Lignite coal, which is a low rank coal with low carbon content and high moisture content, requires combustible additives such as biomass to improve combustion performance. On the other hand, anthracite coal, a high-rank coal with high carbon content but low volatility, faces challenges in achieving efficient combustion, thus requiring biomass to accelerate the oxidation reaction. The following types of lignite coal and several types of biomass used for blended combustion based on previous journals are listed in **Table 3**.

Table 3. Lignite Coal with Several Types of Biomass

Research Name	Type of Biomass	Blending Ratio (%) (Biomass:Coal)	Combustion Efficiency
Haykiri & Yaman	Sunflower Seed Shells	10:90	92%
Varol, et. al.	Wood Powder	75:25	88,1%
Liu, et. al.	Sawdust	30:70	90%

Based on research by H. Haykiri-Acma and S. Yaman in 2009, the highest combustion efficiency was achieved at 92% with a mixture composition of 10% sunflower seed shell biomass and 90% lignite coal.

This high efficiency is as result of its low ash content the biomass and the calorific value of the biomass which is close to the calorific value of lignite, thus creating an optimal synergy in the combustion process. Sunflower seed shell biomass also contains a high level of volatile matter content, which helps to accelerate the combustion process and enhance the burnout efficiency characteristics of lignite coal. In addition, using biomass in relatively small proportions can minimize operational risks, such as slagging or fouling.

Research conducted by M. Varol and colleagues in 2010 showed that the use of sawdust as biomass with a mixing ratio of 75% biomass and 25% lignite coal resulted in a combustion efficiency of 88.1%. This high biomass ratio indicates that sawdust, with its high volatile matter content and adequate fixed carbon, can support the combustion process effectively and improve overall combustion performance. Research conducted by Li Liu et al, in 2023 showed that the use of sawdust biomass with a mixture ratio of 30% biomass and 70% lignite coal resulted in a combustion efficiency of 90%. This result indicates that the use of biomass at a medium ratio can provide optimal combustion efficiency, making it suitable for practical applications in energy generation systems. Sawdust has a high volatile matter content, which contributes significantly to improving the reactivity of lignite combustion. This volatile content accelerates combustion at an early stage and improves the overall combustion characteristics. In addition, the use of a more conservative biomass ratio, such as 30%, reduces operational risks such as slagging and fouling that are often associated with using larger proportions of biomass. With a combustion efficiency that almost matches that of the sunflower seed shell blend, this sawdust biomass blend offers an ideal balance between high efficiency and operational stability. This combination provides great potential for use on an industrial scale, especially in cofiring-based combustion systems. Meanwhile, the efficiency of anthracite coal can be seen in **Table 4** below.

Table 4. Anthracite Coal with Several Types of Biomass

Research Name	Type of Biomass	Blending Ratio (%) (Biomass:Coal)	Combustion Efficiency
Li, et. al.	Tobacco	90:10	78%
Hao, et. al.	Sawdust	50:50	85,5%
Ye, et. al.	Wheat Straw	60:40	60%

Research conducted by X. G. Li et al. in 2011 showed that blending anthracite coal with biomass from tobacco waste resulted in a combustion efficiency of 78% with a blending ratio of 90% biomass and 10% coal. Although this efficiency is relatively lower than blending low-grade coal with biomass, this result reflects the challenges faced in co-firing anthracite coal which has a high carbon content, is harder to burn, and requires higher combustion temperatures. Tobacco biomass, although it has a high volatile content and can help initiate combustion, does not fully compensate for the less reactive nature of anthracite. However, this study still highlights the environmental benefits of using tobacco biomass, such as the reduction of organic waste and the potential reduction of net carbon emissions. This study shows that although the combustion efficiency in this combination is not optimal, co-firing anthracite with biomass still offers opportunities for fuel diversification and improved energy sustainability, especially if further optimization of the mixture composition and combustion operating conditions is carried out.

Research conducted by Runlong Hao et al. in 2018 using sawdust in co-firing blends with coal showed that a blending ratio of 50% biomass and 50% anthracite coal resulted in a combustion efficiency of 85.5% which is the highest efficiency among other results in this table. Sawdust, which has a high volatile and fixed carbon content, provides a significant synergistic effect with anthracite coal. This mixture shows that a balanced ratio of biomass to coal can maximize anthracite combustion by reducing ignition temperature and increasing burnout speed. This ratio also provides optimal combustion stability, making it an ideal choice for combustion systems designed for high efficiency.

Research conducted by Lian Ye et al. in 2022 showed that blending anthracite coal with wheat straw biomass resulted in a combustion efficiency of 60% at a blending ratio of 60% biomass and 40% coal. Although this is lower than the efficiency of blending biomass with lower-grade coals such as lignite, the result reflects the combustion challenges of anthracite which is less reactive due to its high carbon content and low volatile content. Wheat straw biomass, with its relatively high volatile content and low ash content, plays an important role in supporting the combustion initiation process and providing initial heat to accelerate anthracite combustion. However, the lightweight structure of wheat straw and its lower heating value compared to other biomasses limit its contribution to the overall thermal efficiency. The efficiency achieved is also affected by the difficulty of anthracite to achieve complete combustion under certain blend conditions, which require high temperatures and longer combustion times. Nonetheless, this study highlights the potential for efficiency improvement through the optimization of mixture proportions and control of operating conditions, so this combination remains an opportunity to be utilized in co-firing technologies with the goal of energy sustainability.

Overall, combustion efficiency is influenced by fuel properties, blend composition, and the thermal characteristics of the biomass used. The combination of lignite with biomass demonstrates greater potential than anthracite due to the more reactive nature of lignite. However, with further optimization, the co-firing of anthracite and biomass can be enhanced, especially for energy applications requiring high efficiency and reduced environmental impact. This co-firing technology represents a strategic step in the sustainable energy transition, leveraging existing resources while reducing dependence on pure fossil fuels.

CONCLUSION

Based on the analysis of the combustion efficiency of lignite and anthracite coal in co-firing technology with biomass, in conclusion the combustion efficiency is influenced by the characteristics of the fuel and biomass used. Lignite coal demonstrates higher combustion efficiency than anthracite when combined with biomass, with the highest efficiency reaching 92% when using sunflower seed shell biomass. In contrast, anthracite coal achieves a maximum combustion efficiency of 85.5% when combined with sawdust biomass. This difference is attributed to the less reactive nature of anthracite, which requires higher temperatures for complete combustion. Overall, co-firing technology is effective in enhancing combustion efficiency and utilizing biomass as an alternative fuel. However, its success largely is influenced by the proper selection of biomass and the optimization of operating conditions. A carefully designed strategy for co-firing can be an effective solution to enhance energy efficiency, lower greenhouse gas emissions, and support energy sustainability.

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M T J

Mining Technology Journal
Vol.(2), No.(2), 2024
E-ISSN: 2460 - 8386
http://jurnal.upnyk.ac.id/index.php/mtj

Techniques for Rare Earth Elements Recovery from Coal Fly Ash: A Comparative Analysis

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ARTICLE INFO

Keywords: Rare Earth Elements Recovery, Coal Fly Ash Utilization, Extraction Techniques, Circular Economy, Environmental risk

ABSTRACT

Rare Earth Elements (REE) are essential for high-tech and renewable energy applications; however, extracting these elements from primary sources presents significant environmental and economic challenges. Coal fly ash (CFA), a byproduct of coal combustion, offers a viable alternative as a secondary source for REE recovery due to its abundance and REE content. This approach also supports coal downstreaming efforts. This study evaluates physical, chemical, and biological techniques for recovering REE from CFA, focusing on efficiency, cost, and environmental sustainability. Physical methods such as particle sizing and magnetic separation effectively concentrate REE as a preparatory step, enhancing the efficiency of subsequent chemical processes. Chemical techniques, particularly acid and alkaline leaching, achieve recovery rates exceeding 90%, though they require careful waste management to mitigate environmental impacts. Meanwhile, biological methods like bioleaching and biosorption provide a more sustainable alternative with minimal waste, albeit with lower recovery efficiencies. An integrated approach combining these techniques demonstrates significant potential to optimize REE recovery while reducing costs and environmental risks, aligning with circular economy principles.

INTRODUCTION

Rare Earth Elements (REE) consist of 17 metallic elements, including the lanthanides, yttrium, and scandium, which are essential to a wide range of contemporary industries. These elements are essential in manufacturing high-tech devices such as smartphones, wind turbines, electric vehicles, and defense products, making them integral components of a global sustainable technology-based economy (Park and Liang, 2019). The growing importance of REE has led to a surge in global demand over the past few decades. However, the production of REE is highly concentrated in a few countries, particularly China,

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which controls over 80% of the global supply. This dependency and supply uncertainty in international markets have driven other countries to explore sustainable alternative sources to meet the increasing demand (Wang et al., 2019).

One promising alternative source of REE is coal fly ash (CFA), a byproduct of coal combustion. In Indonesia, coal downstreaming strategies have become a national priority to enhance the added value of domestic coal resources, supported by a coal production total of 296 million tons in 2020, even during the COVID-19 pandemic (Haq et al., 2021). These efforts extend beyond converting coal into energy products, exploring its potential as a raw material for high-value products like REE. Utilizing CFA as a source of REE could reduce import dependence, strengthen national supply independence, and integrate industrial waste management into the circular economy. Furthermore, developing REE recovery technologies through coal downstreaming offers opportunities for job creation, advancements in extraction technologies, and reduced environmental impacts from coal mining and combustion (Haq et al., 2022). However, challenges persist due to the variability of CFA's chemical composition and the complex distribution of REE within its mineral structures, necessitating innovative and environmentally friendly extraction methods (Sreenivas et al., 2021).

REE recovery techniques from CFA can generally be divided into three main categories: physical, chemical, and biological (Das et al., 2018). Physical approaches, such as magnetic separation, particle size reduction, and roasting, aim to concentrate REE in CFA fractions to facilitate subsequent extraction steps (Kumari et al., 2019). Chemical methods, including alkali fusion and acid leaching, are more effective at releasing REE from CFA's mineral matrix through chemical reactions, but these methods are typically more expensive and have a greater environmental impact due to high energy and chemical consumption (Zhang et al., 2020). On the other hand, biological technologies using microorganisms or other biological materials to dissolve or adsorb REE from CFA offer a more environmentally friendly approach, although they often require longer processing times and yield lower efficiencies compared to chemical methods (Pan et al., 2020; Park et al., 2020).

This study aims to analyze these three techniques comparatively to determine the most efficient and environmentally friendly approach for recovering REE from CFA. Each method will be evaluated based on recovery effectiveness, operational costs, and environmental impact. The research intends to provide a comprehensive guide for industries in selecting the most suitable method for REE recovery from CFA, thereby delivering optimal economic and environmental benefits. By understanding the advantages and limitations of each extraction method, the study seeks to identify techniques that are commercially viable with minimal environmental impact.

METHODOLOGY

This review article begins by analyzing a collection of studies discussing methods for recovering REE from CFA using physical, chemical, and biological approaches. The review process starts with data collection from relevant articles, focusing on key aspects such as REE recovery methods, recovery efficiency, and novelty of the research. Keywords used for the search include: "REE from CFA", "REE recovery from CFA", "REE leaching", "REE extraction from CFA", "chemical REE extraction", "alkaline REE extraction", and "biological REE extraction from coal fly ash". The selection of articles was carried out by evaluating their titles and abstracts to confirm their relevance to the focus of the review.

Subsequently, evaluation and data extraction from the selected articles were conducted using MS Excel to analyze five key aspects: extraction techniques, REE recovery outcomes, research objectives, publication year (limited to the last ten years), and contextual relevance. These findings are systematically presented in **Table 2**. Each technique—whether physical, chemical, or biological—was evaluated based on recovery efficiency, cost analysis, and environmental impact, with the aim of identifying promising combinations of techniques for further development.

The purpose of this review is to provide a comprehensive understanding of the topic and to identify the most effective and promising REE recovery methods from CFA. This approach is expected to establish a solid foundation for further analysis of the effectiveness and potential application of the reviewed methods.

RESULT

Recovery REE Techniques

Physical Techniques

Physical techniques are utilized to enrich the concentration of REE in CFA before chemical extraction processes are applied. Typically, three methods are employed: particle size classification, magnetic separation, and roasting treatment (Manurung et al., 2020; King et al., 2018; Cao, 2018; Taggart et al., 2018; Pan et al., 2020; Sreenivas et al., 2021; Kumari et al., 2019).

Particle Size Classification: Particle size separation is an effective physical technique to enhance the REE content in specific fractions of coal fly ash (CFA). According to Pan et al. (2019), the concentration of REEs in smaller-sized fractions can reach up to 1200 ppm, nearly double that found in coarser particles. This size-based separation allows for the enrichment of REE content in finer fractions, which can then be optimized in subsequent chemical leaching processes (Pan et al., 2019). These findings align with Tang et al. (2019), who reported that fractions smaller than 45 micrometers contained up to 1.5 times more REEs than coarser fractions. This separation technique, as part of the pre-treatment process, reduces chemical consumption and operational costs during leaching by targeting REE-rich fractions (Taggart et al., 2018). Additionally, studies have shown that particle size separation decreases the total mass that needs to be processed in subsequent extraction stages, thereby improving overall process efficiency (Park and Liang, 2019). By isolating REE-rich fine fractions, the chemical extraction steps can be more focused, increasing efficiency by up to 50% compared to direct leaching without pre-treatment (Peiravi et al., 2017).

Magnetic Separator: Magnetic separation is utilized for CFA containing ferromagnetic minerals or particles with high Fe content. According to Manurung et al. (2020), CFA with high Fe content can employ magnetic separation as a pre-treatment step. This technique enables the separation of approximately 30% of magnetic material associated with REEs in the tested fly ash. These ferromagnetic minerals often contain trace amounts of REEs linked to specific magnetic minerals. The findings indicate that magnetic separation is not only effective in isolating iron-rich fractions but also enhances the REE concentration in the fractions selected for subsequent extraction stages (Manurung et al., 2020). Furthermore, previous studies by King et al. (2018) and Cao et al. (2018) reinforce the effectiveness of magnetic separation, which can separate 10–30% of the total CFA mass. These fractions can then be processed using chemical methods for higher REE recovery (King et al., 2018; Cao, 2018).

Roasting Treatment: The roasting method applied to CFA involves the use of additives such as CaO, NaOH, Na_2CO_3, $(NH_4)_2SO_4$, and $CaSO_4$ prior to leaching, which has been proven effective in enhancing REE recovery rates (Taggart et al., 2018; Liu et al., 2019). In a study conducted by Liu et al. (2019), the extraction process began with an alkali roasting stage using Na_2CO_3 at a temperature of 1133 K. Following this step, H_2O leaching was performed to extract Al and Ga released during roasting. The next stage involved HCl acid leaching to recover REEs, followed by the use of ion adsorption resin to separate Al and Ga from the solution. This study reported an REE extraction efficiency of approximately 80% (Liu et al., 2019). In another study by Taggart et al. (2018), the combination of roasting treatment and HNO_3 acid leaching for REE recovery from CFA achieved even higher extraction rates, exceeding 90%.

By combining various physical techniques, including particle size classification, magnetic separation, and roasting, the efficiency of REE recovery in subsequent stages can be significantly enhanced. The detailed flowchart illustrating this process is presented in **Figure 1**.

Chemical Techniques

Acid leaching: Acid leaching is the most commonly used chemical method for recovering REEs from CFA. This process involves the use of strong acids such as H_2SO_4, HCl, and HNO_3 to dissolve REEs bound within the mineral matrix of CFA. In a study conducted by Taggart et al. (2018), HNO_3 was used as the leaching agent, achieving REE recovery rates of over 90%. This effectiveness is attributed to the ability of acid ions to break the bonds between REEs and the aluminosilicate structure within CFA (Taggart et al., 2018). Another study by Wang et al. (2019) demonstrated that using 2 M HCl with a solid-to-liquid ratio of 1:20 at a temperature of 80°C achieved recovery efficiencies of up to 75% for elements such as La, Nd, and Y. However, one major drawback of this method is the risk of acid waste contamination and the need for complex chemical residue management. Despite these challenges, acid leaching remains a reliable option, particularly for CFA with high REE content.

Alkaline leaching: Alkaline leaching utilizes alkaline solutions such as NaOH or Na_2CO_3 to dissolve silicate or aluminosilicate minerals in CFA, facilitating the release of REEs. According to Wen et al. (2020), alkaline leaching with NaOH at 120°C for 2 hours successfully dissolved 41.1% of the silica in CFA, thereby enhancing REE availability for subsequent separation steps. Furthermore, Pan et al. (2019) observed that this method is particularly effective for CFA with high silica content, achieving REE recovery rates of up to 60%. While alkaline leaching is less effective for direct REE recovery compared to acid leaching, it is often employed as a preparatory step to condition CFA for further leaching processes. This pre-treatment ensures that REEs are more accessible, improving the overall efficiency of subsequent extraction methods.

Alkaline leaching-acid leaching: A highly effective method for recovering REEs from CFA involves combining alkaline leaching with subsequent acid leaching. This process begins with alkaline leaching to dissolve silicate fractions and other obstructive minerals, followed by acid leaching to extract the remaining REEs, as illustrated in **Figure 1**. Research by Ma et al. (2019) demonstrated that using 5 M NaOH at 80°C for 2 hours, followed by 2 M HCl, achieved REE recovery rates of up to 88.15%, particularly for elements such as Ce, Nd, and La. Additionally, Taggart et al. (2018) highlighted that this combined process reduces acid consumption, making it both more environmentally friendly and cost-effective. Tang et al. (2019) further noted that this combination could improve recovery efficiency to 90% for CFA containing REEs in complex mineral forms. This approach is particularly effective for CFA with REEs bound in challenging aluminosilicate matrices, ensuring higher recovery rates while optimizing resource utilization.

Biological Techniques

Bioleaching: Bioleaching is a biological method that utilizes microorganisms to dissolve REEs from CFA. Microorganisms such as *Acidithiobacillus thiooxidans* produce organic or inorganic acids, such as H_2SO_4, which can leach REEs from the mineral matrix of CFA. Research by Su et al. (2020b) demonstrated that bioleaching with *Acidithiobacillus thiooxidans* achieved recovery rates of up to 76.37% for Ce and 64.77% for La at 30°C over a 7-day period. These results indicate a reasonable efficiency, albeit with a longer processing time compared to chemical methods. Additionally, the bioleaching process generates acidic waste with lower toxicity, simplifying waste management and making it more environmentally friendly than chemical leaching methods (Su et al., 2020b). The advantages of bioleaching lie not only in the microorganisms' ability to selectively dissolve REEs but also in their capacity to operate under relatively moderate environmental conditions without requiring high temperatures or pressures. However, the primary challenges of this technique include its relatively lengthy extraction time and the need to maintain a stable microbial culture environment (Sreenivas et al., 2021).

Biosorption: Biosorption is a biological technique that utilizes microorganisms or biomaterials to adsorb REEs from CFA leachate solutions. According to Park et al. (2020), Escherichia coli modified with lanthanide-binding peptides exhibits high selectivity toward heavy REEs (HREEs), such as La and Nd. This technique is capable of recovering up to 85% of REEs from leachate derived from Powder River Basin (PRB) fly ash. The main advantage of biosorption lies in its high selectivity for specific elements, enabling the separation of REEs with higher purity compared to other techniques. Additionally, biosorption uses renewable biological materials, making it a more sustainable solution. However, this technique requires pre-processing steps to produce REE-rich leachates, such as prior acid or alkaline leaching, to ensure effective biosorption (Park et al., 2020). A comparison of bioleaching and biosorption methods is presented in **Table 1**.

Table 1. Advantages and disadvantages of biological techniques

Techniques	Advantages	Disadvantages
Bioleaching	Environmentally friendly; acid waste is easier to manage.	Slow processing (up to 7 days); moderate efficiency.
Biosorption	High selectivity towards HREE; increasing REE purity.	Limited to leaching solutions; requires microbial modification.

Table 2. Summary study of REE Recovery Techniques from CFA

Physical Techniques	Chemical Techniques	Biological Techniques	Persen Recovery REE	Ref, [Code Ref]
Filtration, magnetic separator, hydrocyclone	Leaching water, leaching ammonium acetate, leaching ammonium acetate + acetic acid, acid leaching (HCl), leaching HNO_3 + H_2O_2, leaching (HF-HNO_3), Fusion (Na_2O_2)	x	98% LREE, 81% HREE	Sreenivas et al. (2021)
x	Alkali pretreatment (NaOH), acid leaching (HCl)	x	100% La, 90% Ce, 93% Nd	Wen et al. (2020)
x	Super-critical CO_2, tributylphosphate (TBP)	x	>99% Y, >99% Eu, <7% La, Ce, Tb	Das et al. (2018)
x	Acid leaching (HNO_3), solvent extraction	x	90.9% LREE, 94.2% HREE, 90.5% TREE*	Peiravi et al. (2017)
Alkaline roasting	Acid leaching (HNO_3)	x	>90% TREE	Taggart et al. (2018)
x	Alkali pretreatment (NaOH), acid leaching (HCl)	x	88.15% REE*	Wang et al. (2019)
x	Alkaline leaching (NaOH), acid leaching (HCl)	x	Alkali: 85% REE Acid: 40% REE	King et al. (2018)
x	Acid leaching (HCl)	x	80% REE	Honaker et al. (2019)
Precipitation	Acid leaching (HCl), solvent extraction	x	78% Ce, 80% La, 88% Nd, and 35% Y	Kumari et al. (2019)
Physical separation	Acid leaching (HCl)	x	80% TREE	Pan et al. (2020)
x	Hydrothermal alkali treatment (NaOH)	Bioleaching (*Acidithiobacillus thiooxidans*)	100% Sr, 90.8% V, 79.3% Y, 76.37% (Ce), 64.77% (La)	Su et al. (2020b)
x	Acid leaching (HCl)	Biosorption (*E. Coli*, *A. nicotianae*)	85% (La, Nd), 80% TREE	Park et al. (2020)

x	Alkali pretreatment (NaOH), Acid leaching (citric acid)	x	77.6% TREE	Rosita et al. (2023)
x	Liquid emulsion membrane (LEM), supported liquid membrane (SLM)	x	LEM: >70% TREE* SLM: 75% HREE, 50% LREE	Smith et al. (2019)
x	Alkali fusion (Na_2CO_3), Acid leaching (HCl)	x	72.78% TREE	Tang et al. (2019)
x	Acid leaching (HCl)	x	71.9% La, 66.0% Ce, 61.9% Nd	Cao et al. (2018)
x	Acid leaching (HNO3)	x	69.90% TREE	Zhang et al. (2020)
x	x	Indirect bioleaching (*C. Bombicola*)	63.0% Sc, 67.7% Yb, 64.6% Er	Park and Liang (2019)
x	Combined acid (HCl), alkali extraction (NaOH)	x	55% TREE*	Ma et al. (2019)
x	Acid leaching (HCl)	x	62.1% Y, 55.5% Nd, 65.2% Dy	Tuan et al. (2019)
x	Acid leaching (H_2SO_4, HNO_3, HCl)	x	H2SO4: 60% TREE HNO3: 29% TREE HCl: 2% TREE	Rao et al. (2020)
Physical separation (Particle separator, magnetic separator)	Alkali leaching (NaOH), Acid leaching (Acetic acid)	x	20.58% Ce, 43.53% Dy, 17.38% La, 40.96% Nd, 18.45% Y, 32.74% Yb	Manurung et al. (2020)

Economic Evaluation

The recovery of REE from CFA offers significant economic opportunities, particularly by transforming industrial waste into high-value products. In terms of processing costs, physical techniques such as magnetic separation and particle size classification require relatively low initial investment. According to Manurung et al. (2020), these methods can reduce material volume by up to 30% before further processing, lowering chemical leaching costs by approximately 20%. Meanwhile, roasting treatment, although highly effective with recovery rates exceeding 90% (Taggart et al., 2018), demands substantial thermal energy, making it more expensive than other physical techniques.

Chemical methods, such as acid leaching with HNO_3, achieve recovery efficiencies of over 90% (Taggart et al., 2018). However, the cost of chemicals and acid waste management can account for up to 40% of the total process cost (Wang et al., 2019). Alternatively, combining alkaline and acid leaching is more economical, as NaOH is used to break silicate matrices before acid leaching, reducing chemical consumption by up to 25%. Ma et al. (2019) reported that this combination achieved recovery rates of 88.15% at a cost of $500–700 per ton of ash, making it one of the most cost-efficient approaches for large-scale applications.

Biological techniques, such as bioleaching, provide a more environmentally friendly approach with lower operational costs compared to chemical leaching. Su et al. (2020) demonstrated that bioleaching with *Acidithiobacillus thiooxidans* recovered up to 76.37% Ce and 64.77% La, while generating waste that is easier to manage. This method reduces waste management costs by 30% compared to chemical leaching. However, the longer processing time (up to 7 days) and lower efficiency make it more suitable for small-scale projects or areas with strict environmental regulations. Biosorption, as highlighted by Park et al. (2020), offers high efficiency, recovering up to 85% of heavy REEs (HREEs), but requires microbial modifications, which add to operational costs.

From a value-added perspective, REE recovery from CFA holds attractive economic potential. REE content in CFA can reach 2100 mg/kg (Rao et al., 2020), with an economic value of approximately $3.5–5.0 per kg, depending on global markets. Additionally, high scandium (Sc) content further enhances economic value by up to 15%, with scandium priced at $2000 per kg in global markets (Das et al., 2018). Utilizing CFA also reduces the cost of coal ash waste management by $10–30 per ton (Sreenivas et al., 2021).

Overall, the combination of roasting, alkaline, and acid leaching techniques offers the best balance between recovery efficiency (>90%) and operational costs, making it the preferred choice for industrial-scale applications. Meanwhile, biological methods are better suited for small-scale applications due to their lower costs and minimal environmental impact, despite longer processing times. Integrating physical, chemical, and biological approaches can optimize REE recovery from CFA, providing competitive costs and controlled environmental impacts.

Environmental and Sustainability Review

Physical techniques such as magnetic separation, particle size classification, and roasting treatment generally have minimal environmental impact, as they do not produce direct chemical waste. According to Manurung et al. (2020), particle size classification utilizes the natural properties of materials without adding chemicals, resulting in waste limited to unused particle fractions. However, roasting treatment has a higher environmental footprint due to significant thermal energy consumption, which can increase carbon dioxide emissions (Taggart et al., 2018). Consequently, this method is better suited for facilities powered by sustainable energy sources.

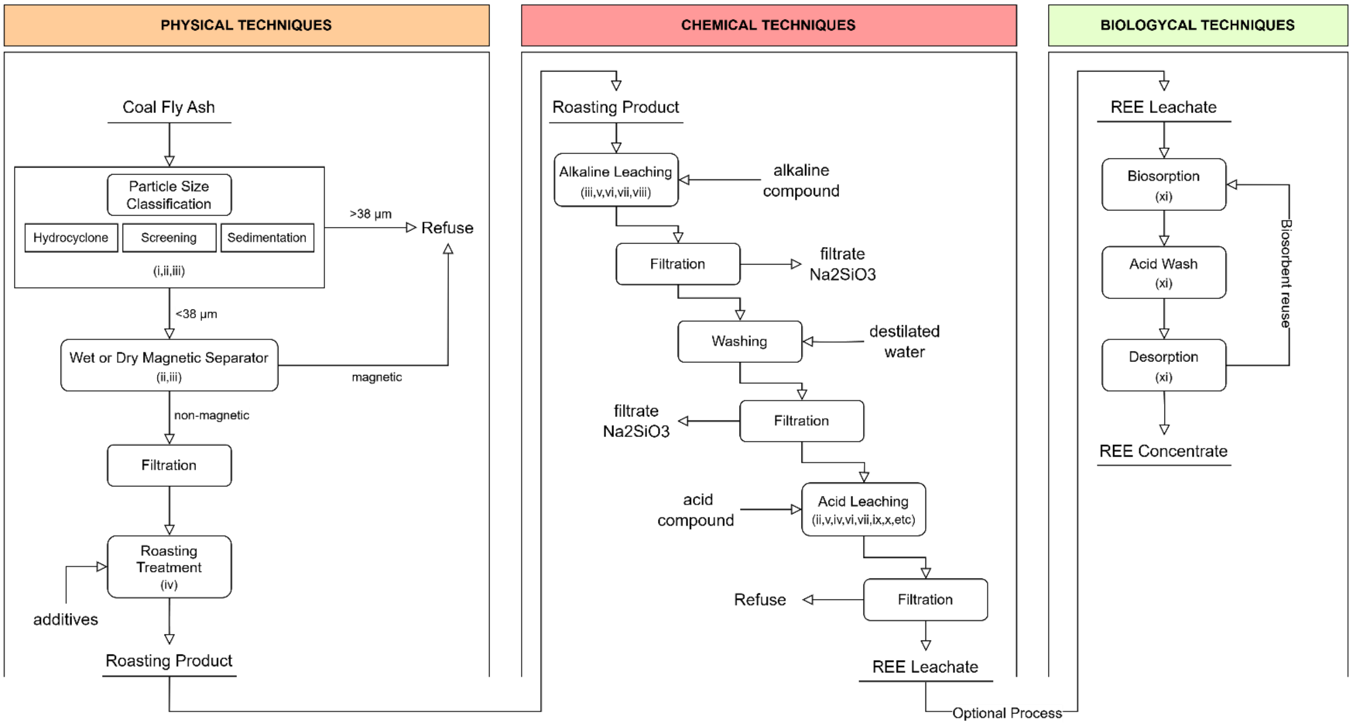
Chemical techniques like acid leaching and alkaline leaching, while highly efficient, generate liquid waste containing hazardous chemicals. Leaching with HCl or HNO_3, as reported by Wang et al. (2019), produces acidic waste that poses risks of groundwater and soil contamination if not managed properly. However, the combination of alkaline-acid leaching reduces acid consumption by up to 25% (Ma et al., 2019), thereby decreasing the volume of liquid waste generated. Chemical waste management remains a critical challenge for these techniques. Heavy metals such as arsenic and mercury often mix with the leachate, increasing toxicity risks (King et al., 2019). As such, stringent waste management systems are essential to prevent environmental contamination.

Unlike chemical techniques, biological approaches such as bioleaching and biosorption offer more environmentally friendly alternatives. In Su et al. (2020), bioleaching with *Acidithiobacillus thiooxidans* produced less liquid waste compared to chemical leaching. Moreover, the near-neutral pH of the solution made the waste easier to manage. This method also relies on natural microorganisms, reducing dependence on hazardous chemicals. Biosorption, as described by Park et al. (2020), employs modified microbes to adsorb REEs from leachate. This technique generates negligible liquid waste and requires only relatively safe buffer solutions. Such approaches are highly environmentally friendly and can be applied in the final stages of extraction to enhance selectivity without adding to the waste burden. By integrating physical, chemical, and biological techniques, REE recovery can be optimized while maintaining better control over environmental impacts. This combination ensures a more sustainable recovery process with reduced ecological risks.

Potential Technique for Recovery REE from CFA

Based on **Figure 1**, the evaluation of REE recovery techniques using a combination of physical and chemical methods demonstrates significant potential for selectively extracting REEs from coal fly ash. This approach includes physical steps such as particle sizing, wet magnetic separation, and roasting treatment to enhance REE concentration. Subsequently, chemical or hydrometallurgical processes are applied, involving alkaline solutions and acidic reagents for digestion and acid leaching. This combined method enables higher and more efficient REE recovery, especially when tailored to the characteristics of the processed ash (Sreenivas et al., 2021).

Alternatively, biological methods can be employed to reduce reliance on costly and environmentally impactful alkaline and acidic reagents. Bioleaching, utilizing microorganisms such as *Acidithiobacillus* or modified *E. coli*, offers a more environmentally friendly approach. However, to achieve optimal REE recovery rates, microorganisms need to be engineered for greater selectivity, particularly for heavy REEs such as lanthanides (Park et al., 2020). Integrating biological methods with physical and chemical approaches holds promise for enhancing process sustainability without compromising extraction efficiency.



Sources index: (i) Pan et al. (2020); (ii) Sreenivas et al. (2021); (iii) Manurung et al. (2020); (iv) Taggart et al. (2018); (v) Wen et al. (2020); (vi) Wang et al. (2019); (vii) King et al. (2018); (viii) Rosita et al. (2023); (ix) Peiravi et al. (2017); (x) Honaker et al. (2019); (xi) Park et al. (2020)

Figure 1. Potential flowchart techniques for recovering REE

CONCLUSION

This study highlights various techniques for recovering REEs from CFA, encompassing physical, chemical, and biological approaches, each with its own advantages and challenges. Physical techniques, such as particle separation, wet magnetic separation, and roasting treatment, are effective in enhancing REE concentration as a pre-treatment step for subsequent chemical processes. Chemical methods, particularly acid leaching and the alkaline-acid combination, offer high recovery efficiencies of up to 90%, although they require careful waste management to minimize environmental impacts. Meanwhile, biological techniques, such as bioleaching and biosorption, provide a more environmentally friendly alternative, albeit with lower efficiency compared to chemical methods. An integrative approach combining these three techniques shows significant potential for improving recovery efficiency, reducing costs, and minimizing environmental impacts, thereby supporting the principles of a circular economy and sustainability in the REE industry.

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Mining Technology Journal
Vol.(2), No.(2), 2024
E-ISSN: 2460 - 8386
http://jurnal.upnyk.ac.id/index.php/mtj

Analysis of Geostatistical Methods for Mineral Resource Estimation: A Literature Review

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ARTICLE INFO

Keywords: OK, IK, IDW Estimation

ABSTRACT

Mineral resource estimation is the process of determining the volume and grade of mineral deposits based on exploration data (SNI 4726:2011). Its objective is to provide a quantitative assessment of the economic potential of mineral deposits. This process involves geological, statistical, and geostatistical principles, while considering data quality, distribution, and deposit characteristics. Geostatistical methods, such as Ordinary Kriging (OK), Indicator Kriging (IK), and Inverse Distance Weighting (IDW), are widely used in resource estimation due to their ability to integrate spatial relationships between data, making them superior to conventional methods. Each method has specific characteristics that make it suitable for certain conditions. OK is well-suited for data with homogeneous distribution, such as nickel, as it can produce accurate estimates with low RMSE. IK is often applied to gold deposits with fluctuating grades and complex spatial relationships. IDW, though simpler, is effective for minerals with homogeneous distributions, such as nickel and iron ore. Previous studies emphasize that the choice of method should consider parameters such as data distribution, type of mineralization, and regional geology. By analyzing the characteristics of these methods, this study evaluates the suitability of OK, IK, and IDW based on the type of mineral and data distribution. This approach aims to support more optimal exploration and management of mineral resources.

INTRODUCTION

Mineral resource estimation is the process of determining the volume and grade of a mineral deposit based on acquired exploration data (SNI 4726:2011). This estimation aims to provide a quantitative overview of the economic potential of a mineral deposit. The process is conducted by adhering to geological, statistical, and geostatistical principles while considering data quality, distribution, and deposit characteristics. The primary classifications emphasized are measured, indicated, and inferred resources, as

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outlined in the SNI 4726:2011 standard. Resource estimation using geostatistical methods plays a critical role in determining resource quantities. Geostatistical estimation methods are considered superior to conventional approaches because they incorporate spatial relationships between data points. This spatial analysis enhances the accuracy and reliability of resource estimation, making it an essential tool in mineral resource evaluation.

Geostatistics is a field of study that examines spatial distributions, which is highly beneficial for mining engineers and geologists. It is particularly useful in analyzing mineral grades, thickness, accumulation, and practical applications related to challenges in ore deposit evaluation (Matheron 1963). Various methods can be employed to predict the distribution and volume of minerals, such as Ordinary Kriging (OK), Indicator Kriging (IK), and Inverse Distance Weighting (IDW). Each method has unique characteristics that make it more suitable for specific situations, depending on the data characteristics, estimation objectives, and the mineral distribution being evaluated. Although these three methods are widely used, this research focuses on determining which geostatistical method is most appropriate for specific minerals. The objective is to evaluate the suitability of OK, IK, and IDW methods for particular mineral types based on existing literature and to analyze their applicability in various geological scenarios and data distributions. This study aims to contribute to the development of more optimal resource estimation approaches, particularly in supporting the exploration and management of mineral resources.

METHODOLOGY

The steps undertaken by the author are illustrated in the flowchart shown in Figure 1. This research is based on a literature review encompassing both national and international journals. The study aims to identify the most suitable method for resource estimation using geostatistical approaches, as outlined in the stages depicted in Figure 1.

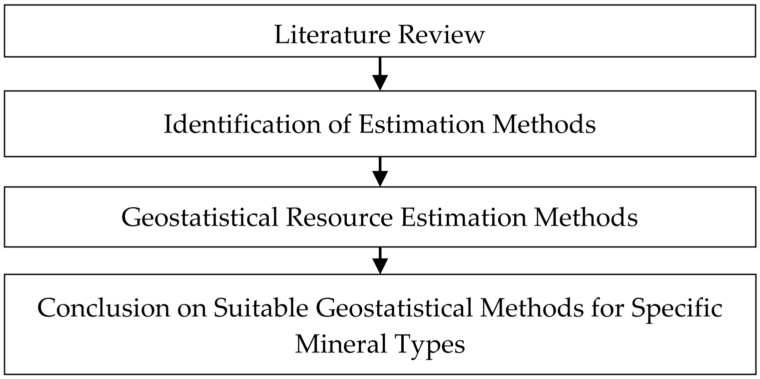

Figure 1. Research Flowchart

The initial stage of this research begins with data collection related to geostatistical estimation studies and various estimation methods used. The next stage involves identifying the characteristics of estimation methods in relation to the minerals being estimated. This analysis includes several parameters such as the type of mineralization, spatial variability of data, geology of the minerals (mineralization), and data distribution. The final stage draws conclusions through an analysis of which methods are suitable or closely aligned with the requirements for specific types of minerals, as not all methods are applicable to every mineral. The results of this analysis can serve as recommendations for selecting and determining the appropriate geostatistical method to be used. Previous studies on the use of geostatistical methods are presented in Table 1.

Table 1. Previous Studies on the Use of Geostatistical Methods for Resource Estimation in Minerals

Researcher	Year	Research Findings
Amadua, et. al.	2022	Inverse Distance Weighting is more suitable than Ordinary Kriging in all ore zones.
Bargawa & Amri	2021	IDW performs better than OK overall; however, in the limonite zone, the Ordinary Kriging (OK) method demonstrates better performance compared to IDW for both Ni variables and thickness.
Carvalho, D., et. al.	2017	The Indicator Kriging method can be used for complex mineralization, such as gold deposits.
Conoras, et. al.	2021	Based on the correlation coefficient (R) values, the Ordinary Kriging (OK) method is more recommended than Inverse Distance Weighting (IDW) for resource estimation.
Kurniawan, A, R., dan Amri	2019	Based on the analysis of values *r* and RMSE, the Indicator Kriging method is more accurate than Ordinary Kriging for estimating epithermal gold deposits.
Arief Pambudi Nugraha, et. al.	2020	Isotropic orientation performs better than anisotropic orientation, as observed from the lower error (RMSE). Furthermore, the results of the Co-Kriging method (IK) are superior compared to those of Kriging.
Hendro Purnomo	2021	The estimation of iron (Fe) content using the Ordinary Kriging method is **underestimated**, while the Indicator Kriging method tends to **overestimate**. The Ordinary Kriging method is considered more suitable for this analysis.
Hassan Riyadi	2023	The results of the Ordinary Kriging estimation are considered sufficiently accurate and satisfactory.
M Rizky	2022	The analysis results indicate that the IDW method provides estimates that are closer to the composite values compared to the Ordinary Kriging (OK) method.
Alan Budiman Thamsi, et. al.	2023	The IDW method is suitable for use in nickel resource estimation.
Zhexenbayeva, A., et. al.	2024	Multi-point geostatistics (IK) demonstrates superior results in geological modeling of vein-type gold deposits.
Bargawa, W. S	2009	The Indicator Kriging (IK) method is suitable for application in precious metal deposits, such as gold ore, which exhibit asymmetric grade distributions.
Safrudin, R., & Conoras, W. A.	2021	The Ordinary Kriging method provides better results, as indicated by the correlation coefficient (R) value approaching 1.

The IDW method assigns higher weights to data that is closer, resulting in more variable estimates. In contrast, the OK method tends to produce more homogeneous values because it emphasizes spatial uniformity through variogram structures. The conclusion of this study indicates that although the OK method offers stability and smoothness in its results, the IDW method can provide insights into the choice of estimation methods depending on the specific data conditions. The choice of method depends on the objectives of the estimation and the nature of the analyzed data. The interpretation of IDW is commonly used in resource estimation, particularly in mining. The magnitude of an estimate is significantly influenced by distance and weights, which change based on the distance between the estimation point and the target point (Rafsanjani et al., 2016). This method is based on the principle that closer values have a greater influence compared to those farther away. It is suitable for data with homogeneous distribution and areas with limited spatial information. However, it is less effective for complex or heterogeneous data. Ordinary Kriging is a method that assumes the mean of an unknown population, and the spatial data does not contain any trend. In addition to the absence of trends, the data used must also be free of outliers. Ordinary Kriging is one of the methods included under the Kriging methods commonly used in geostatistics. This method has an assumption for its practical application, which is the intrinsic stationarity of the spatial field and the availability of sufficient observations for estimation (Puspita, 2013). Indicator Kriging (IK) is a non-parametric geostatistical method used to estimate probability values based on specific threshold values (Antunes and Albuquerque, 2013; Goovaerts, 1997). The Indicator Kriging (IK) technique was first introduced by Journel (1983). This technique is used when the spatial correlation of variance parameters is very difficult to model or when ordinary kriging does not provide accurate estimates for areas with high-grade concentrations mixed with waste (Sullivan, 1984). Indicator Kriging can be used in cases where ordinary kriging fails to provide precise estimations, particularly in situations involving high-grade mineral concentrations mixed with waste materials.

RESULT

From previous studies, all methods can be used for mineral resource estimation; however, several parameters must be considered, such as data distribution, type of mineralization, regional geology, and the characteristics of the mineral. According to research by Hendro and Purnomo (2021), the Ordinary Kriging (OK) method can be applied to nickel estimation because its data distribution tends to be uniform and has a good RMSE value. Indicator Kriging (IK) and Ordinary Kriging (OK) are suitable for gold deposits because they exhibit asymmetric grade distributions (Bargawa, 2009). These methods are effective in handling complex spatial relationships within data. On the other hand, the Inverse Distance Weighting (IDW) method is more suitable for estimating nickel and iron ore types.

Table 2. Comparison of Methods in Estimating Mineral Resources

Research	**Type of Mineral**				
	Gold	**Nickel**	**Iron Ore**	**Galena**	**placer**
Amadua, et. al.					IDW
Bargawa et. al.		IDW			
Carvalho, D., et. al.	IK				
Conoras, et. al.	OK				
Kurniawan, A, R., et. al.	IK				
Arief Pambudi Nugraha, et. al.					
Hendro Purnomo		OK			
Hassan Riyadi				OK	
M Rizky			IDW		
Alan Budiman Thamsi, et. al.		IDW			
Zhexenbayeva, A., et. al.	IK				
Bargawa, W. S	IK				
Safrudin, R.,		OK			

CONCLUSION

Based on the analysis, it can be concluded that the geostatistical methods OK (Ordinary Kriging) and IK (Indicator Kriging) are suitable for use with gold minerals due to their advantages in handling data with fluctuating grade distributions and complex spatial relationships. Meanwhile, the IDW (Inverse Distance Weighting) method is suitable for nickel minerals because it is sufficient for minerals with homogeneous and stable grade distributions.

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Mining Technology Journal

Mapping the Distribution of Lead and Zinc In Skarn Deposit

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ARTICLE INFO

Keywords: Pb, Zn, Kriging, Grade

ABSTRACT

In Magmatic belts formed mineralization in West Java, and most of that are epithermal deposits and porphyry deposits bearing with Cu, Au, Pb or Zn. Lately, there are indication of Pb-Zn mineralization in Cihaur area, and it is a new economic discovery for Pb-Zn skarn deposit in Java Island. Geostatistics offers the ways of describing and modeling the spatial continuities of the regionalized variables and allows to integrate the inferred continuity parameters into the regression techniques used for their spatial interpolations. The experimental variogram for ordinary kriging in the horizontal direction utilized an azimuth of 135°. The fitting results of the experimental variogram for the Pb-Zn assay indicated a spherical variogram model type. The distribution map of Pb-Zn grades indicates clear mineralization zonation classified into low grade (3% – 6%), medium grade (6% – 9%), and high grade (>9%).

INTRODUCTION

Indonesia is an archipelagic country that surrounded by Ring of Fire. In addition, located at Indo-Australia plate, Eurasian plate and Pacific plate that causes high frequency of magmatic activity in Indonesia. Java Island, especially West Java has two magmatic belts, from Cenozoic magmatic belts and late Miocene-Pliocene magmatic belts (Zheng et al., (2017). Magmatic belts formed mineralization in West Java, and most of that are epithermal deposits and porphyry deposits bearing with Cu, Au, Pb or Zn. Lately, there are indication of Pb-Zn mineralization in Cihaur area, and it is a new economic discovery for Pb-Zn skarn deposit in Java Island. This research area is in Cihaur, Simpenan, Sukabumi, West Java. Based on subsurface data, skarn Pb-Zn deposit is mainly hosted by limestone, but some part of them associated with volcanics rocks (Arsah et al., 2023).

Base metal minerals found in this area are galena and sphalerite with an abundance of pyrite around it. Galena has the characteristic form of triangular pits textures with a cloudy gray color and has associated with the minerals pyrite and sphalerite. Sphalerite is identified by dark gray color with anhedral shape and isotropic. Some gaps in sphalerite were found to have been filled by native minerals like gold and silver. Galena and sphalerite are known as the carrier of valuable base metals. Galena (PbS) is the main Pb-carrier mineral in the research area, while sphalerite (ZnS) is the main Zn-carrier mineral (Laksana et al., 2023).

One of the main factors to consider when evaluating a deposit is its concentration condition (Amir et al., 2022). To determine the characteristics of laterite deposits, a systematic drilling exploration stage and grade analysis are required. These results are then visualized as a map model with the help of specialized

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software (Rahman A. et al., 2015). Therefore, this research was conducted to analyze the distribution of Pb-Zn based on grade mapping derived from drilling data. Mapping the distribution of Pb-Zn in skarn deposit is crucial for optimizing exploration in the Cibujang Project area. This allows drilling activities to be focused on the most prospective zones within the project area. Additionally, such mapping supports the development of efficient mine designs, maximizing the extraction of high value ore while minimizing waste.

METHODOLOGY

Geostatistics offers the ways of describing and modeling the spatial continuities of the regionalized variables and allows to integrate the inferred continuity parameters into the regression techniques used for their spatial interpolations. Applications of the geostatistical techniques in mining industry is cery broad and ranges from estimation of the mineral resources to assessment of the model uncertainty, quantification of the risks and determining the optimal drilling and sampling grids (Abzalov,2016).

Data Colletion

This research uses samples from the results of drilling in the Cibujang project, with data collection and processing conducted following the standards of SNI 4726:2019 and KCMI 2017 :

1. Assay data is grade sample of drilling results.
2. Collar data is coordinate and elevation data from drilling point.
3. Lithology is drilling point distribution data.
4. Survey is the total drilling depht data.

Data Processing and Data Analysis

The stages carried out in data processing in this research are as follows:

1. Combining data assay, collar, lithology and survey menggunakan microsorf excel then save file in the form of *.csv.
2. Contructing the ore body base on the upper and lower grade boundaries at each drill hole, then correlating them with one another.
3. Creating a block model base on the ore body with dimensions of 7,5 x 7,5 x 1 m.
4. Interpolation with kriging method using micromine software with variable levels of Pb and Zn. Variogram and kriging equations used in weighthing are as follows (Isaak dan Srivastava, 1989) :

$$y(h) = \frac{1}{2n(h)} \sum_{i=1}^{N(h)} [Z(x_i + h) - Z\,(X_i)]^2 \ (1)$$

To calculate the value of the estimated point, the following formula :

$$Z^* = \sum_{i=1}^{n} W_i . Z(\,x_i) \ (2)$$

Keterangan :

$\gamma(h)$: estimated or expeirmental semivariogram

$n(h)$: number of pairs h units apart

$Z(x_i)$: observation at site xi

$Z(x_{i+h})$: value on location (x_{i+h})

h : vector that expresses the distance between to points

Z^* : estimated value

W_i : sample weight, where $\sum_{i=1}^{n} W = 1$

$Z\,(x_i)$: sample rate

RESULT

Ore Body and Block Model

An ore body model is a method used to constrain the estimation of Pb-Zn resources within a specific population in the study area. This approach ensures that grade estimation does not involve excessive extrapolation beyond the boundaries of mineralization. The dimensions of the block model are crucial in three-dimensional (3D) estimation. This is because the block-shaped structure is designed to represent the mineral deposits at specific locations accurately.

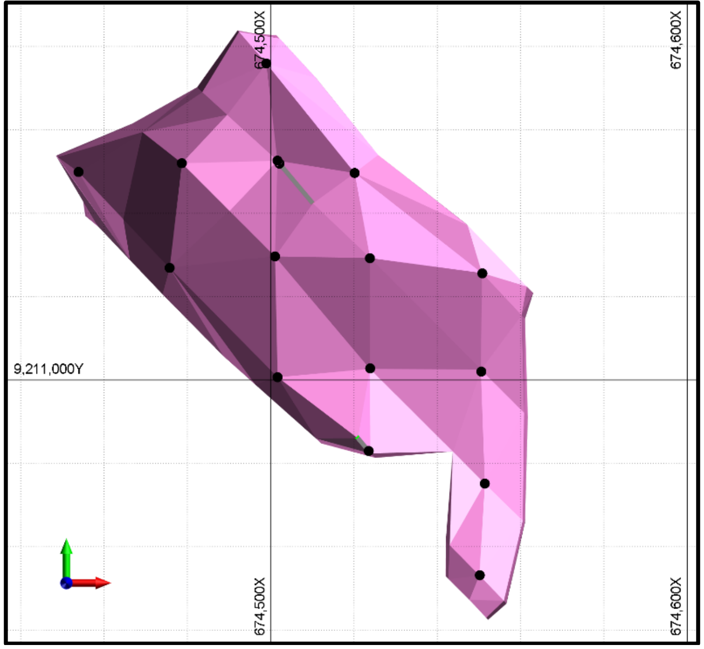

Figure 1. Ore Body

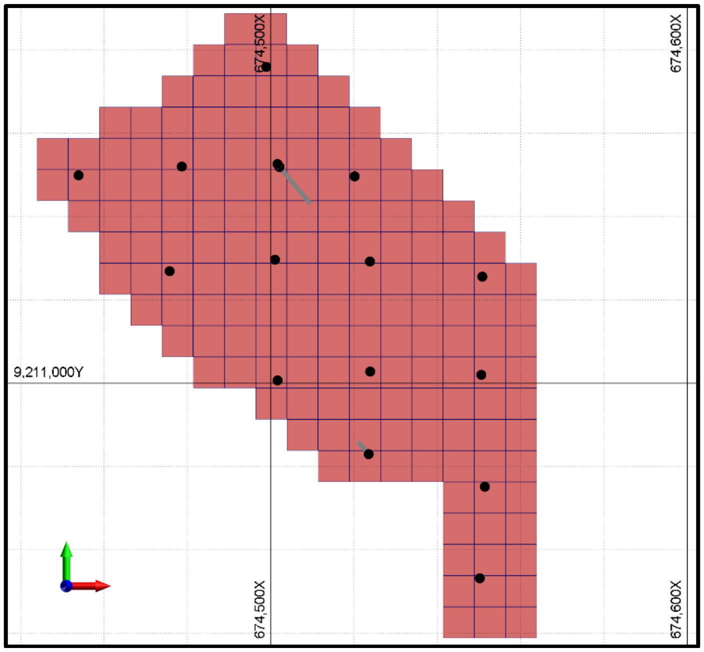

Figure 2. Block Model

Variogram

A variogram study using the ordinary kriging method was conducted with Pb-Zn assay data from the study area. The experimental variogram for ordinary kriging in the horizontal direction utilized an azimuth of 135°. The fitting results of the experimental variogram for the Pb-Zn assay indicated a spherical variogram model type.

Table 1. Variogram fitting result parameters

Nugget	Partial sill	Range	Azimuth
0.10	0.90	56	135

Ordinary Kriging

Estimation using the OK technique was carried out using the pb-zn assay database with The amount of data used in the estimation is a maximum of 16 drill point data, as well as a search area of 56 m corresponds to the range value of the selected variogram, namely spherical. InIn this research, the interpolation process was carried out using the kriging method with a variogramspherical anisotropy, and in its calculations using equations (1) and (2). Figure 1 shows the spatial distribution of Pb and Zn grades.

Table 2. Grade and tonnage

Grade	Tonnage
3-6	10.440
6-9	98.640
>9	338.940

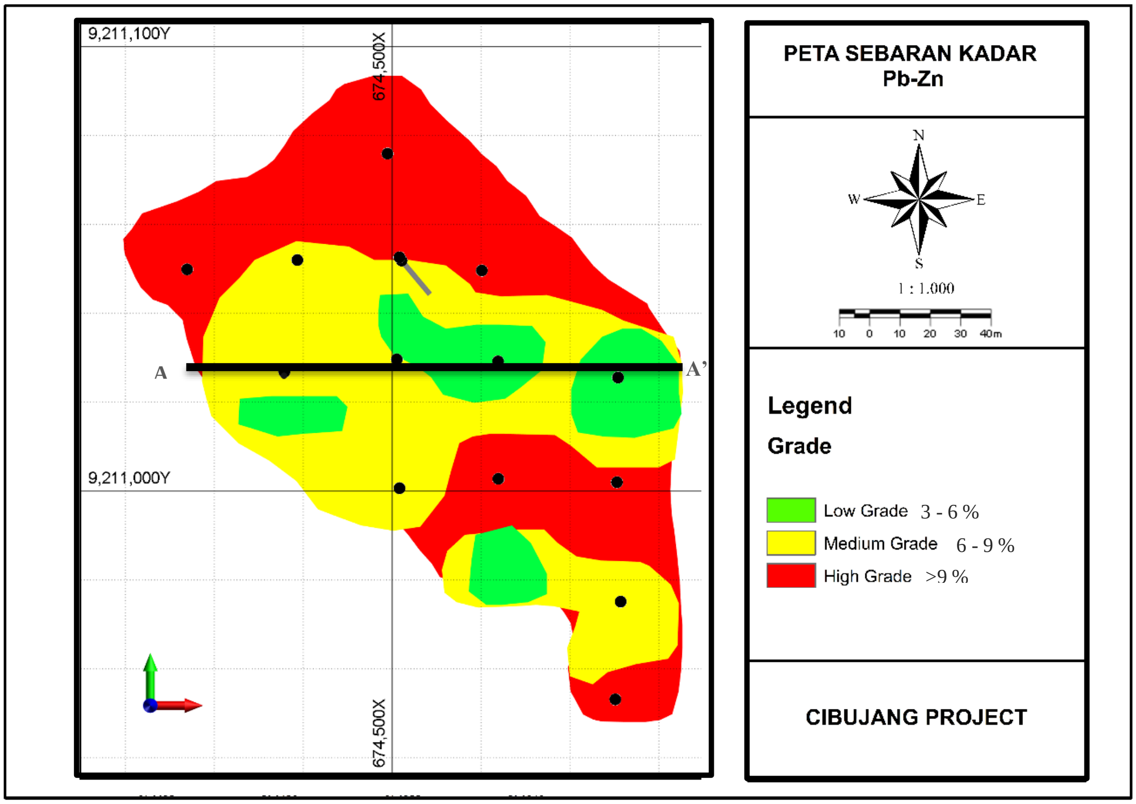

Figure 3. Distribution map of Pb-Zn grades

Low-Grade Distribution (3% – 6%) The map with green shading shows the distribution of low-grade

Pb-Zn, concentrated in the central to southeastern parts and some areas in the southwest. This distribution also mixes with the yellow zones (medium grade) in certain locations, indicating a transition between the outer alteration zone and areas with more intense mineralization. The wide extent of the low-grade distribution suggests potential additional exploration to understand the alteration zonation in the skarn deposit system.

Medium-Grade Distribution (6% – 9%) The map with yellow shading highlights the distribution of medium-grade Pb-Zn, which dominates the study area, particularly in the central, northwestern, and northeastern parts. This grade covers a larger area compared to the low- and high-grade zones, representing a major transition zone where Pb-Zn mineralization occurs with moderate intensity. The consistent pattern of medium-grade distribution indicates stable mineralization across the region, making it a key target for further exploration.

High-Grade Distribution (>9%) The map with red shading reveals that high-grade Pb-Zn is distributed relatively evenly across most of the study area, with dominance in the central to southern regions. This broad distribution suggests widespread intense mineralization, likely associated with hydrothermal processes or geological structures that facilitated the dispersion of metal-bearing fluids across a wide area. The widespread high-grade zones emphasize the significant economic potential for mining development and should be prioritized for exploration and mine planning.

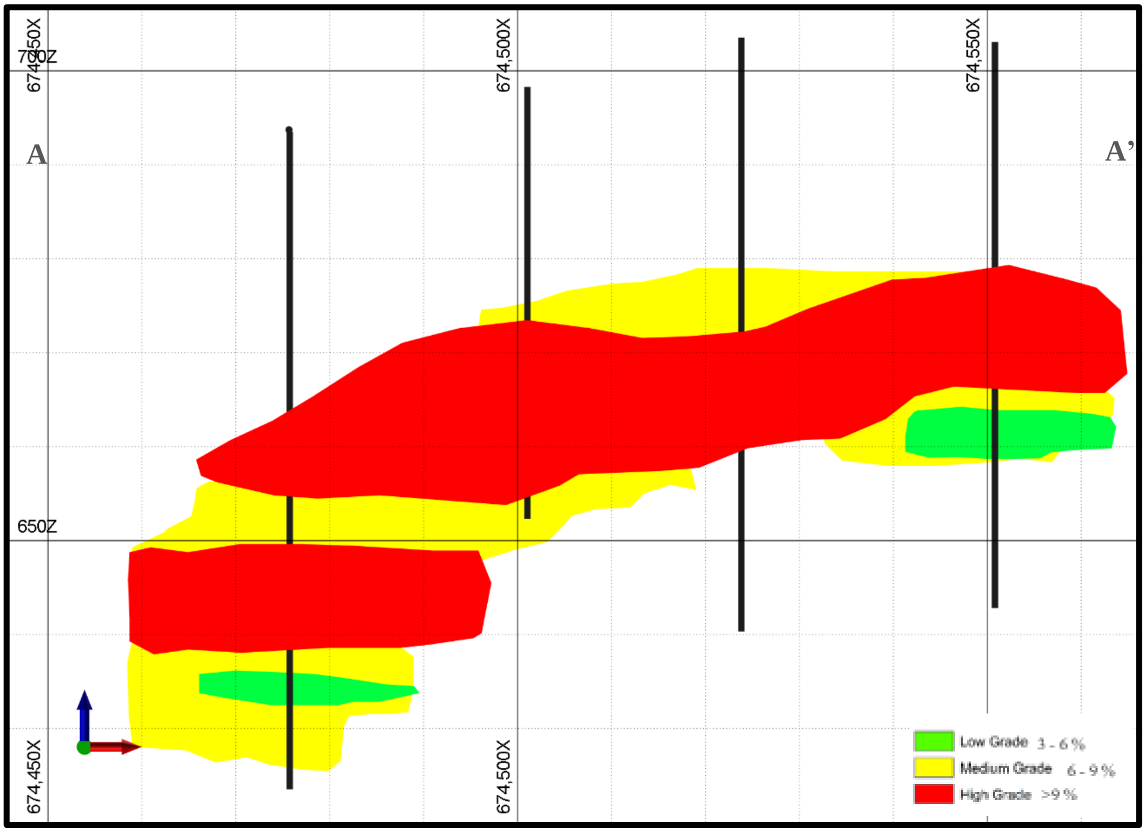

Figure 4. Section A – A'

Low-Grade Distribution (3% – 6%) The green zones represent low-grade Pb-Zn mineralization and are observed in the lower portions of the section, particularly concentrated near the southwestern and southeastern edges of the cross-section. These areas indicate zones of minimal mineralization intensity, likely corresponding to the outer alteration zones where hydrothermal activity was weaker. The presence of low-grade zones interspersed with medium-grade areas suggests a gradual transition in mineralization intensity.

Medium-Grade Distribution (6% – 9%) The yellow zones, representing medium-grade mineralization, are relatively consistent along the cross-section and are more prominent in the upper and middle portions of the section. These areas appear to act as transition zones between the low- and high-grade zones, reflecting moderate mineralization intensity. This distribution pattern suggests an environment of ongoing metasomatic processes with sufficient but not intense hydrothermal fluid flow. The medium-grade zones are widespread and form the majority of the observed mineralized areas.

High-Grade Distribution (>9%) The red zones, indicating high-grade Pb-Zn mineralization, dominate the central part of the cross-section and extend horizontally across the majority of the section. These areas are concentrated in regions closer to structural features (represented by the vertical black lines), suggesting that faults or fractures acted as pathways for hydrothermal fluids. The high-grade zones reflect intense mineralization processes and are likely associated with areas of significant fluid accumulation and favorable permeability conditions. These zones are critical targets for future drilling and mining operations due to their high economic value.

CONCLUSION

The distribution map of Pb-Zn grades indicates clear mineralization zonation classified into low grade (3% – 6%), medium grade (6% – 9%), and high grade (>9%). Low-grade Pb-Zn dominates the southeastern, southwestern, and some central areas, reflecting outer alteration zones with lower mineralization intensity. Medium-grade Pb-Zn is widely distributed, particularly in the central, northwestern, and northeastern regions, representing the main transition zone with stable mineralization. High-grade Pb-Zn is relatively evenly distributed across the study area, with notable dominance in the central and southern parts, indicating widespread intense mineralization with significant economic potential.

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