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Characteristics of Nickel Laterite Mine Waste in Caraga Region, Philippines and Its Potential Utilization

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ABSTRACT

Nickel laterite mining is one of the sources of nickel-iron material used for producing steel and various materials. This mining activity leaves waste in the mine, including rocks, overburden, silt, and dust. Characterization is an important primary step in understanding waste for proper management, utilization, and disposal. The pH, organic matter, and elemental composition are analyzed in this study. The pH of nickel laterite mine waste is neutral to moderately alkaline, which makes it unlikely to cause acid mine drainage, which is one of the most prevailing environmental problems of mines. The organic matter content also showed favorable results for plant growth. However, the macronutrients necessary for the plant are too high, making it less favorable for agricultural utilization. Elemental composition shows the presence of nickel and other elements lower than the economically acceptable level. However, processing the lower grade can be the best option when all higher-grade resources are exhausted. The nickel laterite mine waste can be reused to further extract the metals when sources of higher grades are depleted, repurposed such as in the production of bricks and ceramics, or mined-out mines can be repurposed for renewable energy sources such as solar and wind farms.

INTRODUCTION

In the next several years, humanity will face extreme challenges as sources of fresh raw mineral materials become depleted and scarce (Lottermoser 2010, Sahajwalla 2018). While this may cause global concern, this can also be an opportunity for scientists and engineers to develop technology and apply concepts and results of numerous research to cope with the demand of the times. Economists, scientists, and researchers have presented different concepts like circular economy, industrial symbiosis, life cycle assessment, and sustainable development, which have one common goal: to optimize the use of the limited resources today and provide for the future. Therefore, researching cost-effective processes that can turn waste materials into valuable resources is necessary (Lottermoser 2011, Sahajwalla 2018).

Mining is extracting materials from the earth to recover one or more valuable minerals. Along with this process is producing solid, liquid, or gaseous unwanted by-products of no current economic value called mine wastes. Additionally, any mineral-containing unexploited material on-site may be considered waste (Lebre et al. 2017). Mine wastes can be classified into mining, processing, and metallurgical wastes (Lottermoser 2010). Mining wastes, which is the focus of this study, are everything left in the mine after extracting the valuable material. Mine waste may include waste rocks, overburden, spoils, mining water, atmospheric emissions, acid mine water, dust, and silt.

Nickel laterite is one of the sources of nickel, along with the less complex ore of nickel sulfide. Laterite constitutes about 70% of the worldwide nickel resource, but sulfide contributes to about 60% of the world's nickel production (Elias 2013). This is due to the complexity of laterite ore, making it more difficult and costly to process than sulfide ore. With the increasing demand for nickel and improved processing economics for nickel laterite, nickel production has increased. But due to its complexity, nickel laterite mining is known to produce more waste than nickel sulfide.

The Philippines is the 2nd largest nickel ore producer, next to Indonesia in 2020 (Garside 2021). The country has 24 nickel laterite mines, of which 16 are found in the Caraga Region, the southern part of the Philippines (MGB13 2021). The extraction of nickel in the country is using an open cast or strip mining method, which involves the removal of 1 to 2 meters of topsoil or the overburden to remove the limonite and saprolite deposits that occupy the soil from 3 to 25 meters below the ground (Tabios III 2020). Most nickel and iron ores in the Philippines are exported to countries like China to extract and refine nickel, iron, chromium, cobalt, and even some highly valued metals such as platinum, vanadium, and titanium (Tabios III 2020).

In general, mining has substantially improved the Philippines' economic status, specifically in the Caraga Region, creating more than 23,000 jobs in a 2020 report from Mines and Geosciences Bureau (MGB). However, despite the economic contribution of mining, the industry is still controversial because of environmental issues, inherent to the destructive nature of mining activity. About 2-12 tons of overburden material is removed as waste for every ton of metal produced (Mohanty et al. 2010). Active and abandoned mines significantly contribute to metal contamination worldwide (Schaider et al. 2007). Uncontrolled disposal of nickel mine wastes, for example, increases turbidity in receiving waters. Turbidity is visually evident in the red-orange bay area along causeways, stockpiles, and siltation ponds (Tabios III 2020). The Total Suspended Solid (TSS) reaches as high as 1000mg/L during heavy runoff (Apodaca et al. 2018). Moreover, mining generates enormous amounts of waste (Lebre et al. 2017) and is among the world's most significant prevailing waste concerns (Bian et al. 2012, Ceniceros-Gómez et al. 2018).

This study determines the characteristic of the nickel laterite mine waste in a nickel laterite mine project in Caraga, Philippines. Mineralogical characterization in mine waste helps improve risk assessment, guide proper mine planning, and optimize pollution control design (Jamieson et al. 2015). The chemical composition and geotechnical properties determine the most appropriate uses and whether reuse is economically feasible (Bian et al. 2012). Understanding the waste's physical, chemical, and mineralogical content is vital in developing appropriate and effective waste management protocols. Information on the characteristics of mine wastes is also required to select the most reliable and cost-effective treatments that will lead to successful site reclamation and restoration (Amacher & Brown 1999). Understanding the waste's physicochemical and mineralogical characteristics can predict the potential for acidic drainage, metal leaching, and reactivity (Anderson et al. 1999, Van der Ent et al. 2013). Characterization, therefore, is an integral part of properly managing waste (Chileshe et al. 2020). In particular, the pH, organic matter, and elemental composition of a nickel laterite mine waste are analyzed.

Further, some published research and reports are reviewed to provide information on the potential utilization of the waste and the mined-out area after all valuable minerals are exhausted. The industry can reference these studies to give them options other than the usual mine rehabilitation by revegetation.

MATERIALS AND METHODS

Samples and Study Area

A nickel laterite mine in the Caraga region, Philippines, was chosen for this particular study. The laterite profile of this mine consists of ferruginous laterite, limonite, and saprolite (Gifford 2013). This mining project ended in 2022, and the area is under rehabilitation. Soil samples were taken randomly from each of the eight mine settling ponds and stockpiles of waste rocks and analyzed for pH, organic matter, and elemental composition. Settling ponds are usually located at a lower elevation in the mine and contain silt, eroded soil from the upper stockpile of waste rocks, overburden, and other waste, such as degraded plants.

pH

The pH is measured using a 1:1 mine waste/ deionized water suspension method using a pH meter (Amacher & Brown 2000, Thomas 1996). 20g of mine waste sample is added with 20 mL of deionized water, and stirred for 5 minutes at 240 rpm. The sample was allowed to rest for 30 minutes, and the pH was measured using an APERA PH800 pH meter. The probe is swirled around the sample without touching the bottom part.

Organic Matter

The loss-on-ignition method estimates the soil organic matter based on gravimetric weight change associated with high-temperature oxidation of organic matter (Amacher & Brown 2000). Mine waste samples were placed in previously dried and weighed crucibles. Samples in the crucible were then dried in an oven at 105°C for 16 h, cooled in a desiccator, and weighed. The samples were ignited in a muffle furnace at 450°C for 16 h, cooled in a desiccator, and weighed again. The loss-on-ignition (LOI) organic matter is then calculated using the equation:

$$\text{LOI Organic Matter (\%)} = \frac{\textit{oven dried weigth} - \textit{ignited weight}}{\textit{oven dried weight}}\, x\ 100 \quad \ldots(1)$$

Elemental Composition

The elemental composition was analyzed using X-Ray Fluorescence (XRF), the most widely used method to analyze nickel laterite elemental content in Philippine mines. The samples were analyzed at the mine laboratory, where the samples were taken.

RESULTS AND DISCUSSION

Besides giving information on the acidity or basicity of the sample, pH can be used to estimate the available nutrients and toxicity of the elements present in the sample using its relationship with pH (Thomas 1996). The pH analysis results in Table 1 showed that the pH in mine 5 is neutral, mines 2, 3, 4, and 9 are slightly alkaline, mine 7 is moderately alkaline, and mine 1 is strongly alkaline. The pH range also indicates that this type of waste will likely not cause acid mine drainage problems to the surrounding water bodies. Normally soil at 7.6-8.3 pH is calcareous and most likely controlled by calcium carbonate, which usually does not need further treatment (Thomas 1996). The pH of 8.57 at mine 1 could mean the presence of sodium carbonate controlling the soil system rather than calcium carbonate, which could indicate future soil degradation (Thomas 1996). A little amendment to lower the pH may be necessary.

The loss-on-ignition analysis revealed 1.77%-7.95% organic matter, which can be considered a good percentage for OM for plant growth. The highest OM percentage is at mine 5 (7.95%) and the lowest at mine 1 (1.77%). Organic matter is an important characteristic of soil to be considered when considering the rehabilitation of mine waste by revegetation or growing plants. The OM contains all essential plant nutrients and serves as a storehouse for the nutrients necessary for plant growth. It can be easily reinforced with organic fertilizers. OM also influences the soil to form a stable structure. In mines, the higher organic matter content of the soil is more favorable since it lowers soil erodibility and the risk of soil erosion (Kadlec et al. 2012).

The elemental composition in Table 2 show that the average nickel content of the sample ranges from 0.50 to 1.10% by weight, confirming that it is low-grade and currently of no economic value. The lowest economic grade for a nickel at this particular mine is 1.2%. Iron (Fe) content ranges from 9-46%, a typical characteristic of lateritic soil. A lateritic soil profile is divided into two, which are limonite with 25% or higher iron content and saprolite with less than 25% iron. Other elements like cobalt, aluminum, magnesium, potassium, chromium, and tin were also found. Though the elemental composition of the mine waste is already below the minimum economic grade, the metal concentration is still too high for plant growth. Discharge of these elements caused by soil erosion or water runoff during heavy rainfall can contaminate neighboring agricultural land and water bodies. Most micro and macronutrients like iron, nickel, potassium, zinc, and others are found in too high concentrations for farming applications. Vegetables can absorb elements at high concentrations, which can harm humans in the long term.

Utilization of Nickel Laterite Mine Waste

Given that the nickel concentration of the mine waste is below 1.2%, the researchers reviewed some of the studies using low-grade nickel laterite. The industry can further explore these studies to utilize the mining waste. The low-grade nickel laterite mine waste can be reused or repurposed based on the information gathered. Reuse means using the waste to extract the remaining metals using new or old technology, which allows profitable extraction in the future. Reuse can be further categorized into metallurgical processing, biomining, or using bacteria or fungi to concentrate the metal, and phytomining, which uses plants to harvest the metals. On the other hand, repurposing can be divided into two; repurposing the mine waste and the mined-out area. To repurpose the mine waste is to use it for other purposes such as in brick making, ceramic, and as an additive to construction materials. Repurposing the mined-out area means converting the mined-out area into tourism sites (Aysan et al. 2019), solar farms (Pouran 2018, Murphy 2022), or other renewable energy-generating industries.

Reuse by Metallurgical Process

In Table 3 are some studies proposed to improve the current widely used high-pressure acid leaching (HPAL), caron process, and smelting to recover the nickel-iron and by-products like cobalt. Guo et al. (2021a) studied the effects of the different dosages of red mud (RM) from China and low-grade laterite ore in co-reduction with laterite. The recorded iron and nickel recoveries are 94.71 wt%, and 95.98 wt%, respectively. Guo et al. (2021b) did a related study on using straw charcoal as a reductant on the co-reduction of RM and laterite. Recovery of nickel is 97.21 wt%, and iron is 98.87% using 15wt.% of straw charcoal and roasted for 80 min. at 1250°C. Xiao et al. (2020) tried selective roasting garnierite

Table 1: pH and Organic Matter content of nickel laterite mine waste in Caraga, Philippines.

Characteristic	Mine 1	Mine 2	Mine 3	Mine 4	Mine 5	Mine 7	Mine 9	Final Discharge
	Average of 4 samples (Standard Deviation)							
pH	8.57(0.14)	7.82(0.12)	7.69(0.07)	7.47(0.11)	7.17(0.16)	7.91(0.15)	7.72(0.08)	8.24(0.06)
Organic matter (%)	1.77(0.91)	4.87(1.04)	3.93(0.62)	6.52(2.86)	7.95(1.28)	3.24(1.58)	2.84(1.46)	3.84(0.78)

Table 2: Elemental Analysis results using XRF of nickel laterite mine waste in Caraga, Philippines.

Ave. Element % (n = 4)	Mine 1	Mine 2	Mine 3	Mine 4	Mine 5	Mine 7	Mine 9	Final Discharge
Ni	0.84	0.96	1.10	1.04	0.91	0.94	0.83	0.50
Fe	9.53	24.53	17.71	28.04	46.38	19.63	19.08	15.38
Co	0.04	0.06	0.06	0.06	0.11	0.06	0.05	0.05
Al	0.47	2.55	0.98	1.75	2.55	1.07	1.01	3.00
Mg	16.80	9.57	12.11	11.54	4.11	13.55	13.72	9.43
P	LDL	0.01	LDL	0.01	0.01	LDL	LDL	0.01
Si	18.18	12.59	17.03	12.60	5.48	15.10	15.26	16.39
Ca	0.82	0.18	0.17	0.14	0.05	0.13	0.15	1.47
Cr	0.41	1.31	0.79	1.02	1.64	0.81	0.83	0.62
K	0.03	0.01	0.01	0.01	0.01	LDL	LDL	0.27
Mn	0.20	0.44	0.32	0.51	0.85	0.37	0.36	0.33
Na	0.02	0.02	0.02	0.03	0.05	0.02	0.02	0.03
Ti	0.03	0.08	0.04	0.06	0.07	0.04	0.04	0.10
NiO	1.06	1.22	1.40	1.33	1.17	1.20	1.06	0.64
Fe_2O_3	13.62	35.07	25.34	40.09	66.31	28.07	27.28	21.98
CoO	0.05	0.07	0.07	0.08	0.14	0.07	0.06	0.06
Al_2O_3	0.89	4.81	1.85	3.31	4.81	2.02	1.90	5.66
MgO	27.86	15.88	20.08	19.13	6.80	22.46	22.76	15.64
P_2O_5	LDL	0.03	0.01	0.01	0.03	0.01	0.01	0.03
SiO_2	38.90	26.94	36.42	26.96	11.73	32.30	32.63	35.07
CaO	1.15	0.24	0.24	0.19	0.07	0.18	0.21	2.05
Cr_2O_3	0.59	1.91	1.16	1.49	2.40	1.18	1.22	0.90
K_2O	0.04	0.01	0.01	0.01	0.01	LDL	LDL	0.32
MnO	0.26	0.57	0.41	0.66	1.10	0.48	0.46	0.43
Na_2O	0.03	0.03	0.03	0.04	0.07	0.03	0.03	0.04
TiO_2	0.04	0.13	0.06	0.09	0.12	0.07	0.07	0.16

LDL – lower than detectable limit

laterite (0.72% Ni) ore to form ferronickel. The ferronickel produced is at 16.16% Ni and 73.67% Fe or 90.33% Ni recovery. Xue et al. (2020) modified the traditional sintering process in nickel extraction by introducing pressurized densification sintering. An external mechanical pressure field is added by weight adjustment at the top of the sinter bed after ignition. As a result, productivity and tumble index increased by 18.6% and 19.2%, respectively. The solid fuel rate is decreased by 10.3%, making it more economical than the traditional process. A related study on CO_2 reduction with this new sintering method was also made by Zhu et al. (2020). In the study of Komnitsas et al. (2019), low-grade Ni (0.97%) and the effect of adding sodium sulfite (Na_2SO_3) in the leaching medium (sulfuric acid, H_2SO_4) were investigated. After 25 days at 147 g/L of H_2SO_4 and 20 $g.L^{-1}$ of Na_2SO_3, the extraction was 72.5% and 47.4% for Ni and Co, respectively. The group also investigated the possibility of using the leaching residue as an inorganic polymer (IP). The residue was mixed with alkali activators NaOH and Na_2SiO_3 and added with metakaolin. The IP exhibited high compressive strength at 40 MPa, which is suitable for various applications in construction. Zhu et al. (2019) proposed improving nickel laterite processing by a selective reduction-wet magnetic separation process. The proposal was to use silica and calcium sulfate. The nickel content of the laterite used is 0.97% by wt. from Indonesia. The laterite, the reductant (graphite), and additives (silica and calcium sulfate) were mixed and roasted at 900-1300°C for a pre-determined time for the reduction process. After reduction, the roasted samples were crushed and grounded to 90 wt% passing 0.043 mm for magnetic separation using magnetic field strength of 1800 G. The highest Ni recovery is 95.6%, and Fe is 42.8% at a reduction temperature of 1250°C for 60 min, 3% calcium sulfate and 8% silica. Li et al. (2018a) studied the solid-state deoxidation of low-grade nickel laterite (0.82% Ni) with methane at various reduction temperatures, times, and concentrations. The nickel laterite, of particles size <0.25mm, was made into pellets for reduction. CH_4 and N_2 gases were used in the reduction process using a fixed bed apparatus. The volumetric gas rate used was 30 $mL.min^{-1}$ at a reduction time of 30-90 minutes. The best condition identified was at a temperature of 700°C, 60 min., and 20vol% % methane reduction time. The metallization at this condition was 91.17% and 23.67% for Ni and Fe, respectively. Li et al. (2018b) proposed a new method to improve atmospheric acid leaching. Atmospheric phosphoric acid leaching was used to select Ni and Co. The laterite ore (Ni at 1.043%) was first calcined and treated with different concentrations of acid (1M, 2M, 3M, and 4M) at different temperatures (20°C, 40°C, 60°C, 80°C, and 90°C). Based on the results, the best condition was at 3M phosphoric acid, at 90°C and 180 min leaching temperature and time, respectively. Ni's leaching efficiency is 98.7 %, and Co's is 89.8%. The result was higher than previous studies, indicating about 40-60% of Ni recovery by atmospheric leaching using sulfuric acid (Coto et al. 2008, Luo et al. 2015). Luo et al. (2015) used an alternative processing method for HPAL by using sulfuric acid in the presence of sodium sulfite at atmospheric pressure. The influence of temperature and agitation rate on atmospheric acid leaching (AL) was studied by MacCarthy et al. (2016). They believe that nickel laterite processing will be greatly improved through greater knowledge of the factors that influence atmospheric AL. Results showed that leaching greatly improved at a higher temperature of 95°C than at 70°C (from %9 to %67 for Ni). Agitation, on the other hand, had no noticeable impact on AL. The sintering behavior of low-grade nickel laterite (1.2% Ni) was studied by Guo et al. (2014) to provide technical information on ferronickel production.

Table 3: Research using nickel laterite mine waste with < 1.2% Ni by the metallurgical process.

No	Process	Ni (*wt%)	Fe (*wt%)	Method/ Description	Reference
Metallurgical Processing					
1.	Co-reduction – Roasting	0.98	37.57	Recovery of nickel and iron from low-grade laterite using the co-reduction roasting technique	(Guo et al. 2021a)
2.	Roasting-Leaching	1.2	41.9	Selective recovery of scandium from nickel laterite ore by acid roasting–water leaching	(Anawati et al. 2020)
3.	Roasting-Separation	0.72	8.65	Extraction of nickel from garnierite with iron concentrate using roasting and magnetic separation	(Xiao et al. 2020)
4.	Sintering	0.15-0.34	31.59-40.36	Improved limonitic laterite sintering using a pressurized densification process	(Xue et al. 2020, Zhu et al. 2020)
5.	Leaching	0.97	21.79 Fe_2O_3	Column leaching using sulfuric acid and sodium sulfite. Valorization of leaching residues as inorganic polymer	(Komnitsas et al. 2019)
6.	reduction-separation	0.97	40.09	selective reduction-wet magnetic separation process using silica and calcium sulfate	(Zhu et al. 2019)
7.	Reduction-Deoxidization	0.82	9.67	Reduction of nickel and Iron from low-grade nickel laterite via a solid-state deoxidization method using methane	(Li et al. 2018a)
8.	Leaching	1.03	43.95	Leaching of calcined laterite using phosphoric acid	(Li et al. 2018b)
9.	Atmospheric Acid Leaching	0.93	22.01	Effect of temperature and agitation rate on atmospheric acid leaching	(MacCarthy et al. 2016)
10.	Sintering	1.2	46.26	Ferronickel production via sintering blast furnace route	(Guo et al. 2014)
11.	Direct extraction	0.62-1.1	35.70-44.30	Direct extraction of nickel from laterite ore by carbonyl method	(Terekhov & Emmanuel 2013)
12.	Reduction-Deoxidization	1.09	9.12	Reduction of nickel from low-grade nickel laterite via a solid-state deoxidization method using CO_2-CO gas mixture	(Li et al. 2011a)
13.	Leaching	1.03	43.95	Selective leaching of cobalt by acidic thiosulfate solution	(Li et al. 2011b)
14.	Leaching	0.98 NiO	15.80 Fe_2O_3	Green process technology for recovering nickel	(Zhai et al. 2010, Liu et al. 2012)
15.	Reduction	0.38 NiO	50.88	Reduction of laterite by CO- CO_2	(Purwanto et al. 2001)
16.	Digestion – Neutralization-Calcination	0.93 NiO	34.41 Fe_2O_3	Chromite overburden as a source of nickel. Low-grade nickel is enriched through the digestion – neutralization-calcination process.	(Bhattacharjee et al. 2000)

The study showed that the yield increased with basicity from 1.1 to 1.7 and decreased with a further increase in basicity. Terekhov & Emmanuel 2013 evaluated the use of carbonyl in the direct extraction of Ni and iron from nickel laterite (0.62%). The reduction process was carried out using carbon monoxide in a high-pressure thermogravimetric analyzer. The carbonyl + metal in gaseous form (at 60 bar, 180°C) was then passed through a heat exchanger and condensed in storage tanks. Fractional distillation separated Ni and Fe, which is the process in a pilot unit. But in this study, the Ni recovery is calculated by mass balance using the weight loss of the sample. The limonite sample with the lowest Ni grade (0.62wt%) yielded a 0.02 percent Ni residue, equivalent to an estimated Ni yield of 98.9% and 86.5 percent Fe. Li et al. (2011) also studied the solid-state deoxidation of low-grade nickel laterite (1.09% Ni) with CO_2-CO gas mixture as the gaseous reductant and anthracite as the solid reductant. Based on the study, the conversion of total nickel to metallic nickel generally increases with the increase in reaction temperature until not more than 850°C. Overall results showed that 90% of metallic nickel could be obtained using CO_2-CO gas and 80% anthracite. Bhattacharjee et al. 2000 proposed a process to enrich nickel concentration in chromite overburden, a low-grade laterite. The process includes digestion with acid or a combination of HCl, HNO_3, and H_2SO_4, neutralization with alkali (Na_2CO_3, NaOH), and calcination at 900°C. The final product was found to have 2.54% NiO from an initial concentration of 0.93% or increased by 173%. Iron and nickel extraction from chromite overburden is also studied by Boi et al. (2011). Their study used reduction roasting, magnetic separation, and smelting processes to recover iron and nickel.

Most of the studies on low-grade nickel laterite are alternative processing routes. The recovery of metals like cobalt (Li et al. 2011) and scandium (Anawati et al. 2020) was also studied. Anawati et al. (2020) tried to extract scandium, an expensive rare earth metal, from low-grade nickel laterite. They used a two-stage process of acid roasting and water leaching. The ore was mixed with sulfuric acid and roasted at 600°C. Water-leaching at ambient temperature followed. The highest extraction of scandium is at 80%, with less than 15% co-extraction of the iron. In the study of Li et al. (2011), sodium thiosulfate and sulfuric acid were used as leaching agents. The thiosulfate selectively recovered 91% of the cobalt in the sample.

Reuse by Biomining

Biomining describes systems that utilize microorganisms to extract and recover metals from ores and other materials (Johnson 2014, Johnson et al. 2013). This process finds its earlier application with copper in the 1960s (Barrie 2018) and nickel as early as the 1980s. A summary of the studies on the biomining of nickel laterite is in Table 4. Oliveira et al. (2021) applied a new method in processing low-grade nickel by reduction with hydrogen gas followed by bioleaching with *Acidithiobacillus ferooxidants*. After the reduction process at 900°C and H_2 gas (99.9990%), the Ni content increased from 1.2% to 1.46%.

Bioleaching at 32°C with 35g of sulfuric acid/ kg of ore resulted in the overall extraction of nickel and cobalt at 92% and 35%, respectively. Newsome et al. (2020) also proposed a new bioprocessing strategy for cobalt extraction from lateritic soil. Organic substrates (acetate or glucose)

Table 4: Research on biomining to extract nickel and other metals from nickel laterite.

No	Process	Ni (*wt%)	Fe (*wt%)	Method/ Description	Reference
1.	Reduction of roasting/ bioleaching	1.2	44.9	Reduction with hydrogen gas followed by bioleaching using *Acidithiobacillus ferooxidants*	(Oliveira et al. 2021)
2.	Bioprocess	< 0.30	13.4-44.6	Manganese and cobalt enrichment through biogeochemically enhanced process	(Newsome et al. 2020)
3.	Bioprocessing (leaching)	0.91	44.51	Enhanced bioleaching with the use of *Acidithiobacillus (At.) thiooxidans*	(Marrero et al. 2017)
4.	Bioprocessing (leaching)	1.2	49.8 Fe_2O_3	biological leaching of nickel by indigenous fungi (Indonesia) isolated from Indonesian limonite	(Handayani & Suratman 2017)
5.	Bioprocess	0.99	48.88	Anoxic microbial reduction of nickel from lateritic soil (chromite overburden)	(Behera et al. 2012)
6.	Bioprocessing	0.4	7.0	Four species of iron-reducing acidophilic bacteria were evaluated in their ability to make nickel soluble.	(Hallberg et al. 2011)
7.	Bioprocess (leaching)	8.5 ppm	2014 ppm	Bio-extraction of different metals by *Penicillium chrysogenum*	(Ahmad et al. 2011)
8.	Bioleaching and bioprecipitation	0.92 NiO	19.36 Fe_2O_3	Leaching of nickel laterite with heterotrophic organisms	(Alibhai et al. 1993)

generated metal-reducing conditions and separated cobalt by washing it with acetic acid. Their study mobilized minimal iron oxide, which may generate less waste. The Marrero group tried to compare the reductive capability of *Acidithiobacillus (At.) thioxidants* in aerobic conditions and using *At. Ferrooxidants* in anaerobic conditions. Nickel laterite overburden from Cuba was used in the study. Based on the results using *At. thioxidants* in aerobic condition was more efficient than the ferrooxidants. The sample treated with the oxidants achieved the highest solubilization (Co 85%, Mn 74%, Ni 16%) after seven days at pH 0.8, while the ferrrooxidants sample achieved the same values after 28 days increased pH of 1.8. Handayani and Suratman (2017) studied the feasibility of using fungi as a new technique in nickel metal recovery. Two types of fungi were used, the *Aspergillus sp* and *Penicillium sp*. The experiment used low-grade nickel laterite (1.66% NiO) from Pomalaa, Southeast Sulawesi. *Aspergillus* sp. showed better nickel recovery of 57% at 5% pulp density after 20 days than 48% using *Penicillium* sp. Using fungi is a potential technique in nickel recovery; however, the primary concern is the long fermentation period of about 8-14 days of the fungi. Behera et al. (2012) investigated the microbial extraction of nickel from lateritic soil of chromite overburden. *A. ferroxidans* was used, and the experiment showed a promising result for anoxic microbial processing without energy-intensive pre-processing activities. The maximum nickel extraction was at 41% from 0.99% Ni. Hallberg et al. (2011) proposed bio-processing as an alternative for the energy and reagent extensive processing (i.e., smelting, HPAL, etc.) of nickel laterite. Low-grade nickel (0.4%) from a mine in Western Australia was used in the study. Four acidophilic bacteria were used, namely; (i) *ferrooxidans* a mesophilic iron- and sulfur-oxidizing chemolithotroph; (ii) *Sulfobacillus benefaciens*, a thermotolerant iron- and sulfur-oxidizing mixotroph; (iii) *Acidicaldus organivorans*, a moderately thermophilic, sulfur-oxidizing heterotroph; (iv) *Acidiphilium SJH*, a mesophilic heterotroph. Based on the findings, an acidophilic sulfur-oxidizing bacterium could be utilized for nickel separation from laterite. Ahmad et al. (2011) studied the use of *Penicillium chrysogenum* in extracting various metal ions from laterite ore. The incubation period was 24 days, and they extracted 57.31% of the nickel, which employed some flask shaking compared to 46.53% recovery without shaking. Iron extraction was at 97.78%, aluminum (86.78%), manganese (77.61%), and chromium (34.32%).

Reuse by Phytomining

In phytomining, hyperaccumulator plants are used to grow and concentrate metals by burning, which can be a potential source of heat for energy generation. In the 1990s, Anderson et al. (1999) used *Alyssum bertolonii* from Italy and *Berkheya coddii* from South Africa to recover nickel, thallium, and gold. In Indonesia, the world's largest producer of nickel laterite, a phytomining viability study was conducted from 2004 to 2007. Identification of hyperaccumulator plants was also conducted in Malaysia for its potential in phytomining. There are over 400 identified hyperaccumulator plants for nickel (Laubie et al. 2021), and numerous studies have been conducted in different mining countries. As part of a long-term rehabilitation plan, phytomining allows for revegetation and ensures good erosion control while generating revenue from the extracted nickel (Van der Ent et al. 2013).

Both, biomining and phytomining have the advantage of being environmentally friendly and less energy intensive. Still, the drawback of these processes is the longer processing time to extract the valuable mineral in the ore, which can take months or years (Johnson 2014).

Repurpose for Other Products

There are also some studies on the use of nickel laterite for other purposes (Table 5), such as the use of waste for indirect carbon sequestration (Eusebio et al. 2020), as geopolymer precursor (Longos et al. 2020), ceramic tiles (Bernardo-Arugay et al. 2022) and bricks (Shanmukha et al. 2017). Eusebio et al. (2020) evaluated waste rock from a nickel laterite mine in Southeastern Philippines for its potential utilization in indirect carbon sequestration. Hydrochloric acid was used in the acid-leaching process. The group concluded that nickel laterite waste rock could be a feedstock. However, further study is necessary on cost and energy requirements

Table 5: Repurpose nickel laterite mine waste for other products.

No.	Type of Waste	Description	Reference
1.	Waste Rock	Use of nickel laterite waste rock as feedstock for carbonation in indirect carbon sequestration	(Eusebio et al. 2020, Razote et al. 2021)
2.	Silt	The potential of nickel laterite mine waste as geopolymer precursor by mechanical and thermal activation	(Longos et al. 2020, Tiguea et al. 2021)
3.	Silt	Production of ceramic tiles from nickel laterite mine waste through the ceramic casting method	(Bernardo-Arugay et al. 2022)
4.	Laterite soil	Production of stabilized and compressed lateritic soil bricks	(Shanmukha et al. 2017)

and the effect of reducing agents to yield to prove applicability. Longos et al. (2020) investigated the possibility of producing geopolymer cement using nickel laterite silt or nickel mine waste (NMW). The silt was mixed with coal fly ash (CFA) and sodium hydroxide with sodium silicate (SH-SS) as activators. Different NMW, CFA, and SH-SS ratios were prepared and tested for compressive strength. The results show that the 50%NMW-50%CFA- 0.5 SH-SS attained the highest unconfined compressive strength of 22.10 ± 5.40MP after 28 days of curing. Bernardo-Arugay et al. (2022) used slip casting to make ceramic tiles from nickel laterite mine waste. They found NMW a suitable raw material for producing ceramic wall and floor tiles. Lastly, Shanmukha et al. (2017) prepared different proportions of laterite, cement, and sand to produce stabilized blocks or bricks. The mix was compacted with a hydraulic press instead of burning to save energy, which is an energy-intensive process. The group found out that the required compressive strength was achievable after 28 days of curing time, and compressive strength is higher than red clay bricks produced by firing.

Processing the NMW for bricks, ceramic, and other products shows great potential to reduce waste in the mined-out areas. However, once the laterite is formed into these products, the metals contained in the material, which is a potential resource in the future, will be contained in the products. The use of the lowest-grade waste rocks and silt should be considered. It is also important to consider the cost of producing such products, especially the energy requirement, to confirm viability.

Repurpose of Mined-Out Area

In a report by the Intergovernmental Forum (IGF) for Mining, Minerals, Metals and Sustainable Development, two case studies were presented on the successful use of mined-out areas in the production of renewable energy resources, the solar energy field in Sullivan Mine, British Columbia and the wind energy park in Ruhr coal mine in Germany (IGF Case Study 2022). In addition, there is the floating solar farm conversion from a collapsed coal mine in China (Pouran 2018). Conversion of the mined-out area to energy farms and tourism sites is a very good option as the final utilization of the area. But much consideration should be taken on the soil stability since mined-out areas are usually filled with loose soil from the overburden and waste rocks previously removed to access the valuable materials. Also, the same as repurposing for other products, it must be considered that there is a potential that the mine waste will become a resource in the future. This must be considered before putting any structure for solar or wind farms. The industry may consider one or a combination of alternative utilization. The mine may allocate a portion of the mined-out area to store the low-grade material and repurpose some areas for solar or wind energy farms. Using hyperaccumulator plants with high heating value to revegetate the temporary storage areas is also a good alternative for phytomining and biomass-to-energy conversion. Studies to recover nickel and other metals in the low-grade nickel laterite are already available. However, applying these studies on an industrial scale has a long way to go. Usually, processing low mineral concentrations increases the amount of the material that must be processed and requires capital-intensive processing technologies (Turcheniuk et al. 2021). Processing waste is often expensive and requires a lot of energy (Mauthoor 2017, Neves et al. 2019). Hence, economics is vital in conducting and presenting research on the reuse of waste. It is not enough to consider only the environmental benefit since it is always the profit that drives the industrial-scale application of these processes.

CONCLUSIONS

The pH of nickel laterite mine waste in this area is neutral to moderately alkaline; hence, the threat of acid mine drainage is unlikely to be a problem. The organic matter is acceptable for plant growth whenever revegetation is considered for mine rehabilitation. Moreover, the laterite mine waste still contains metals that are too low to process for profit but too high for plants and animals if discharged into water and agricultural soil. The plants can absorb high metal content, making them unfit for agricultural products for human consumption.

Considering that nickel laterite is a limited resource, the fate of lower-grade nickel laterite regarded as waste today may change when the higher grade is fully exhausted. Therefore, the best option is to consider further extraction of metals by metallurgical processing when technology and economics allow or use environmentally friendly processes like biomining or phytomining. With this, mines should consider strategic mine rehabilitation, which may include planned positioning and mapping of the waste based on its grade to provide easier access to the waste, which can be a potential resource in the future. Using the lowest grade material for other purposes, such as in brick or ceramic production and additive to construction materials, is also a good option. The, conversion of the mined-out area to renewable energy farms and tourism sites is best for final land use when all extractable materials are exhausted. Finally, it is advisable to take into account the combined application of the various utilization possibilities

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