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MORALITY BEFORE KNOWLEDGE

Utilization of used lubricating oil for anfo-emulsion production: A study on blasting activities in the copper mining area

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ABSTRACT

Background: Copper is crucial for the development of electric vehicles and renewable energy technologies. In Indonesia, PT ABC's open-pit mining operations are expanding, leading to increased waste generation, particularly used lubricating oil, which is contaminated with water and metal particles but has caloric value comparable to diesel. This study explores the potential of using this oil as a diesel substitute in explosives, focusing on economic and environmental benefits. **Method:** The study used data collection methods to measure the annual volume of waste oil, cost savings from using it as a fuel substitute, and compliance with hazardous waste utilization regulations. The research analyzed the impact of substituting up to 80% of diesel fuel requirements with used lubricating oil. **Findings:** PT ABC utilizes approximately 2,699,850 liters of used lubricating oil annually. The company achieves a 99.99% compliance rate with hazardous waste permits. Substituting up to 80% of diesel with used oil resulted in an economic gain of IDR 38,885,321,437 in 2023 and diesel procurement savings of IDR 2,473,012,791. These findings highlight the economic and environmental advantages of waste management practices in mining operations. **Conclusion:** The integration of used lubricating oil as an alternative fuel in mining operations reduces operational costs, enhances environmental sustainability, and aligns with circular economy principles. This approach contributes to sustainable mining practices by transforming waste into reusable resources, offering significant economic and environmental benefits. **Novelty/Originality of this article:** This study is original in demonstrating the use of used lubricating oil as a substitute for diesel fuel in mining, showing its potential to reduce costs, improve sustainability, and support circular economy practices in the mining sector.

KEYWORDS: used lubricating oil utilization; ANFO-emulsion; sustainable mining.

1. Introduction

The ninth goal of the Sustainable Development Goals (SDGs) in the 2030 Global Agenda is sustainable industrialization. In this context, the correlation between industrialization and economic growth plays a pivotal role. Fundamentally, industrialization represents a transformation process that adds value and produces semi-finished and finished products for local and international markets. Since the nineteenth century, the concept that industrialization contributes to economic growth has been supported by classical theory, reinforced by growth theory, and proven through various empirical studies (Ahmadi & Toghyani, 2011). Nevertheless, this relationship is not always significant and can yield unfavorable outcomes in certain circumstances. Furthermore, global crises such as the

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ongoing pandemic and the Russia-Ukraine conflict have demonstrated that countries with high levels of economic dependence are more susceptible to adverse effects, prompting policymakers to re-examine the factors influencing economic growth. Industrialization is a complex process involving numerous actors and factors that can potentially foster economic growth, reduce poverty, and promote greater equity. Consequently, it is crucial for a nation to possess a dynamic and well-functioning industrial economy to effectively compete in the global marketplace (Yuni et al., 2023).

Law of the Republic Indonesia Number 3 of 2014 on Industrial Affairs has established industry as a cornerstone of the national economy, conferring upon the government a significant responsibility to facilitate the advancement of the domestic industry in a structured and coordinated manner. This role is of great consequence in directing the growth of the national economy, with the objective of enabling it to attain a level of development comparable to that of developed countries. To reinforce and elucidate the function of the government in national industrial advancement, a systematic, comprehensive, and futuristic national industrial development plan has been devised in the form of the 2015-2035 National Industrial Development Master Plan, henceforth designated as RIPIN 2015-2035. The RIPIN 2015-2035 plan includes, among other elements, a vision of national industrial development. This vision entails the transformation of Indonesia into a resilient industrial country, characterised by a robust and diversified national industrial structure, a high level of global competitiveness, and a foundation in innovation and technology. Additionally, the RIPIN 2015-2035 plan outlines the development of the national industry, comprising future mainstay industries, supporting industries, and upstream industries as illustrated in Figure 1, which highlights the integration of key industrial sectors, supporting frameworks, and enabling prerequisites to achieve the vision of a globally competitive and sustainable industrial ecosystem (Ministry of Industry, 2015).

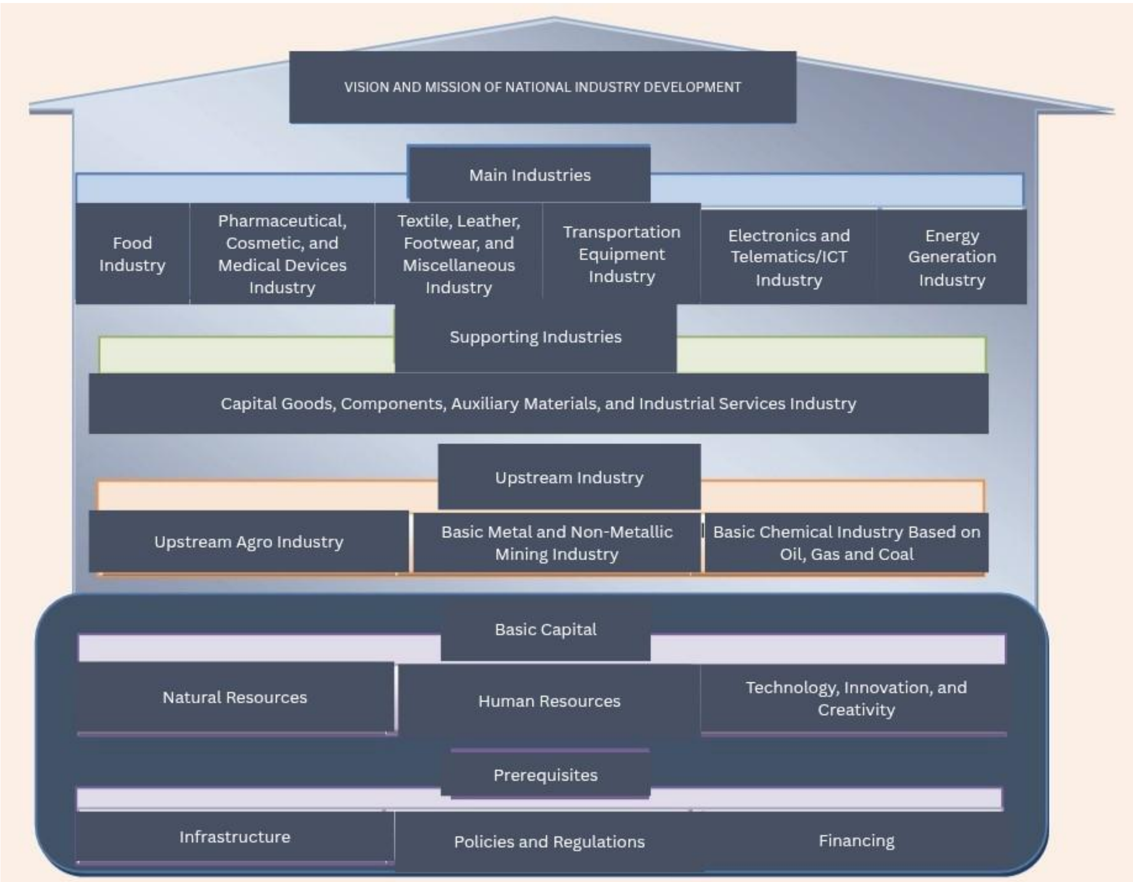


Fig. 1. National industrial development
(Ministry of Industry, 2015)

The upstream industry forms the backbone of the manufacturing sector by supplying raw materials that can be processed further to meet the specific requirements of downstream industries. Within the Priority Industrial Development Plan, copper-based commodities are emphasized as strategic upstream products to be developed from 2015 to 2035 (Ministry of Industry, 2015). Copper, as a critical mining commodity, is utilized across a wide range of applications, including construction, infrastructure, transportation, heavy machinery, as well as electronic and automotive equipment. The global demand for copper is projected to grow significantly, driven by the increasing adoption of electric vehicles and renewable energy technologies. As depicted in Figure 2, global copper consumption is forecasted to rise steadily from 2016 to 2035, reaching 12,840 kilotons by 2035. This growth is attributed to heightened demand across sectors such as energy efficiency, electromobility, and renewables. The demand for electric vehicles is expected to grow at a compound annual growth rate (CAGR) of 14% during this period, reflecting a paradigm shift toward sustainable energy and transportation solutions. This projection underscores the strategic importance of developing Indonesia's copper-based upstream industries to meet future global market demands while fostering national economic growth (Ministry of Energy and Mineral Resources, 2020).

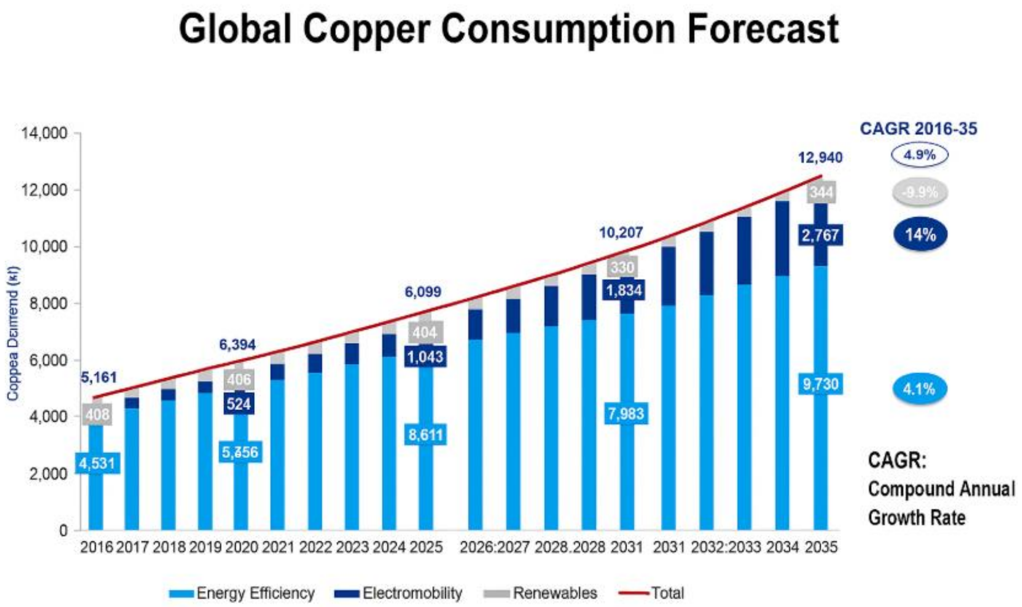
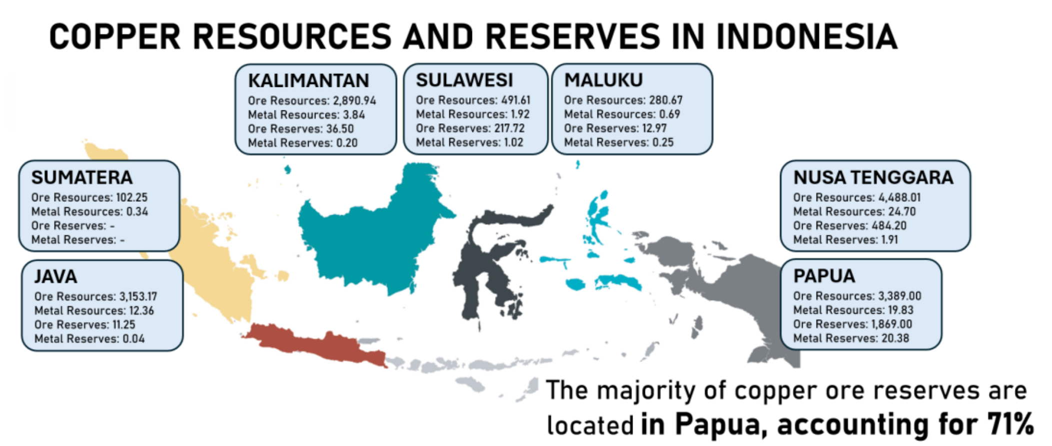


Fig. 2. Global copper consumption forecast
(Ministry of Energy and Mineral Resources, 2020)

According to data from the U.S. Geological Survey (2024), global copper production increased to 22 Mt in 2023. Indonesia, as the seventh-largest copper-producing country, contributes 0.84 Mt annually to this total. This production capability is underpinned by the country's 24 Mt of copper reserves, which constitute 2.4% of the world's total reserves. As depicted in Figure 3, Indonesia's copper resources and reserves are distributed across several key regions, with Papua accounting for 71% of the nation's total copper ore reserves. Other significant contributions come from regions such as Nusa Tenggara, Sulawesi, and Kalimantan. This extensive resource base not only supports Indonesia's domestic copper production but also underscores its strategic role in the global copper market. The distribution of these reserves highlights the critical importance of sustainable mining practices and effective resource management to ensure long-term economic benefits. The production of copper commences with the extraction of copper ore at the mining site. Three distinct mining methods are employed for the extraction of copper ore, each contingent upon the ore's position relative to the surface of the Earth. In instances where the ore is situated near the Earth's surface, open pit mining is utilized, entailing the excavation of overburden material (topsoil). Conversely, in situations where the ore is located at a considerable depth below the surface, underground mining techniques are employed, involving the creation of an underground tunnel (Subowo, 2011). Open pit mining is the predominant method of mining on a global scale due to its mechanical simplicity and higher productivity compared to underground mining. The excavation process in open pit mining is conducted through drilling and blasting (Asmiani et al., 2016). Explosives utilized in mining operations are composed of emulsion, ammonium nitrate (AN), and fuel oil (FO). The explosives were detonated through the use of a digital electric detonator in order to remove the overburden (Moorthy et al., 2012).



Resources (million tons)										Reserves (million tons)					
Hypothetical		Indicated		Measured		Proven		Total		Probable		Proven		Total	
Ore	Metal	Ore	Metal	Ore	Metal	Ore	Metal	Ore	Metal	Ore	Metal	Ore	Metal	Ore	Metal
16.36	0.20	8,485.31	28.85	5,030.15	28.25	1,263.84	6.39	14,795.66	63.69	1,774.86	14.79	856.79	9.01	2,631.64	23.79

Fig. 3. Distribution of Indonesian copper resources and reserves
(Ministry of Energy and Mineral Resources, 2020)

In the initial stages of copper mining in Indonesia, the operations were conducted exclusively by PT XYZ. However, since 2000, large-scale mining has also commenced at the site under the auspices of PT ABC (Tresnadi, 2014). PT ABC is a copper mining company situated within the Batu Hijau Mine, located in the West Nusa Tenggara province. A feasibility study of the Batu Hijau Mine conducted in 2015 estimated that the mine's copper ore reserves would be depleted in 2028, with the entire project life projected to conclude in 2037. However, the geological drilling data on the Batu Hijau deposit from 2019 to 2020 indicates the potential for additional reserves that can be developed technically and economically. These include 1,594 Mt of ore rock and 4,116 Mt of waste rock (PT ABC, 2023). The development of ore rocks will have implications for the increasing need for mine pit explosives and mining operational equipment. As mineral exploitation increases, so likewise does the demand for fragmentation of rock to an optimal degree. This in turn requires a greater use of explosives. The relationship between the amount of rock mined and the explosives requirement is often determined by factors such as rock density, compressive strength, and blasting pattern. For example, as the compressive strength of the rock increases, the mine requires more explosives to achieve effective fragmentation (Dotto & Pourrahimian, 2024). Moreover, Terhune (2023) underscored the difficulties inherent in the management of operational costs within the mining sector, particularly in light of the considerable influence exerted by the costs associated with explosives and fuel.

In some of the mine models reviewed, explosives constituted between 62% and 77.5% of the total supply costs, depending on the daily production rate, which ranged from 2,000 to 32,000 tons. Accordingly, a reduction in the use or cost of explosives and fuel can have a considerable impact on the profitability of a mine operation. Other operational costs, such as those associated with hourly labor, frequently represent a significant proportion of the total cost per ton of ore, often accounting for approximately one-third or more. In contrast, labor costs constitute a relatively minor expense in large-scale mining operations, particularly when compared to the costs associated with equipment and consumables. As observed by Buirski (2005), the global industrial explosives market reached a value of $7.1 billion in 2019 and is projected to reach $10.9 billion by 2027, exhibiting a compound annual growth rate of 5.5% between 2020 and 2027. It is therefore necessary to improve the efficiency of mining processes to reduce the consumption of consumables. The intensification of operational activities at the mine site, including the advancement of ore rock development and the generation of additional waste products such as used lubricating oil, has led to a notable increase in overall activity. As the number of heavy equipment and vehicles in use increases, so too does the consumption of lubricants, which in turn results in an increase in waste. According to data from the Ministry of Environment and Forestry's Digital Reporting and Evaluation System (SPEED), used lubricating oil represents the second-largest waste product in the mineral mining industry, surpassed only by tailings (Ministry of Environment and Forestry, 2024). This oil is derived from either crude oil refining (mineral base oil) or chemical synthesis (synthetic base oil) with a hydrocarbon structure comprising carbon atoms ranging from C18 – C40 (Pinheiro et al., 2021). During its use, the lubricant absorbs impurities such as water, metal particles, and organic acids. Despite this, it retains a calorific value similar to diesel, thereby offering the potential to be employed as a component fuel for explosives (Oxley et al., 2002). These analogous characteristics provide a potential avenue for recycling used lubricant waste as a partial solution to the problem of waste generation (Kookos et al., 2011) and could contribute to the reduction of solar as a fossil fuel (Fyffe et al., 2016).

The management of waste oil is of critical importance in mines, as contamination by dust and combustion residues has the potential to accelerate the deterioration of machinery. By implementing regular monitoring and scheduled analysis, mines can reduce the necessity for costly component replacements and prevent equipment failures, which directly impact productivity. For instance, Dominion Diamond Mines saved up to $900,000 over two years by optimizing oil usage by extending drain intervals and reducing equipment downtime (Nazario et al., 2024). This strategy proved effective in reducing the volume of waste lubricants while enhancing overall operational cost efficiency. In accordance with the principles of sustainable mining management set forth by the International Council on Mining and Metals (2024), mining activities must prioritize environmentally conscious production design through the implementation of the 3R concept, encompassing reduction, reuse, and recycling, while ensuring that waste management is conducted in a responsible manner. Accordingly, this study will concentrate on the calculation and analysis of the volume of used lubricating oil, the reduction of the volume of diesel as a component of fuel oil on explosives, and the efficiency of overall production costs. The objective of this analysis is to provide specific recommendations on pertinent environmental aspects, namely through the utilization of the energy contained in lubricating oil to support a circular economy and provide ecological benefits. Thus, the utilization of this waste is expected to reduce dependence on conventional raw materials and make a significant contribution to reducing environmental impacts due to mining activities. The research results can serve as a guideline for the mining industry to enhance the efficiency of resource use, mitigate environmental impacts, and generate economic value from waste management.

2. Methods

2.1 Description of research location

The research location is PT ABC, located within the Batu Hijau Mine in Sekongkang District, West Sumbawa Regency, West Nusa Tenggara Province. This site lies within the boundaries of the Special Mining Business Permit Area for Production Operations, as depicted in Figure 4. The permit, granted by the Minister of Energy and Mineral Resources of the Republic of Indonesia in 2017, remains valid until 2030. The WIUPK spans a total area of 25,000 hectares, divided into four blocks, including the Batu Hijau block, which covers 12,197 hectares and has been under exploitation since 2000.

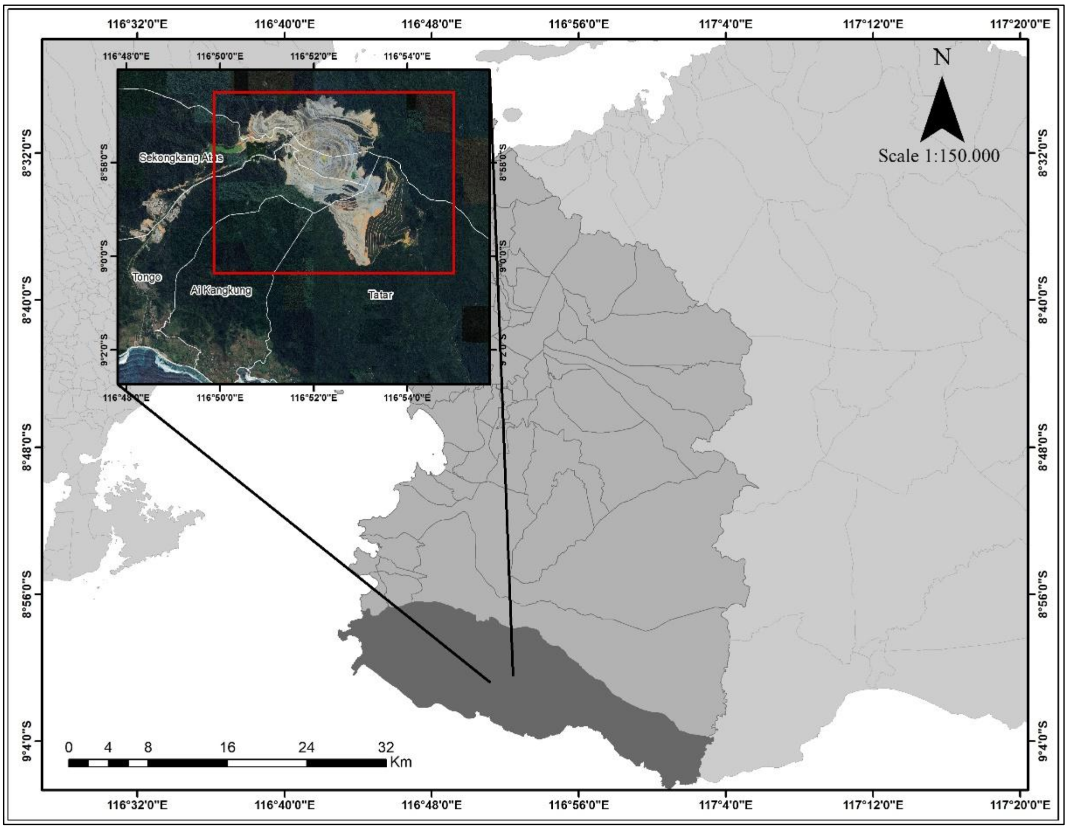


Fig. 4. Special mining business permit area PT ABC
(PT ABC, 2023)

The critical importance of selecting this research location is based on the significance of PT ABC as one of the principal copper producers in Indonesia. The exploitation of this location has been ongoing for over two decades, resulting in a wealth of data and experience related to waste management and resource efficiency. Furthermore, this area has the potential to develop sustainable practices, which are highly relevant in the context of a circular economy and environmental conservation. The focus on a circular economy allows for reduced dependence on conventional raw materials and optimised value from the waste generated, thus encouraging more sustainable mining practices. Additionally, research at this location is expected to contribute to the improvement of responsible mining practices and inform natural resource management policies in Indonesia, in line with the government's efforts to achieve sustainable development goals.

2.2 Research method

This study is based on a quantitative methodology and aims to assess the economic value of utilizing used lubricating oil as a component fuel oil in explosives used in mining activities. The historical data was obtained through an inventory of PT ABC's RKL-RPL Report for the period 2016-2022, which provided information on the generation of used lubricating oil and the need for blasting raw materials. The data will be subjected to statistical assessment to ascertain the potential viability of substitution of diesel with used lubricating oil in the manufacture of ANFO-Emulsion, expressed as a percentage. Based on this percentage, an analysis is carried out to project the need for fuel oil in explosives in the development phase, resulting in the volume of used lubricating oil utilization. Furthermore, based on the price of diesel per liter, the economic value of waste is calculated as a function of the volume of used lubricating oil utilization to represent the potential savings in the cost of procuring diesel as a component fuel oil on explosives.

Furthermore, an analysis was undertaken to ascertain the daily generation of used lubricating oil, with a maximum storage period of 90 days being considered in accordance with Regulation of the Minister of Environment and Forestry Number 6 of 2021 concerning the Procedures, Methods and Requirements for Hazardous Waste Management. A simulation was conducted based on the calculated volume of used lubricating oil utilized with the objective of testing the effectiveness of used lubricating oil utilization to reduce waste accumulation in Temporary Storage Areas, thus ensuring that it does not exceed the permitted storage period. This affords mining companies the opportunity to manage their waste independently, without necessarily relying on third parties. This is compliant with the principle of absolute responsibility in Hazardous Waste Management, whereby the waste producer is held fully responsibility for the impacts and risks that may be caused by the waste throughout its life cycle, including storage and reuse. This study focuses on the utilization of used lubricating oil as an alternative material, which not only reduces dependence on fossil fuels but also reduces the generation of hazardous waste. This approach encourages companies to adopt a more sustainable circular economy paradigm than a linear economy, thereby enhancing their reputation as entities committed to the principles of sustainable environmental management. This study provides a comprehensive analysis of the interrelationship between waste management, cost efficiency, and environmental sustainability in the mining industry.

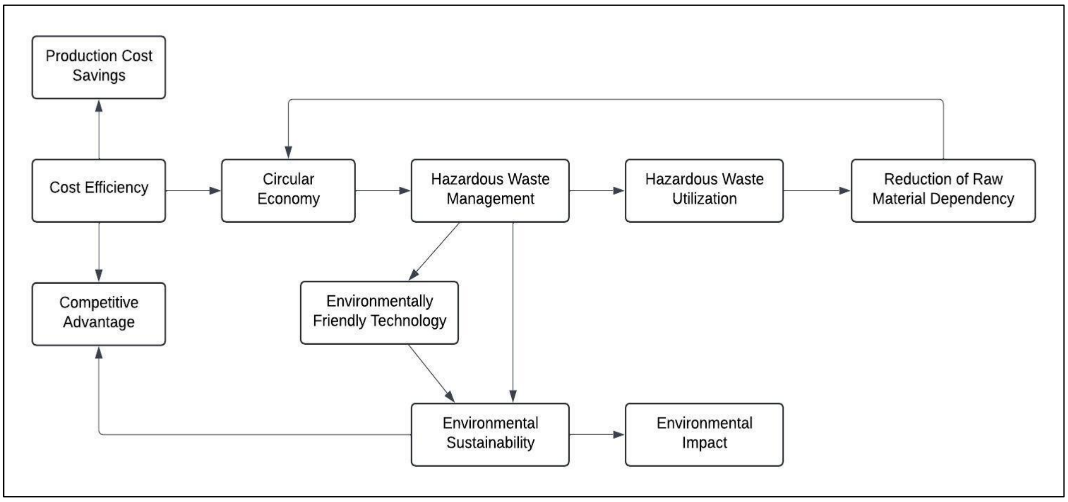


Fig. 5. Schematic of the relationship between waste management, cost efficiency, and environmental sustainability in the mining industry (Geissdoerfer et al., 2017; Hajam et al., 2023; Kalisz et al., 2022; Onifade et al., 2024)

This study applies the circular economy theory, which emphasises the importance of waste utilization in reducing dependence on new raw materials and, consequently, production costs (Geissdoerfer et al., 2017). The implementation of effective waste management strategies enables organisations to achieve a reduction in waste management costs while simultaneously minimising the environmental impact of mining activities, including the prevention of soil and water pollution (Kalisz et al., 2022). The utilization of used lubricating oil in mining operations has the dual benefit of reducing operational costs by eliminating the acquisition of new raw materials and minimizing the volume of waste generated. This demonstrates that effective waste management offers financial advantages while supporting environmental sustainability (Hajam et al., 2023). Moreover, the implementation of environmentally friendly technologies in waste management, such as material and energy recovery systems, has the potential to enhance operational efficiency and reduce the company's carbon footprint (Onifade et al., 2024). Figure 5 illustrates the relationship between waste management, cost efficiency and environmental sustainability. It also demonstrates the interconnectivity between the circular economy, production cost savings and competitive advantage. Consequently, the integration of waste management into mining business strategies can drive cost efficiency, foster more sustainable practices, support environmental conservation and provide a competitive advantage in an increasingly sustainability-focused market. This study represents a novel contribution to the field of waste management, cost efficiency, and environmental sustainability in the mining industry. It provides a historical data-based analysis (2016-2022) of the RKL-RPL Report, which is used to project needs in the mine development phase. This innovative approach offers insights into potential improvements in waste management and cost efficiency in the mining sector.

3. Result and Discussion

3.1 Description of waste utilization plan

Referring to the Regulation of the Minister of Environment and Forestry Number 6 of 2021 concerning Procedures and Requirements for Hazardous Waste Management, hazardous waste is defined as residual materials from operations and/or activities that, due to their characteristics, concentration, and/or quantity, may directly or indirectly pollute, damage, or pose risks to the environment, human health, livelihoods, and other living organisms. The utilization of hazardous waste involves management methods such as reuse, recycling, and/or recovery, aiming to transform it into products that can serve as alternative material or alternative fuel while ensuring safety for human health and the environment. Hazardous waste may be used as a substitute for raw materials if it has similar properties and/or functions as the materials being replaced, provided that the resulting products comply with environmental quality standards as required by applicable laws and regulations.

Used lubricating oil is classified as hazardous waste under Appendix IX of Government Regulation Number 22 of 2021 on the Implementation of Environmental Protection and Management. According to data from the Digital Reporting and Evaluation System (SPEED) managed by the Ministry of Environment and Forestry (2024), industries in Indonesia including the manufacturing, agroindustry, energy, mining, and oil and gas sectors generated approximately 515,490.71 tonnes of used lubricating oil in 2022, increasing to 863,482.58 tonnes in 2023. Of the total generated in 2023, 336,860.66 tonnes were managed, while the remainder remains in storage. Of the managed waste, approximately 50% (167,797.887 tonnes) was utilized as a substitute for raw materials in product manufacturing. This. This predominant use of waste lubricating oil as a raw material substitute highlights its significant potential to reduce dependence on new raw materials, such as diesel. Furthermore, utilizing waste as a feedstock aligns with the principles of a circular economy and helps mitigate the environmental impact of waste disposal.

The mining industry, such as PT ABC, heavily depends on new raw materials, particularly diesel fuel, to support operations like blasting, which is crucial for extracting metal ore through open-pit mining. Blasting involves the preparation of ore and waste rock blocks through drilling, with each block representing one segment per level (bench) and having an approximate volume of 116,000 m^3 per blast (PT ABC, 2023). After drilling, the holes are filled with an emulsion of ammonium nitrate and fuel oil (ANFO) and are detonated using a digital electric detonator. Multiple mine blocks in different areas are often detonated simultaneously. Blasting activities are conducted during the day following precise engineering designs and tight schedules to minimize disruption, even though the mine site is approximately 10 km from the nearest village. The associated effects, including noise, vibration, and dust, are temporary and localized around the mining area. The Peak Particle Velocity (PPV) threshold of 40 mm/s is used as a safety reference for industrial buildings, as it aligns with best practices from the Batu Hijau mine and complies with National Standard 7571:2010 (BSN, 2010a), which governs vibration levels from open-pit mining activities in relation to building safety. In line with PT ABC's planned increase in mining capacity, fluctuations in the volume of used lubricating oil are anticipated. Due to the comparable characteristics and functions of used lubricating oil and fuel oil in explosive formulations, used lubricating oil can be utilized as a substitute for raw materials. This approach offers a practical solution to reduce PT ABC's reliance on fuel oil. The systematic composition of PT ABC's explosive mixture is illustrated in Figure 6.

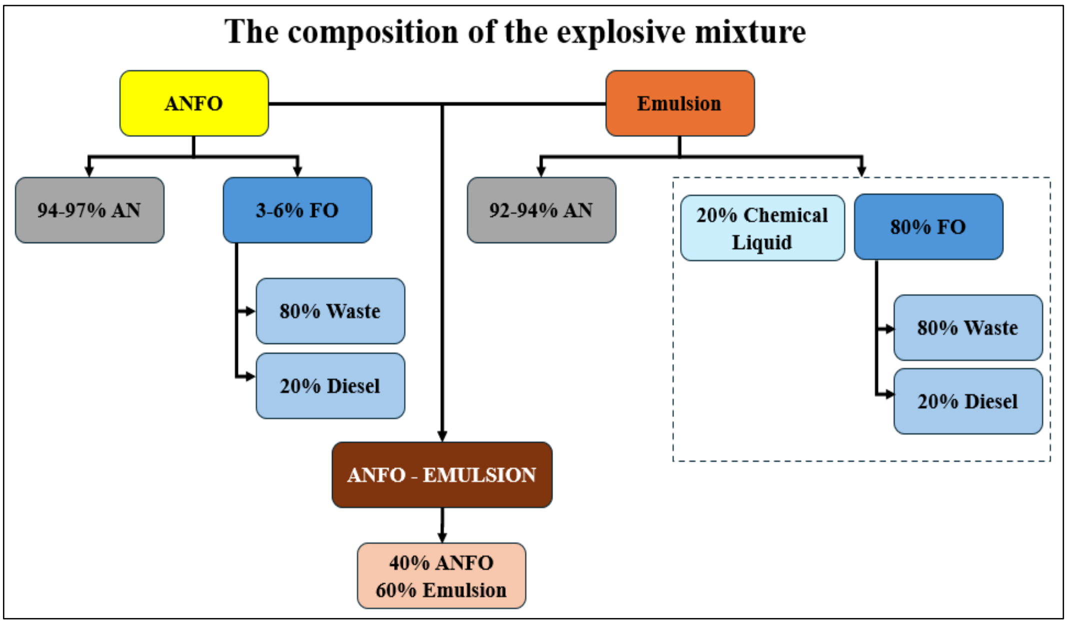


Fig. 6. The composition of the explosive mixture at PT ABC
(Ministry of Environment and Forestry, 2024)

3.2 Results of identification of criteria for utilized waste

Used lubricating oil intended as a substitute for raw materials in producing ANFO-Emulsion must meet the criteria listed in Table 1. PT ABC conducts routine testing at least once a year to ensure that the used lubricating oil meets the criteria for recycling. This waste is generated from the Mine Maintenance Area (MMA), with varying quantities depending on the intensity of mining activities, particularly the transport and processing of ore. Used lubricating oil is primarily utilized as a raw material substitute to produce ANFO-emulsion used in blasting operations. However, used lubricating oil that does not meet the criteria listed in Table 1 is used as an energy source in steam power plants. As a result, the primary focus of used lubricating oil management is on blasting activities, with only a small portion being directed to power plants.

Table 1. Criteria for used lubricating oil before utilize

Parameter	Criteria
Arsenic, As	≤ 5 ppm
Cadmium, Cd	≤ 2 ppm
Chromium, Cr	≤ 10 ppm
Lead, Pb	≤ 100 ppm
Mercury, Hg	≤ 1,2 ppm
PCBs	≤ 2 ppm
Total organic halide (TOX) as Fluoride (F) and Chloride (Cl)	≤ 2%
Sulphur (S)	≤ 3%
Caloric Value	≥ 2,500 kcal/kg

(Appendix XIII Regulation of the Minister of Environment and Forestry Number 6 of 2021)

Used lubricating oil for explosive mixtures is stored in both the quarantine tank and the primary tank. The quarantine tank is used when the lubricating oil has a relatively low level of contamination, typically from engine drain activities in the MMA shop. The primary tank is used when the oil is contaminated with water and requires cleaning with an oil purifier before being transferred to the quarantine tank. Both storage areas, the quarantine and primary tanks, are equipped with secondary containment made of concrete to prevent spills from contaminating the environment. The surface of the secondary containment is designed to slope toward the sump pit, where spills are contained. These spills are directed through pipes to an oil-water separator, where the water is reused for vehicle washing at the MMA wash pad, while the oil is returned to the primary tank.

The utilization of used lubricating oil as a substitute for raw materials in producing ANFO-emulsion consists of two stages. The first stage, involving the blending of fuel oil (FO), is conducted in the MMA area, while the second stage, which involves blending ammonium nitrate (AN), occurs in the explosives warehouse. The FO mixture is transported from the MMA area to the explosives warehouse in an ISO tank, where it is then transferred into a mixing tank to produce ammonium nitrate fuel oil (ANFO) and ammonium nitrate emulsion (ANE). The outcome of the mixing process is stored in a tank. When required, the ANFO-emulsion is delivered to the blasting site by truck. This truck, a Mobile Manufacturing Unit (MMU), is equipped with a compartment for mixing ANFO and emulsion, allowing for the direct production of explosives at the site as needed. This setup provides both flexibility and efficiency in supporting blasting operations at the mine.

3.3 Results of calculation of potential utilization of used lubricating oil

Based on data from the Digital Reporting and Evaluation System (SPEED) managed by the Ministry of Environment and Forestry, as illustrated in Figure 7, the quantity of used lubricating oil at PT ABC experienced a significant increase in 2019 compared to the 2016–2018 period. This increase occurred due to the intensification of mining activities following the change in ownership and the rebranding of the company from PT DEF to PT ABC. Furthermore, during the 2019–2022 period, the development of the mine to Phase 7AC contributed to the increased production of used lubricating oil. In parallel, the utilization of used lubricating oil as a substitute for diesel in producing ANFO-emulsion for blasting activities in the mining area also grew proportionally, reaching 2,483.86 tons by 2022. Conversely, the use of used lubricating oil as fuel in power plants showed a declining trend. Meanwhile, unused and expired lubricating oil, as regulated under Ministerial Regulation Number 6 of 2021 concerning Procedures and Requirements for Hazardous and Toxic Waste Management, is transferred to licensed waste management companies for proper handling.

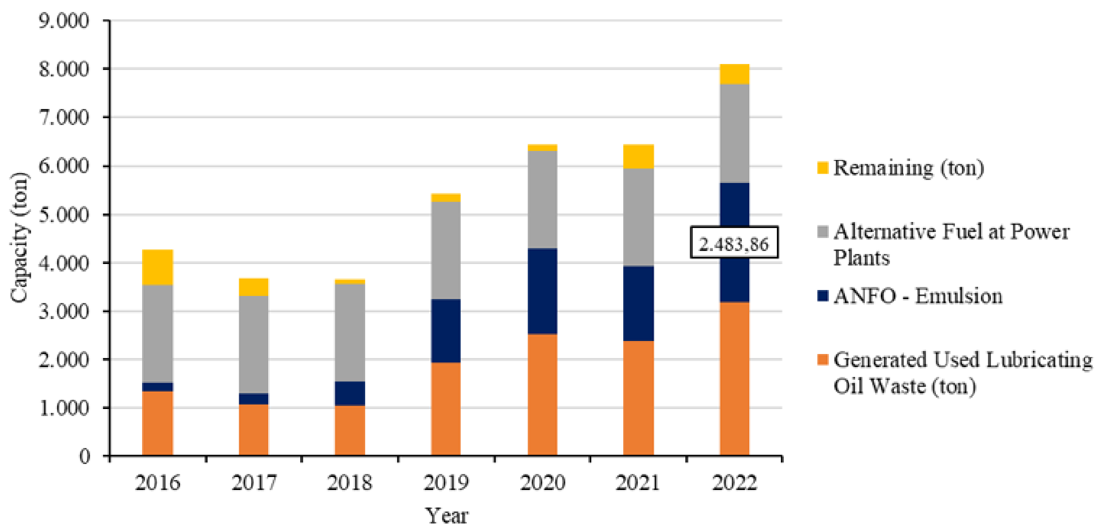


Fig. 7. Used lubricating oil waste balance by PT ABC (2016–2022)
(Ministry of Environment and Forestry, 2023)

Furthermore, based on data from PT ABC's RKL-RPL report, as outlined in Table 2, since the initial phase of mine development up to Phase 7AC in 2019, PT ABC has consistently utilized used lubricating oil as a substitute for diesel fuel in producing ANFO-emulsion for blasting operations. The highest recorded utilization volume reached 2,699,850 liters per year, approaching the maximum limit permitted under the Hazardous Waste Management license of 2,700,000 liters per year, representing a utilization rate of 99.99%. During the ANFO-emulsion manufacturing process, PT ABC blends used lubricating oil and diesel as fuel oil components, maintaining a ratio between 79.2% and 79.9%. This ratio aligns with the maximum allowable limit specified in the B3 Waste Management license (80%) and National Standard 7642:2010 (BSN, 2010b) which governs the procedure for utilizing waste oil in blending ammonium nitrate with fuel oil in open-pit mining operations. This level of achievement demonstrates PT ABC's commitment to sustainable hazardous waste management practices in full compliance with regulatory standards.

Table 2. Ratio consistency of used lubricating oil and diesel in producing anfo-emulsion at PT ABC

Year	Volume of fuel oil (L) (Used lubricating oil)	Volume of fuel oil (L) (Diesel)	Volume of fuel oil (L) (Used lubricating oil ratio)
2019	1,409,327	369,238	79.24%
2020	1,922,994	484,793	79.87%
2021	1,680,235	423,593	79.87%
2022	2,699,850	679,186	79.90%

(PT ABC, 2023)

Based on the drilling data from 2019, the potential for mining ore rock is 1.594 Mt and overburden rock is 4.115 Mt, which can still be developed technically and economically in Phase 8A (PT ABC, 2020). With this potential, the demand for explosives is expected to continue increasing. Figure 8 illustrates the estimate of lubricating used oil generation, fuel oil requirements for explosives, and the capacity of rock being mined by PT ABC from 2023 to 2030.

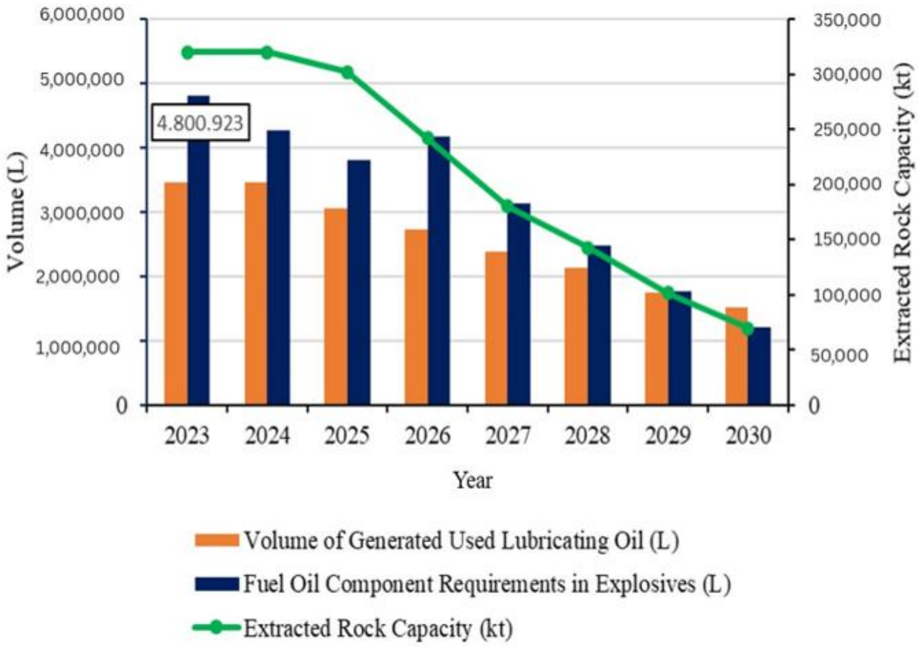


Fig. 8. Estimated used lubricating oil generation and fuel oil component requirements in explosive at PT ABC
(PT ABC, 2023)

The difference between the generated lubricating used oil (represented by the orange bar graph) and the fuel oil requirement for explosives (represented by the blue bar graph) indicates the additional volume of diesel that needs to be supplied by the company.Gradually, this gap narrows as the mining development phase approaches completion. This suggests that, although the generation of lubricating used oil decreases due to reduced mining intensity, from 320,105 kt at the beginning of the development phase to 69,813 kt at the end of mining, the potential for utilizing lubricating used oil as a substitute for diesel in producing ANFO-Emulsion for blasting increases. This condition demonstrates not only a reduction in dependence on fossil fuels such as diesel but also supports the application of a circular economy, enhancing operational efficiency and environmental sustainability.

3.4 Results of calculation of economic value of used lubricating oil

Various theoretical frameworks can be applied to determine the economic value of resources and waste. The theory of renewable resource value, also known as the renewable resource value framework, evaluates the economic benefit of using waste as a replacement for new resources. The economic value is derived by calculating the difference between the cost of utilizing waste and the cost of acquiring new raw materials. This approach conceptualizes waste as a renewable resource that reduces dependency on virgin resources (Pearce & Turner, 1989). The replacement cost theory determines the economic value of waste based on the costs avoided by substituting waste for new resources. This theory primarily highlights immediate financial savings without addressing sustainability or the long-term benefits of circularity (Hourcade et al., 2009). The circular economy and cost savings theory integrates waste into a sustainable production cycle, assessing its value not only from cost savings but also from its potential to minimize environmental impacts. This framework emphasizes long-term efficiency and sustainability by treating waste as a key component of the economic cycle (Geissdoerfer et al., 2017). The primary distinction between these theories lies in their focus. The renewable resource value theory emphasizes the utility derived from waste, while the replacement cost theory prioritizes avoided expenses. In contrast, the circular economy and cost savings theory incorporates waste into a broader framework of sustainability, aligning it with the goals of a circular economy.

In this study, the circular economy and cost savings theory is particularly relevant for evaluating the feasibility of using used lubricating oil as a substitute for diesel in producing explosives for the mining industry. This theoretical framework emphasizes the integration of waste into the production cycle, reducing reliance on fossil fuels such as diesel while addressing challenges associated with waste generation. Consistent with this theory, the use of used lubricating oil as a replacement for diesel represents a sustainable approach that not only utilizes waste as a valuable resource but also aligns with the research objectives of minimizing hazardous waste and improving resource efficiency in mining operations. The economic value of used lubricating oil, under this framework, is reflected in the cost savings from reduced diesel consumption and the mitigation of environmental risks related to excessive waste storage or third-party disposal. Additionally, the theory offers a broader perspective by accounting for long-term financial benefits through recycling and its critical contribution to environmental sustainability. This is particularly significant for the mining sector, which faces considerable waste management challenges as production capacities grow. Beyond cost advantages, this theory supports sustainable practices that enhance corporate reputation by positioning companies as environmentally responsible entities, as demonstrated in the findings of Kookos et al. (2011) and Fyffe et al. (2016). The alignment of financial, operational, and environmental benefits highlights the critical role of integrating circular economy principles into industrial processes, particularly in resource-intensive sectors such as mining. Referring to the theory of circular economy and cost savings, the economic value of waste is formulated as follows:

$$Economic\ value = Purchase\ cost \times utilization\ percentage \quad \text{(Eq. 1)}$$

$$Cost\ savings = Purchase\ cost - economic\ value \quad \text{(Eq. 2)}$$

The purchase cost refers to the diesel purchase cost each liter, which is IDR12,700.00 based on the price adjustment effective from October 1st, 2024, in West Nusa Tenggara Province regarding to Decree of the Minister of Energy and Mineral Resources Number 245.K/MG.01/MEM.M/2022 concerning Amendments to the Decree of the Minister of Energy and Mineral Resources Number 62.K/12/MEM/2020 concerning the Basic Price Formula in Calculating the Retail Selling Price of General Fuel Types of Gasoline and Diesel Oil Distributed Through General Fuel Filling Stations and/or Fishermen's Fuel Filling Stations. The Utilization percentage represents the average potential utilization of used lubricating oil, which, based on discussions in section C, is determined to be 79.72%. Based on Eq. 1 and Eq. 2, the calculation proceeds as follows:

Economic value (per liter of waste) = IDR12,700.00 x 79.72% = IDR10,124.44 (Eq. 3)

Cost savings (per liter of diesel) = IDR12,700.00 - IDR10,124.44 = IDR2,575.56 (Eq. 4)

The economic benefits and cost reductions achieved by PT ABC since the start of Phase 7AC mine development in 2019 are shown in Table 3. During this phase, the company successfully replaced diesel with used lubricating oil in the production of ANFO-emulsion for blasting. This change led to a steady rise in the consumption of both used lubricating oil and diesel, resulting in significant increases in the economic value of waste and savings on diesel costs over time. On the other hand, Table 4 presents the projected economic value and cost savings for PT ABC's Phase 8A operations, which began in 2023.

Table 3. The economic value of waste and the diesel costs savings for PT ABC during phase 7AC

Year	Volume fuel oil (L) (Used lubricating oil)	Volume fuel oil (L) (Diesel)	Volume fuel oil (L) (Economic value of waste)	Volume fuel oil (L) (Diesel cost savings)
2019	1,409,327	369,238	IDR,14,268,646,652	IDR,950,994,623
2020	1,922,994	484,793	IDR,19,469,237,373	IDR,1,248,613,459
2021	1,680,235	423,593	IDR,17,011,438,443	IDR,1,090,989,187
2022	2,699,850	679,186	IDR,27,334,469,334	IDR,1,749,284,294

(PT ABC, 2023)

The data show a peak in used lubricating oil consumption and diesel savings in the first year, followed by a gradual decline until 2030. Together, these phases reflect PT ABC's strategic efforts to reduce diesel reliance and enhance operational cost efficiency. An evaluation of the mine development in Phases 7AC and 8 indicates that PT ABC is expected to reach its peak mining activity in 2023. Accordingly, the company has successfully optimized the use of used lubricating oil, generating an economic value of IDR,38,885,321,437. This optimization has resulted in a reduction of diesel procurement costs by IDR,2,473,012,791.

Table 4. The economic value of waste and the diesel costs savings for PT ABC during phase 8A

Year	Volume fuel oil (L) (Used lubricating oil)	Volume fuel oil (L) (Diesel)	Volume fuel oil (L) (Economic value of waste)	Volume fuel oil (L) (Diesel cost savings)
2023	3,840,738	960,185	IDR,38,885,321,437	IDR,2,473,012,791
2024	3,840,738	852,818	IDR,34,537,218,688	IDR,2,196,483,928
2025	3,040,472	760,118	IDR,30,783,076,336	IDR,1,957,729,516
2026	3,343,861	835,965	IDR,33,854,720,063	IDR,2,153,078,659
2027	2,505,511	626,378	IDR,25,366,895,789	IDR,1,613,273,478
2028	1,980,696	495,174	IDR,20,053,437,810	IDR,1,275,350,347
2029	1,416,715	354,179	IDR,14,343,446,015	IDR,912,208,621
2030	970,619	242,655	IDR,9,826,973,828	IDR,624,971,868

(PT ABC, 2023)

3.5 Discussion

The sustainable development strategy encompasses five key dimensions that collectively form the foundation for achieving long-term prosperity. The first dimension, economic stability, emphasizes efficient resource allocation and strategic management, supported by private investment and sustainable government policies. This economic base is vital for fostering the resources required to sustain progress in other dimensions, ensuring a stable platform for social and environmental development. The second dimension, social sustainability, highlights the need for equitable distribution of assets and income to reduce social inequalities. This approach seeks to ensure fairness and inclusivity in the development process. The third dimension, ecological sustainability, focuses on preserving the natural environment by minimizing reliance on non-renewable resources, reducing waste and pollution, and adopting environmentally friendly technologies. This is critical for maintaining ecological balance and safeguarding natural resources for future generations. The fourth dimension, sustainable spatial planning, plays a pivotal role in integrating these aspects. It involves the coordination of land use, transportation, energy systems, and infrastructure to harmonize economic, social, and environmental objectives. Finally, cultural continuity serves as the fifth dimension, achieved through modernizing agricultural practices and other cultural processes that maintain societal traditions. This integration is fundamental to minimizing the environmental impacts of development while ensuring an improved quality of life for both present and future generations (Ahmadi & Toghyani, 2011).

The progress of a nation is intrinsically linked to the development of its population, making socio-economic advancement and the enhancement of societal welfare critical for national growth. Industrialization and urbanization, often regarded as indicators of economic development, have also been identified as significant contributors to the increased generation of hazardous waste (Saeidi-Mobarakeh et al., 2020). In accordance with the United Nations Environmental Programme (UNEP), waste is classified as hazardous waste if it possesses one or more characteristics that have the potential to cause significant adverse effects. These include the capacity to ignite during routine handling, corrosivity when exposed to air or specific conditions, chemical reactions that result in the production of toxic gases, and long-term impacts on the environment, geology, and ecology. Given these risks, the sustainable management of hazardous waste is essential for ensuring a safe, clean, and environmentally sustainable future. This objective can be achieved through the implementation of policies and strategies that align with environmental standards. However, the efficient and cost-effective of hazardous waste management often requires the integration of various advanced technologies. A key challenge lies in designing and operating industrial projects that are both sustainable and environmentally friendly while addressing the economic constraints of hazardous waste treatment (Safdar et al., 2020). Therefore, careful planning, policy frameworks, and technological innovation are indispensable for realizing sustainable waste management solutions.

The concepts of waste utilization and the circular economy are closely interconnected frameworks that promote environmental sustainability. Waste utilization focuses on converting hazardous waste into products that can replace raw materials or fuels while ensuring safety for both human health and the environment. This aligns with the guidelines set out in Regulation of the Minister of Environment and Forestry Number 6 of 2021 concerning Procedures and Requirements for Hazardous Waste Management. Conversely, the circular economy emphasizes the development of sustainable products, waste minimization, and efficiency improvements to address environmental, economic, and social challenges. By integrating the cradle-to-cradle and circular economy principles, waste recycling is encouraged, facilitating the transformation of waste into new, usable products. This approach not only reduces the environmental impact but also generates employment opportunities and fosters the growth of environmentally friendly industries. Consequently, effective waste management becomes a pivotal strategy for waste utilization into valuable resources, thereby supporting ecosystem sustainability and advancing holistic development (Bandh et al., 2023).

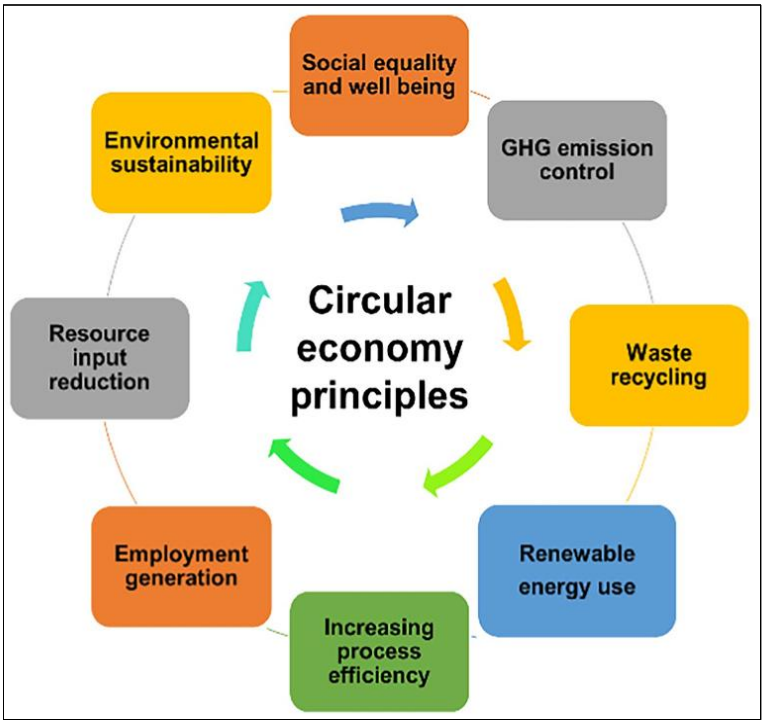


Fig. 9. Circular economy guidelines in waste management (Kumar et al., 2023)

The 3R framework, comprising reduction, reuse, and recycling, is a cornerstone of the circular economy. In the mining industry, the 3R scheme is implemented by PT ABC through the utilization of used lubricating oil as a substitute for diesel in producing ANFO-emulsion, which is used for blasting activities in the mining area. This initiative achieves dual objectives, reducing the volume of waste lubricants and minimizing the reliance on fossil fuels like diesel, which have a higher environmental impact. Additionally, this practice provides economic benefits, such as lowering raw material costs and creating employment opportunities in waste management and recycling units. These outcomes align with the broader principles of the circular economy, as illustrated in Figure 9. The circular economy framework extends beyond environmental sustainability by incorporating significant social and economic advantages. For instance, the European Union has expanded the traditional 3R model into a 10R scheme, including measures like redesign, repair, and remanufacturing. Nevertheless, the 3R strategy remains central to the circular economy, as it is widely regarded as the most effective approach for ensuring long-term sustainability for future generations (Kumar et al., 2023).

4. Conclusions

The utilization of used lubricating oil by PT ABC as a substitute for diesel in producing ANFO-Emulsion for blasting activities in the mining area has demonstrated significant benefits in terms of cost efficiency and environmental sustainability. Since the initiation of the Phase 7AC mine development in 2019, the use of up to 2,699,850 L/year of used lubricating oil has achieved a 99.99% compliance rate with the company's Hazardous Waste Utilization Permit. This practice has enabled the replacement of up to 80% of diesel fuel needs, yielding economic savings of IDR38,885,321,437 in 2023 and reducing diesel procurement costs by IDR,2,473,012,791. Additionally, it has contributed to reducing reliance on fossil fuels while aligning with circular economy principles by converting waste into valuable resources.

Despite these promising results, several limitations must be acknowledged. First, the environmental risks associated with long-term use of used lubricating oil as a fuel substitute, particularly its potential effects on soil, water, and air quality in mining areas, remain insufficiently studied. Furthermore, the variability in waste oil quality and the potential operational challenges of scaling this practice across diverse mining environments may limit its broader application. The need for comprehensive life-cycle assessments and robust monitoring systems also poses a significant challenge for ensuring sustainable and safe implementation.

Future research could address these limitations by a evaluating the long-term environmental impacts of used oil utilization, including it's a interactions with surrounding ecosystems. Studies could also explore advancements in oil purification technology to a enhance efficiency and minimize potential contaminants. Additionally, assessing the feasibility of adopting this approach in varied mining conditions and regions, alongside identifying the necessary policy frameworks and regulatory incentives, would provide valuable insights for the industry and policymakers. In conclusion, while the use of a used lubricating oil as a substitute for diesel shows great potential for a cost savings and environmental benefits, a deeper understanding of its long-term effects and optimization strategies is essential. Advancing research in these areas will help establish a robust foundation for a sustainable mining practices that align with global environmental goals.

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Author Contribution
The author solely conceptualized the study, collected and analyzed data, interpreted findings, and prepared the manuscript, ensuring accuracy, originality, and compliance with research standards.

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References

Ahmadi, F., & Toghyani, S. (2011). The role of urban planning in achieving sustainable urban development. *OIDA International Journal of Sustainable Development*, *2*(11), 23-26. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1980454

Appendix XIII Regulation of the Minister of Environment and Forestry Number 6 of 2021. (2021). *Peraturan Menteri Lingkungan Hidup dan Kehutanan Republik Indonesia Nomor 6 Tahun 2021 tentang Tata Caraa dan Persyaratan Pengelolaan Limbah Bahan Berbahaya dan Beracun*. https://peraturan.bpk.go.id/Details/211000/permen-lhk-no-6-tahun-2021

Appendix IX of Government Regulation Number 22 of 2021. (2021). *Peraturan Pemerintah Nomor 22 Tahun 2021 tentang Pedoman Perlindungan dan Pengelolaan Lingkungan Hidup. In Peraturan Pemerintah Nomor 22 Tahun 2021 tentang Penyelenggaraan Perlindungan dan Pengelolaan Lingkungan Hidup*. https://peraturan.bpk.go.id/Details/161852/pp-no-22-tahun-2021

Asmiani, N., Widodo, S., & Sibali, M. G. D. (2016). Efektifitas pengeboran kedalaman bor rata-rata. *Jurnal Geomine, 4*(2), 80–82. https://doi.org/10.33536/jg.v4i2.57

Bandh, S. A., Malla, F. A., Wani, S. A., & Hoang, A. T. (2023). Waste management and circular economy. In *Waste management in the circular economy* (pp. 1–17). Springer International Publishing. https://doi.org/10.1007/978-3-031-42426-7_1

BSN. (2010a). *SNI 7571:2010 tentang Baku Tingkat Getaran Pada Kegiatan Tambang Terbuka Terhadap Bangunan*. Badan Standarisasi Nasional.

BSN. (2010b). *SNI 7642:2010 tentang Tata Cara Pemanfaatan Oli Bekas untuk Campuran Amonium Nitrat dengan Fuel Oil pada Tambang Terbuka*. Badan Standarisasi Nasional.

Buirski, D. (2005). Market overview. In *Textiles in sport* (pp. 15–24). Woodhead Publishing. https://doi.org/10.1533/9781845690885.1.15

Dotto, M. S., & Pourrahimian, Y. (2024). The influence of explosive and rock Mass properties on blast damage in a single-hole blasting. *Mining*, *4*(1), 168-188. https://doi.org/10.3390/mining4010011

Fyffe, J. R., Breckel, A. C., Townsend, A. K., & Webber, M. E. (2016). Use of MRF residue as alternative fuel in cement production. *Waste Management*, *47*, 276-284. https://doi.org/10.1016/j.wasman.2015.05.038

Geissdoerfer, M., Savaget, P., Bocken, N. M., & Hultink, E. J. (2017). The Circular Economy–A new sustainability paradigm?. *Journal of cleaner production*, *143*, 757-768. https://doi.org/10.1016/j.jclepro.2016.12.048

Hajam, Y. A., Kumar, R., & Kumar, A. (2023). Environmental waste management strategies and vermi transformation for sustainable development. *Environmental Challenges*, *13*, 100747. https://doi.org/10.1016/j.envc.2023.100747

Hourcade, J. C., Ambrosi, P., & Dumas, P. (2009). Beyond the Stern Review: Lessons from a risky venture at the limits of the cost–benefit analysis. *Ecological Economics*, *68*(10), 2479-2484. http://dx.doi.org/10.1016/j.ecolecon.2009.04.011

International Council on Mining and Metals. (2024). *Our Principles*. FutureLearn. https://www.futurelearn.com/about/our-principles

Kalisz, S., Kibort, K., Mioduska, J., Lieder, M., & Małachowska, A. (2022). Waste management in the mining industry of metals ores, coal, oil and natural gas - A review. *Journal of Environmental Management*, *304*, 114239. https://doi.org/j.jenvman.2021.114239

Kookos, I. K., Pontikes, Y., Angelopoulos, G. N., & Lyberatos, G. (2011). Classical and alternative fuel mix optimization in cement production using mathematical programming. *Fuel*, *90*(3), 1277–1284. https://doi.org/10.1016/j.fuel.2010.12.016

Kumar, A., Thakur, A. K., Gaurav, G. K., Klemeš, J. J., Sandhwar, V. K., Pant, K. K., & Kumar, R. (2023). A critical review on sustainable hazardous waste management strategies: a step towards a circular economy. *Environmental Science and Pollution Research*, *30*(48), 105030–105055. https://doi.org/10.1007/s11356-023-29511-8

Ministry of Energy and Mineral Resources. (2020). *Booklet Tambang Tembaga 2020*. https://www.esdm.go.id/id/booklet/booklet-tambang-tembaga-2020

Ministry of Environment and Forestry. (2024). *Sistem Pelaporan dan Evaluasi Digital (SPEED) (Vol. 3)*. https://www.transporter.nonferindoutama.com/artikel/mengenal-speed-2024-klhk-sistem-pelaporan-dan-evaluasi-digital-pengganti-siraja-2024

Ministry of Industry. (2015). *Rencana Induk Pembangunan Industri Nasional 2015 - 2035*.

Moorthy, N. T., Hamdan, H. H., & Phang, C. C. (2012). Identification of fuel oil in absorbent and non-absorbent surfaces in a site of ammonium nitrate-fuel oil (ANFO) blast. *Malaysian Journal of Forensic Sciences*, *3*(1), 26–35. https://www.forensics.org.my/mjofs/volume3no1.php

Nazario, B. C., Technical, S., & Advisor, S. (2024). *Oil monitoring and used oil analysis: Best practices for Read the Expert Q & A HYDREX™ AW Technical Experts at Work for You*. HYDREX. https://www.hydrex.com/oil-monitoring-and-used-oil-analysis-best-practices-for-read-the-expert-q-a-hydrex-tm-aw-technical-experts-at-work-for-you

Onifade, M., Zvarivadza, T., Adebisi, J. A., Said, K. O., Dayo-Olupona, O., Lawal, A. I., & Khandelwal, M. (2024). Advancing toward sustainability: The emergence of green mining technologies and practices. *Green and Smart Mining Engineering*, *1*(2), 157–174. https://doi.org/10.1016/j.gsme.2024.05.005

Oxley, J. C., Smith, J. L., Rogers, E., & Yu, M. (2002). Ammonium nitrate: Thermal stability and explosivity modifiers. *Thermochimica Acta*, *384*(1–2), 23–45. https://doi.org/10.1016/S0040-6031(01)00775-4

Pearce, D. W., & Turner, R. K. (1989). *Economics of natural resources and the environment*. Johns Hopkins University Press.

Pinheiro, C. T., Quina, M. J., & Gando-Ferreira, L. M. (2021). Management of waste lubricant oil in Europe: A circular economy approach. *Critical Reviews in Environmental Science and Technology*, *51*(18), 2015–2050. https://doi.org/10.1080/10643389.2020.1771887

PT ABC. (2023). *Laporan RKL-RPL PT ABC*.

Saeidi-Mobarakeh, Z., Tavakkoli-Moghaddam, R., Navabakhsh, M., & Amoozad-Khalili, H. (2020). A bi-level and robust optimization-based framework for a hazardous waste management problem: A real-world application. *Journal of Cleaner Production*, *252*, 119830. https://doi.org/10.1016/j.jclepro.2019.119830

Safdar, N., Khalid, R., Ahmed, W., & Imran, M. (2020). Reverse logistics network design of e-waste management under the triple bottom line approach. *Journal of Cleaner Production*, *272*, 122662. https://doi.org/10.1016/j.jclepro.2020.122662

Subowo, G. (2011). Penambangan sistem terbuka ramah lingkungan dan upaya reklamasi pasca tambang untuk memperbaiki kualitas sumberdaya lahan dan hayati tanah. *Jurnal Sumberdaya Lahan*, *5*(2), 83–94. https://doi.org/10.21001/jsl.v5i2.132706

Terhune, B. (2023, February 14). *CostMine: Yes, costs have risen*. Canadian Mining Journal. https://www.canadianminingjournal.com/featured-article/costmine-yes-costs-have-risen/

Tresnadi, H. (2014). Perkembangan industri tembaga global sebagai masukan untuk pengembangan industri tembaga nasional. *Prosiding Temu Profesi Tahunan (TPT) XXIII Perhimpunan Ahli Pertambangan Indonesia (PERHAPI)*, 162. https://123dok.com/document/ydmjr5jy-temu-profesi-tahunan-tpt-xxiii-perhapi-makassar-november.html

U.S. Geological Survey. (2024). *Mineral commodity summaries 2024: Copper*. U.S. Geological Survey. https://doi.org/10.3133/sir20185160

Yuni, D. N., Makhetha, L. S., & Lelimo, S. (2023). Analyzing the relationship between Industrialization and economic growth in Lesotho. *Cogent Economics and Finance*, *11*(2). https://doi.org/10.1080/23322039.2023.2285620

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