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Research article

A systematic review of geological resource containing nickel: Resource, distribution, mining, extraction, and advanced material synthesis

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ABSTRACT

Nickel ore is the main source of nickel, an important metal used in many modern materials. This paper gives a brief overview of different aspects of nickel ore, such as its history, types, distribution, demand, and the technology used for mining and processing it. The two main types of nickel ore are nickel sulfide ore and laterite ore. Indonesia has significant nickel ore deposits, primarily in the form of laterite, due to its tropical climate with high temperatures and rainfall. Nickel is essential for making various important materials like stainless steel, special alloys, plating, and batteries. Laterite also contains other valuable elements like iron, magnesium, silicon, and oxygen, found in compounds such as goethite, nickel oxide, magnesium silicate, and quartz. Laterite ore can be processed to produce nickel matte, ferronickel, and nickel pig iron. The paper also discusses advanced materials made from laterite ore, including photocatalysts and batteries. Mining and processing activities have both positive and negative effects on local communities. To minimize negative impacts, it is important to consider the satisfaction of both the local community and the government in the initial planning of mining and processing projects.

INTRODUCTION

Indonesia has various geological resources containing valuable elements such as gold, silver, copper, iron, nickel, cobalt, tin, platinum, zinc, etc. (Brown et al., 2020; Nazir et al., 2020). Each metal has a particular function in the modern world; for example, gold and silver are extracted and refined for accessories, and copper is used as a conductive material and alloying element. As for nickel, it is used as an alloying element in various steel due to its ability to increase strength, especially at elevated temperatures (Mohrbacher and Kern, 2023). The most popular application of nickel is as an alloying element in stainless steel, the most distributed structural metal in the world. The demand for stainless steel is among the indications of a country's infrastructure development. Nickel resources are obtained from two types of ore deposits, sulfide ores, and laterite ores, with about 70% of nickel resources found in the form of laterite (Pandey et al., 2023). Because of its low grade, technology is needed to extract nickel from laterite ore either through high-temperature processing or low-temperature processing (Keskinkilic, 2019).

Nickel laterites play a crucial role in the global nickel industry, currently representing about 40% of the total nickel production (Elias, 2002). These laterites also contribute significantly to the economies of the regions where they are located (Lemougna et al., 2011). As the source of nickel, nickel ore does not contain only nickel but also contains associated minerals that can be converted into usable materials (Moskalyk and Alfantazi, 2002). As a key industrial metal, nickel is widely utilized in industries such as steel production (71%), alloys (12%), electroplating (8%), batteries (6%), and casting (3%), due to its excellent mechanical strength, ductility, magnetism, and high chemical stability. Since the early 21st century, its use has expanded beyond traditional sectors like stainless steel and electroplating to emerging fields such as new energy and advanced materials (Pandey et al., 2023; Zhang et al., 2024).

The investigation into the potential applications of all components within nickel ore necessitates a comprehensive background review that outlines the ore's transformation from a significant deposit to a modern material. This paper provides a succinct overview of this transformation, aiming to assist the reader in linking nickel ore as a geological resource to its various utilization activities.

METHODOLOGY

The method used in this paper is connecting relevant information from various sources with different scientific or engineering backgrounds related to nickel ore and its utilization. Scientific papers from journals and books are the primary basis for the discussion, as well as information from various websites on the Internet. The recent developments regarding nickel ore deposit, mining, and processing are combined with the possibility of synthesizing advanced materials from nickel ore.

The secondary data collected and analyzed in this manuscript is categorized into two groups: research papers and industry data from established technologies. The references included are relevant articles from indexed or accredited journals, all of which have undergone peer review. In contrast, the industry data pertains to recent applications of technology and market insights.

DISCUSSION

Geological Resource of Nickel

Nickel is primarily sourced from two geological types: (1) Nickel sulfide ore and (2) Laterite ore (Mudd and Jowitt, 2014). Various research have extensively examined the genesis of nickel sulfide ore. This type of ore is believed to originate from the partial melting of the Earth's mantle, followed by the segregation and concentration processes that enhance the nickel and other elemental content within silicate magma. This is subsequently accompanied by a reaction with sulfur derived from sedimentary rocks at rift zones, leading to the formation of sulfide minerals (Naldrett et al., 1979; Naldrett, 2004; Barnes and Lightfoot, 2005). In contrast, laterite ore is produced through the weathering of serpentine rock in humid tropical environments (Butt and Cluzel, 2013). Consequently, laterite deposits are predominantly found in tropical regions characterized by high temperatures and significant rainfall, which facilitate the weathering processes of the underlying rocks.

Weathering is a geological term that describes a physical and chemical process caused by weather factors on the rock near the mantle's surface. Climate, including high temperature and rainfall, is the prime factor in weathering on laterite soil (Loughnan, 1969; Gidigasu, 1976). The weathering process converted minerals in the rock into clay, followed by a leaching and deposition process that removed silica and left iron and aluminum oxides at the site (Persons, 1970).

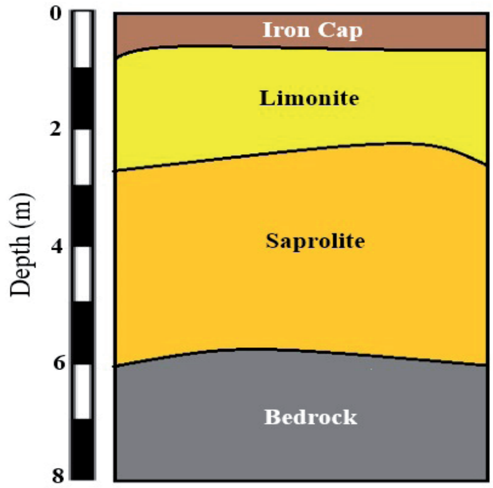

Figure 1 The typical composition of the laterite layer
(Redrawn from Tamehe et al. (2024))

The degree of weathering process on the rock or minerals depends on the depth of the rocks or minerals from the surface; such different degrees result in a gradient of layers with different compositions. Figure 1 illustrates a block of laterite characterized by these distinct gradient layers. The uppermost layer consists of soil rich in iron, commonly referred to as an iron cap. In Indonesia, laterite typically features this iron cap layer, which overlays the underlying strata. Conversely, laterite found in regions outside of Indonesia generally lacks this iron cap (Tamehe et al., 2024). The subsequent layer is composed of limonite, which contains nickel, cobalt, iron, and magnesium oxide in weight percentages ranging from 0.8-1.5%, 0.1-0.2%, 40-50%, and 0.5-5%, respectively. Below this, the third layer is identified as saprolite, with nickel, cobalt, iron, and magnesium oxide present in weight percentages of 1.5-2%, 0.02-0.1%, 10-25%, and 15-35%, respectively (Kyle J, 2010). The deepest layer is the bedrock, characterized by minimal concentrations of nickel, cobalt, and iron, but a significant presence of magnesium oxide. The variations in the elemental composition of metals and magnesium oxides across these layers suggest that magnesium oxide was removed during the weathering process. In contrast, nickel, iron, and cobalt stayed at the site.

Historical Background of Laterite Terminology

The term “laterite” originated in the 19th century when Buchanan (1807), during his exploration of Madras and Malabar in India, encountered a soil-like substance characterized by intermingled granite devoid of quartz or feldspar veins, enveloped in a dark black crust. The local populace referred to this substance as “brick stone,” prompting Buchanan to adopt the term “laterite,” which translates to “brick stone” in Latin. Subsequently, this designation has been applied to both analogous and dissimilar materials exhibiting similar appearances. The ambiguity surrounding the term “laterite” led soil and rock specialists of that era to define it as a soil horizon of sufficient thickness that contains elevated levels of iron and aluminum (Persons, 1970). This material typically results from the weathering processes of igneous and metamorphic rocks in hot, humid climates, conditions frequently found in tropical regions.

Economic Aspect of Laterite Ore

Laterite is composed of metal oxides that possess significant economic potential upon extraction. Nickel laterite ore specifically refers to a category of ore rich in valuable metal oxides, particularly nickel. This metal is extensively utilized in the production of a range of strategic materials in contemporary society, including stainless steel, specialized alloys, electroplating, and batteries (Dilshara et al., 2024). The growth of infrastructure and industries in developed and developing countries in recent years caused an increase in the consumption of stainless steel and other materials, which led to a significant increase in nickel demand. Figure 2 shows that the demand for nickel increases every year, with the highest consumption of nickel held by the stainless steel and nickel foundry alloy industries (Mitchell and Pickens, 2022). However, it is predicted that in the future, electric vehicles will replace fossil fuel vehicles, which, in turn, will increase the nickel demand for battery industries to 41 % of the total world consumption of nickel. (Mitchell and Pickens, 2022). Since nickel is the raw material for nickel-based batteries, the demand for laterite as one of the nickel sources will obviously skyrocket.

Figure 3 presents the distribution of nickel sulfide and nickel laterite deposits in various places in the world. The ratio of nickel laterite and nickel sulfide resources is 70:30, but the ratio of nickel production from laterite and sulfide ore is 30:60 (Crundwell et al., 2011). The gap in resource and output is caused by the nature of laterite ore, which contains some minerals that cannot be economically processed to produce nickel metal

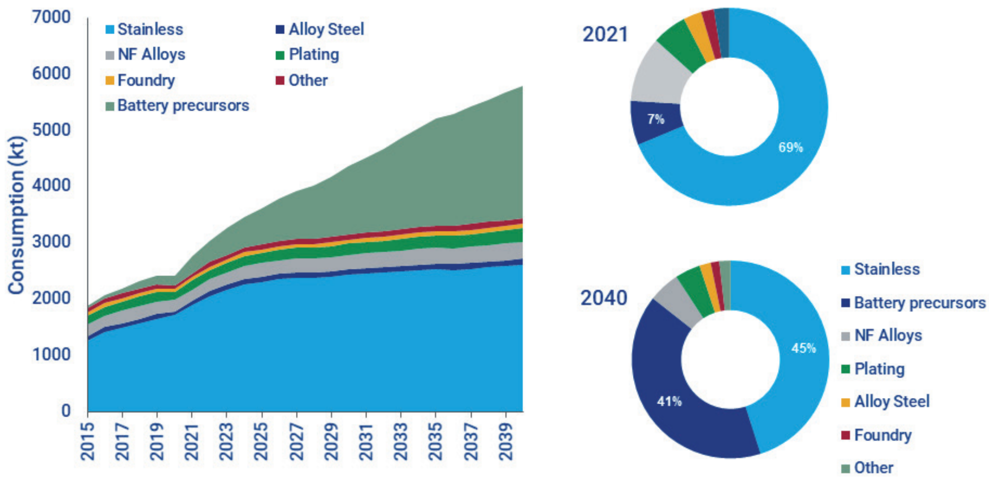

Figure 2. Nickel consumption in various industries (Mitchell and Pickens, 2022)

Figure 3. Distribution of nickel laterite and nickel sulphide ores in the world

(Redrawn based on data from Elias, 2002)

Significant deposits of nickel ore are located in various regions, including Indonesia, Western Australia, South America, Brazil, Russia, the Philippines, and New Caledonia (Einhorn, 2015). Indonesia alone possesses a substantial reserve of 2.1 million tons of nickel ore, primarily in the form of laterite, which constitutes 21% of the global nickel ore reserves (Table 1). The overall nickel ore resources in Indonesia are estimated at 17.7 billion tons, indicating that approximately 12.5 billion tons remain untapped in greenfield resources (Ministry of Energy and Mineral Resource Republic of Indonesia, 2023). Moreover, Indonesia holds the largest nickel reserves in the world, representing 20,6 % of the global nickel reserves (Table 1). The rising demand for nickel, particularly for applications in stainless steel and batteries, necessitates the exploration of these greenfield resources. A notable surge in demand for nickel is evidenced by a marked increase in laterite ore prices in 2024, with prices for nickel laterite ore containing 1.2% and 1.6% nickel rising by over 16% and 50%, respectively (Gerber Group, 2024).

Table 1. Global distribution of nickel ore reserve

Country	Reserve (tons)	Reserve (%)
Indonesia	21,000,000	20,6
Australia	21,000,000	20,6
Brazil	16,000,000	15,7
Rusia	7,500,000	7,3
New Caledonia	7,100,000	7
Philippine	4,800,000	4,7
Canada	2,200,000	2.1
China	2,100,000	2
Others	20,370,000	20
Total	102,070,000	100

(calculated based oh the data from U.S. Geological Survey, 2023)

Mining of Nickel Ore

Mining activity consists of four stages: prospecting, exploration, development, and exploitation (Gabarrón et al., 2019). The initial phase, prospecting, involves geologists collecting evidence of mineral deposits in specific regions, utilizing either direct geological methods or indirect geophysical techniques. The reliability of the data obtained during prospecting is further refined through exploration activities, which yield detailed information regarding the tonnage, grade, and overall richness of the identified deposits.

Subsequent to the exploration phase, a feasibility study is conducted to assess the viability of transforming the deposit into an operational mine, which may employ either open-pit or underground mining methods. The selection of the appropriate mining technique is primarily influenced by the deposit's depth and geometric configuration. Deposits that are relatively shallow are typically extracted using open-pit mining, whereas those located at greater depths necessitate underground mining methods (Hamrin, 1987). Nickel sulfide deposits, which originate from magma-related processes deep within the Earth's crust, are predominantly mined using underground techniques. Conversely, nickel laterite ores, found closer to the surface, are generally extracted through open-pit mining methods. The cost of underground mining is higher than that of open pit mining; however, by using underground mining, the social and environmental effects at the surface can be reduced (Hartman, 1987). The extraction of metals from both sulfide and laterite ores often requires technologies due to the complex nature of the ores. Common methods used on a commercial scale to extract nickel and other metals from laterite include (1) high-temperature processing to produce ferro-nickel or matte and (2) low-temperature processing through caron technology and high-pressure acid leaching.

High-Temperature Processing of Nickel Sulfide and Nickel Laterite Ores

Production of nickel matte

The process of extracting nickel metal from its ore is influenced by several factors, including the specific type of ore, the valuable minerals present, and the gangue minerals associated with the ore. The initial method developed for nickel extraction from nickel ore is the processing of sulfide ores. Typical compositions of nickel sulfide ores range from 3.6% to 12.7% nickel, 0.16% to 11% copper, 0.13% to 0.27% cobalt, along with very low quantities of platinum group metals and rare earth elements (Naldrett et al., 1979). Firstly, the sulfide ore was processed through comminution and flotation process to increase the concentration of nickel-copper sulfide. Flotation is conducted by using a series of collectors, such as ethyl xanthogenate and ammonium dibutyl dithiophosphate, as a collector (Chen et al., 2018). Various aliphatic, cyclic, and aromatic alcohols are also used as frother reagents to maintain bubbles that lift and separate nickel-copper sulfide from gangue minerals during the flotation process (Pawliszak et al., 2024). The recovery of nickel-copper sulfide using flotation is around 50-60% (Chen et al., 2018).

The concentrate is processed through various pyrometallurgical processes using different types of furnaces to obtain nickel-matte (Gupta, 2003). Nickel matte is processed through leaching and solvent-extraction processes to obtain separated nickel and copper metal (Gupta, 2003; Imideev et al., 2014). Later, the technology specialized in sulfide ore processing was adapted to process laterite ore. Laterite ore was roasted with sulfur to form nickel-iron sulfide, which is similar to nickel matte. Then, this nickel matte is processed using the conventional method to obtain separated nickel and iron. The company that is adapting this method to process laterite ore in Indonesia is Vale Indonesia (INCO). The annual production of nickel matte from laterite ore by Vale Indonesia is predicted to be 69,548 tons (Adventy, 2024).

Production of ferronickel

Besides nickel matte, laterite ore can be processed to produce ferronickel, an intermetallic of nickel and iron. Ferronickel is among the main raw materials to make stainless steel, heat-resistant steel, and various other alloys. Iron and nickel content in ferronickel is in the range of 60-80% and 40-20%, respectively (Romero et al., 2022). Ferronickel is made from high-grade nickel, laterite ore, and coal. The process of ferronickel making is shown in Figure 4. The laterite pellet and coal are fed into rotating cylinder dryers and rotary kilns, where drying and partial reduction of iron oxide and nickel oxide take place at 800 °C, respectively. The partially reduced oxides or the calcined are fed into an electric furnace. The resistance of electric current between electrodes converts electric energy into heat that conducts a full reduction reaction of oxides and smelting that produces two different layers of molten metal and slag. The molten metal is tapped into the ladle and refined to remove sulfur, phosphorous, and silicon oxide. The refined molten metal is granulated by using water to produce a luppe or luppen of ferronickel (Moats and Davenport, 2014).

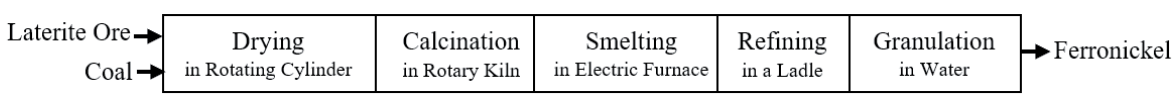

Figure 4. Flowsheet of ferronickel production

Production of Nickel Pig Iron (NPI)

Pig iron was originally a raw material used to produce cast iron and steel. The method utilizes a blast furnace that uses cokes that act as an energy source and a reductant to reduce iron oxide into iron metal (Halim et al., 2024). The blast furnace process is adapted to process a low-grade nickel laterite ore to produce a pig iron that contains nickel, which is often called nickel pig iron (NPI) or nickel contains pig iron (NCPI). The mechanism of NPI formation in the blast furnace is similar to that of ordinary pig iron. Carbon from coke reacts with oxygen to form carbon monoxide, which has a role in reducing iron and nickel oxide in laterite, producing a molten metal of iron-containing nickel (Jamali et al., 2018). The nickel content in pig iron is commonly in the range of 3-4%, which is lower than that of ferronickel. However, the price of nickel pig iron has risen since the start of the year 2024 (Gerber Group, 2024), indicating that nickel pig iron has become an important complement in the making of stainless steel or the alloys that need nickel element as the crucial alloying element.

Low-Temperature Processing of Nickel Sulfide and Nickel Laterite Ores

Caron technology

Caron technology, which is the combination of low and high-temperature processes, has been used to increase the separation degree of nickel and cobalt from iron oxide. Nickel ore is roasted and leached in ammoniacal ammonium carbonate to allow the extraction of nickel-cobalt and leave iron in the residue. The mixed nickel-cobalt carbonate can be calcined to produce nickel oxide or be electrochemically refined to produce nickel powder (Kerfoot et al., 1997; Meshram et al., 2019). Caron technology has been adapted to process nickel laterite ore in Cuba, Brazil, the Philippines, Australia, and Albania (Kerfoot et al., 1997; Elias et al., 2019; Ferreira and Pinto, 2021).

High-Pressure Acid Leaching (HPAL)

The high-pressure acid leaching (HPAL) method is applied to process low-grade laterite ore (Altansukh et al., 2014). High pressure is used to selectively increase the dissolution of nickel and decrease the dissolution of iron. The decrease in iron dissolution is meant to reduce acid consumption. Acid consumption is among the most significant factors that contribute to the high cost of the low-temperature route in nickel extraction. The process has been applied to obtain separated nickel and cobalt from low-grade nickel laterite ore to obtain nickel for electric vehicle battery production (Javanshir et al., 2018; Durant, 2023; Shiddiq, 2024).

Synthesis of Advanced Material Using Laterite Ore

The term nickel laterite is the economic terminology that emphasizes the value of nickel despite the presence of other elements in the laterite. Laterite consists of iron, nickel, magnesium, silicon, and oxygen elements in the form of goethite, nickel oxide, magnesium silicate, and quartz. (Solihin, 2015). These elements can be used to synthesize various advanced materials.

Nickel ore has been processed commercially by using various methods in industry to produce nickel and cobalt. However, only high-grade ore is processed through the high-temperature technology of nickel ore processing. The technical difficulties and the low content of nickel make low-grade nickel ore not be processed through high-temperature technology. Hence, the option left to process low-grade nickel ore is the low-temperature technology. Low-grade nickel ore contains a large amount of iron, an element that can be converted into various advanced materials. The effort to convert iron to advanced material can optimize the utilization of nickel ore and, at the same time, reduce the nickel industry waste.

Advanced materials can be produced using a variety of synthesis techniques. Notably, low-temperature technology plays a significant role in material processing. This technology typically involves a leaching process designed to extract valuable elements from less valuable minerals, followed by a purification stage aimed at enhancing the concentration of these valuable elements by removing other unwanted elements from the filtrate of the leaching process, and the recovery of elements from the solution containing valuable element. Each process of low-temperature technology has been developed and modified to increase the recovery of valuable elements, decrease the cost of the process, and avoid the environmental impact of the process.

Some parts of low-temperature technology to process nickel ore can be adapted and combined to synthesize materials from natural sources such as ore or minerals and secondary sources such as waste from industry. The preferred process is the process that consumes the lowest energy and has the lowest impact on the environment. The high-temperature process of nickel ore consumes a large amount of energy and generates a high amount of carbon dioxide generation. The carbon dioxide intensity in the high-temperature process of nickel ore is 24.5 tons per ton of nickel metal (Adiansyah, 2023). Hence, the high-temperature process of nickel is not preferred in the synthesis of advanced materials. On the other hand, the leaching process in low-temperature technology is preferred in advanced material synthesis due to low energy consumption and no carbon dioxide emission. The following are examples of advanced material synthesis by using low-temperature technology of nickel laterite processing.

Synthesis of battery from laterite ore

High-efficiency, cheap, and safe energy storage technologies are essential to meet the rapidly growing needs for the development of electric vehicles, portable electronics, and renewable energy storage. A battery is an electrochemical cell that can convert chemical energy into electrical energy. World Economic Forum in 2019 (Global Battery Alliance, 2019) reported that, as shown in Figure 5, Global battery demand is expected to increase significantly up to 3562 GWh in 2030. The largest demand comes from electric vehicle industries (95.14 %), followed by energy storage (2.91%), and consumer electronic (1.93%).

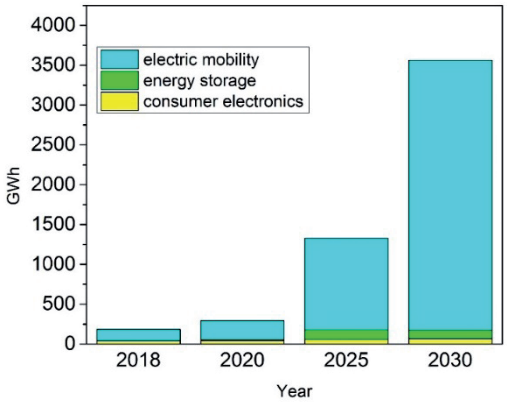

Figure 5. Global battery demand by application (Global Battery Alliance, 2019)

Lithium-ion based batteries are a widely used storage technology because they have good electrochemical characteristics such as high energy density, long cycle life, safety, and environmental friendliness(Duan et al., 2020; Fan et al., 2020). Battery performance is influenced by the property of its components, including electrodes (anode and cathode), electrolytes, binders, and separators. Lithium and cobalt are processed to produce cathode composed of $LiCoO_2$. The limited geological resource of lithium and the small amount of cobalt in the ore makes the price of battery with cathode of $LiCoO_2$ very expensive. Hence, sodium-ion based battery was proposed to replace lithium-based battery. Unfortunately, compared to lithium-ion based battery, sodium-ion based battery has a low energy density, need long time to charge, and short life cycle (Chayambuka et al., 2018; Wu et al., 2024).

Cobalt oxide in $LiCoO_2$ cathode can be replaced by iron phosphate; The cathode containing iron phosphate is $LiFePO_4$. The specific capacity, volumetric capacity, and average voltage of battery with $LiFePO_4$ cathode is 165 mAh/gram, 589 mA/cm^3, and 3.4 Volt, respectively, which is not so much different with those of $LiCoO_2$ (Nitta et al., 2015). Laterite contains abundant of iron, therefore cathode $LiFePO_4$ can be made from laterite. The specific capacity of $LiFePO_4$/C battery made from laterite is 164.56 mAh/gram, which is approaching of common $LiFePO_4$ battery (Chang et al., 2023).

Synthesis of photocatalyst from laterite ore

Photocatalysts use light energy, usually ultraviolet (UV) or visible light to carry out chemical reactions. The effective photocatalytic reaction depends on how easily it generates electron-hole pairs to interact with substrate forming free radicals. The reaction between radical electron and reactant can produce various valuable product (Tahir et al., 2021). The photocatalyst market is estimated to grow from USD 3.27 billion in 2022 to USD 6.07 billion by 2028 (Stratview Research, 2022). Photocatalysts play a role in various fields application, including environmental remediation such as air purification (Geng et al., 2022; Mamaghani et al., 2017), self-cleaning surfaces (Arabatzis et al., 2018; Banerjee et al., 2015)the effect of a self-cleaning, photocatalytic, antireflective glass coating on the efficiency of PV panels is investigated. The optical and photocatalytic properties of the coating were determined via UV–vis spectroscopy and degradation of organic pollutant Methylene Blue, respectively. Increased light transmittance in the visible light region and enhanced self-cleaning of the coated in comparison to the uncoated glass was demonstrated. The adhesion and the stability of the coating were tested in conditions of thermal fluctuations, UV weathering and sandblasting. The outdoor performance of coated and uncoated PV panels and arrays were monitored for several months at different climate conditions (Greece and China, and water purification (Khasawneh and Alaniandy, 2021; Zhang et al., 2020); energy production like Hydrogen production (Nishiyama et al., 2021; Yasuda et al., 2018), and dye sensitized solar cells (DSSC) (Das et al., 2020; Qureshi et al., 2020).

Iron oxide is among the material that can be used as photocatalyst. Iron oxide in laterite can be extracted and used in the synthesis of photocatalyst (Solihin et al., 2024). Photocatalyst made from laterite has been utilized to decompose methylene blue as the representation of organic waste. The photocatalytic reaction with iron oxide photocatalyst to decompose methylene blue can be written as follows.

$$Fe_2O_3 + hv \rightarrow e_{cb}^- + h_{vb}^+ \quad (1)$$

$$O_2 + e_{cb}^- \rightarrow O_2^{\bullet-} \quad (2)$$

$$H_2O_{ads} + h_{vb}^+ \rightarrow OH_{ads}^\bullet + H^+ \quad (3)$$

$$O_2^{\bullet-} + H^+ \rightarrow HO_2^\bullet \quad (4)$$

$$HO_2^\bullet + HO_2^\bullet \rightarrow H_2O_2 + O_2 \quad (5)$$

$$H_2O_2 + e_{cb}^- \rightarrow HO^\bullet + HO^- \quad (6)$$

$$HO^\bullet + MB \rightarrow MB_{oxydized} \quad (7)$$

The optimization of the photocatalytic reaction above to decompose methylene blue resulted in 96% decomposition of methylene blue for 3 hours.

Brief Analysis of Social, Economic, and Environmental Impact of Nickel Mining and Processing Activities

The basic purpose of mining and processing of nickel ore, as well as other ores, is always the economic purpose. The selling of nickel ore or nickel metal and various taxes during its economic activity contribute to the increase of the country's Gross Domestic Product (GDP). Unfortunately, mining and processing activities are large-scale activities that obviously impact society culturally, environmentally, and economically. The local society on mining and processing sites received the direct impact of mining and processing activity. The positive impacts of mining and processing of nickel ore are its contribution to the government's financial revenue and the creation of jobs that increase the economic activities of the local community.

In contrast, negative impacts are the utilization of large areas of land and large amounts of underground water, the damage to the ecosystem, and the disturbance of the social and traditional life of the local community (Trocan et al., 2022). The negative impacts of mining and processing activity make the local community demand the suspension of mining activity or at least demand compensation that can satisfy the local community. Hence, to avoid unwanted reactions from society, the mining company needs to fulfill society's satisfaction, such as economic, infrastructure, basic service, health, education, and ecology satisfaction (Rey-Marti et al., 2023). The recruitment of people from the local community with stable salaries, the erection of infrastructure, road construction, maintaining electricity and water supply, transportation provision, health service, educational aid, and treatment of waste are among the services for society's satisfaction.

The mining company also needs to satisfy the government. The government usually publishes the law that manages the taxes or financial contributions of mining companies if the company belongs to the government, the technology transfer, the product that can support the national interest, and the unit to reduce environmental impact. These satisfaction factors are shown in Figure 6. The Society and government satisfaction factors need to be designed at the planning stage of the mining and processing industry. Among these factors, education, health, and basic services are the most crucial factors. Hence, these factors need to be prioritized (Rey-Marti et al., 2023).

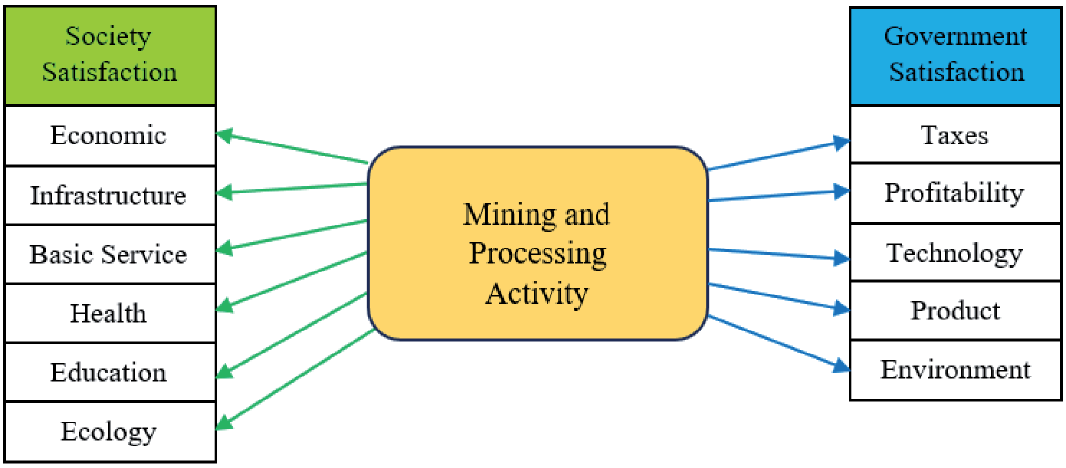

Figure 6. Satisfaction factor of society and government that mining company can provide

Nickel laterite is the natural source of infrastructure materials, functional materials, and other advanced materials. These materials are important to modern society. The development of cities, the design of the military, national systems, and other modern manufacturing industries and daily life rely on these materials. Therefore, the mining and processing of nickel laterite ore must be managed for the national interest. The negative impacts must be reduced, hence allowing the sustainability of nickel laterite mining and processing activity. Technology transfer of recent technology, as well as the original innovation from local researchers and technologists, plays an important role in the development of mining and processing technology in Indonesia. The integration of mining and processing technology with other related social, economic, and environmental factors contributes to the sustainability of mining and processing activity in Indonesia.

CONCLUSION

Indonesia has enormous geological resources of nickel, primarily found in the form of laterite ore, which is a product of the weathering of nickel- and iron-rich rocks. The shallow deposit of these laterite deposits facilitates their extraction through open-pit mining techniques. The proven technology to process laterite ore at high temperatures produces commercial nickel matte, ferronickel, and nickel pig iron (NPI). The rising demand for nickel, particularly for stainless steel production, has resulted in a notable surge in the prices of nickel ore, ferronickel, and NPI. Additionally, nickel-laterite ore can be utilized to produce nickel for the battery sector and photocatalysts for environmental remediation via low-temperature processing methods. Anticipated growth in the electric vehicle market is expected to further escalate the demand for nickel, potentially equating the consumption levels in the battery industry with those in the stainless-steel sector. The activities associated with mining and processing nickel have profound implications for society, encompassing both beneficial and detrimental effects. It is imperative to mitigate the negative consequences while ensuring that the needs of the community and government are met. Essential services such as economic development, infrastructure, healthcare, education, and ecological preservation must be prioritized to achieve satisfaction among local populations and governmental bodies, as mandated by various regulations. Addressing these satisfaction factors is crucial for the long-term sustainability of the mining and processing sector.

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