The Effect of Alkali Roasting Pretreatment on Nickel Extraction from Limonite Ore by Using Dissolved SO₂-Air

Winny Wulandari 1,*, Meiyer Marthen Kinda 2, Rahmaditha Murida 1 and Tjokorde Walmiki Samadhi 1

1 Chemical Engineering Product Design and Development Research Group, Department of Chemical Engineering, Faculty of Industrial Technology, Institut Teknologi Bandung, Bandung 40132, Indonesia; rahmaditham@gmail.com (R.M.); twsamadhi@che.itb.ac.id (T.W.S.)
2 Department of Bioprocess Engineering, Faculty of Biotechnology, Institute of Technology Del, Toba Samosir 22381, Indonesia; meiyer.kindam@del.ac.id
* Correspondence: winny@che.itb.ac.id; Tel.: +62-8191-016-1418

Received: 20 July 2020; Accepted: 30 July 2020; Published: 7 August 2020

Abstract: Extraction of limonite ore using dissolved SO₂–air is an alternative hydrometallurgical method for nickel recovery. This process is carried out at atmospheric pressure and is shown to have good selectivity of nickel over iron, but with a low recovery yield. The literature refers to the application of alkali roasting as pretreatment in laterite ore leaching to increase nickel recovery. Thus, this study aims to apply the combination method of alkali roasting and leaching to extract nickel from limonite ore (1.33% Ni, 46.61% Fe) from the Southeast Sulawesi region. Three alkali compounds were included in the study (NaOH, Na₂CO₃ and Na₂SO₄). The batch-leaching process was carried out at pH 1 and 3 and temperatures of 55 and 80 °C for 180 min. The leach liquors were sampled at 15, 60, 90 and 120 min, and concentrations of the extracted metals were measured by Atomic Absorption Spectrometry (AAS). A mineralogy characterization of the raw ore and its residue after leaching was undertaken by using X-Ray Diffraction (XRD), while the thermal decomposition behavior of the ore was characterized by Thermogravimetry Analyzer (TGA)/Differential Scanning Calorimetry (DSC). The addition of Na₂CO₃, Na₂SO₄ and NaOH in the ore pretreatment increases nickel recovery from 14.80% without alkali roasting to 23.99%, 28.15% and 39.22%, respectively. The optimum extraction condition for nickel recovery is at pH 1 and a temperature of 80 °C. However, the highest Ni/Fe selectivity of 24,947 is obtained at pH 3 and a temperature of 80 °C, preceded by roasting in the absence of alkali. Compared to other hydrometallurgical processes, the process studied in this work exhibits lower recovery, but provides an alternative to extract nickel from low-grade limonite ore.

Keywords: limonite ore; SO₂; pretreatment; alkali roasting; nickel leaching

1. Introduction

The depletion of high-grade nickel sulfide and the growing world demand of nickel have spurred an increasing focus on the processing of low-grade nickel laterite ores [1]. It is estimated that approximately 70% of global nickel resources exist as laterite ores [2]. The U.S. Geological Survey [3] reported that Indonesia has the globally largest nickel reserves of about 21 million tons in the form of laterite deposits (2018 data). These deposits comprise layers such as the limonite layer, which contains a significant amount of goethite (FeOOH), 0.5–1.7% nickel, 40–60% iron and low silica content; and the saprolite layer with containing about 1.5–3% nickel, with lower iron and higher silica contents [4].

Due to the complex mineralogy, heterogeneous nature and low nickel content, the physical beneficiation of Ni from limonitic laterite ore is very challenging [5]. On the other hand, saprolitic
ore is more amenable to utilization via the pyrometallurgical route. In this context, the limonite ore becomes overburden and is generally underutilized. During recent decades, several studies on nickel extraction from limonitic laterite ores have been published, including high-pressure acid leaching (HPAL) [6], atmospheric acid leaching (AL) [7,8], biological leaching [9], heap leaching [10] and citric acid leaching [11]. High-pressure acid leaching (HPAL) is a proven hydrometallurgical technology, in which nickel leaching occurs at high temperature (250–253 °C) in an autoclave, while iron and aluminum are precipitated. However, high operating costs and safety risks are disadvantages of this process [6]. The atmospheric leaching (AL) process has been studied for the processing of various limonitic and saprolitic laterite ores. This process has low energy consumption and capital cost compared to HPAL [12], but often produces leach liquor containing a significant amount of impurities such as trivalent iron, aluminum and chromium ions [13]. An alternative citric acid leaching route was reported to be able to extract nickel up to 96% in the laboratory scale; however, the leaching duration is very long, i.e., 15 days. The development of an economical industrial-scale laterite ore processing technology is therefore clearly still highly desirable.

The utilization of dissolved SO$_2$–air during the extraction of nickel from laterite ore at atmospheric pressure has been known to provide a high nickel to iron selectivity [14]. Iron and other impurities may also be leached from laterite and are therefore regarded as unwanted byproducts in the nickel hydrometallurgical recovery process. Low SO$_2$ concentration is the key in selectivity due to the selective complexation of the metal hydrous oxides with SO$_2$ [15]. Moreover, the utilization of the SO$_2$–air gas mixture as an oxidant is attractive because it is cheaper compared to other strong oxidants [16]. The dissolved SO$_2$–air method does not require the use of strong acids. The dissolved SO$_2$–air approach for limonitic ore extraction has been proved in a previous study by the Authors [14,17]. Conducted at very mild conditions, including a low temperature of 55 to 80 °C and atmospheric pressure, a leaching recovery as high as 21% was obtained. It was also found that at longer leaching duration (3 h), the iron content in the solution decreased due to iron precipitation, providing the possibility to increase the selectivity of nickel over iron in the leaching solution.

Several strategies have been attempted to improve the leaching process to increase the recovery of nickel from limonitic ore. Guo et al. [18] conducted a new extraction technology called the alkali roasting-acid leaching (ARAL) that was developed to process limonitic ore from Indonesia. The result showed the increase of recovery Ni and Co from 79.96% to 97.52% and 70.02% to 95.33% after alkali-roasting with the addition of Na$_2$CO$_3$. Alkali roasting activation pretreatment was thought to break the mineral lattices of laterites, thus Ni and Co are exposed which corresponds to the increasing of the recovery of these two metals under milder conditions [5]. In addition, Li et al. [19] also stated that pre-roasting can change the mineral structure and increase the surface and porosity of the raw ore, thus making it more amenable to leaching.

As the roasting pretreatment is hypothesized to disrupt the crystalline structure of the limonite minerals and expose Ni to leaching, it is important to study the pretreatment of nickel limonite ores to increase its recovery. This research aims to improve the recovery of nickel leaching from limonite ores adding alkali roasting pretreatment and studying its effect to the leaching process by using the SO$_2$-dissolved air method. The alkali used in this study are Na$_2$CO$_3$, Na$_2$SO$_4$ and NaOH.

2. Materials and Methods

2.1. Limonite Laterite Nickel Ore

Limonite nickel ore was obtained from PT. Bhumi Karya Utama in North Konawe, Southeast Sulawesi. The ore is located at a depth of 3 m from the ground surface. The chemical composition of limonite nickel ore is shown in Table 1, presented the metals and oxides content. The sample limonite has high iron content (46.61%) and low nickel content (1.33%). The sulfur dioxide gas was obtained from CV Sangkuriang Gas Bandung.
Table 1. Metal and oxide content in limonite nickel ore.

| Metal and Oxide | Ni  | Co  | Fe  | SiO₂ | CaO | MgO | MnO | Cr₂O₃ | Al₂O₃ | P₂O₅ | TiO₂ | SO₃ |
|----------------|-----|-----|-----|------|-----|-----|-----|-------|-------|------|------|-----|
| Content (%)    | 1.33| 0.14| 46.61| 4.07 | 0.02| 1.18| 1.07| 2.75  | 12.07 | 0.03 | 0.10 | 0.63 |

2.2. Method

The experiments were conducted in two process steps, namely pretreatment and leaching. Two alternative routes were included in the pretreatment step, namely conventional roasting and alkali roasting. In the conventional roasting route, raw ore was roasted at 650 °C for 1 h in a Nabertherm P310 electric furnace. The roasted ore was then cooled down and transferred to the extraction step. In the alkali roasting route, 60% w/w of alkali (Na₂CO₃, Na₂SO₄, NaOH) was mixed with 6 g limonite nickel ore; the blend was then roasted under conditions identical to the conventional roasting route. After cooling, the alkali-roasted ore was then washed with distilled water.

The roasted ores are then transferred into a round-bottom flask 5-neck (see Figure 1) containing 250 mL hot water (55 or 80 °C) at a solid/liquid mass ratio of 2.4 wt%, then SO₂ (99.98% pure) and air was bubbled through the suspension until the required pH is reached. The leaching process was carried out at pH 1 and 3, a temperature of 55 and 80 °C for 180 min. As a reference, the optimum condition of Ni selectivity over iron was identified as pH 3 and temperature of 80 °C in a previous study [14]. The current work investigates the effect of lower pH and temperature. Leach liquor sampled at 15, 90, 120 and 180 min using a syringe and filtered by 0.2-μL syringe filter (Whatman 42, GE Healthcare, Chicago, IL, USA). All filtrates were then analyzed by an AAS instrument (Agilent 8453 UV-visible Spectroscopy System, Agilent Technologies Deutschland GmbH, Waldbronn, Germany). Solid residues collected after the extraction step were characterized using an X-Ray Diffraction (SmartLab XRD, Rigaku, Tokyo, Japan) to identify changes in mineral phases. The recovery metals after leaching as well as the nickel selectivity over iron were calculated the following formulas:

Metal recovery = \( \frac{\text{mass of metal extracted (g)}}{\text{mass of metal in raw ore (g)}} \)  \hspace{1cm} (1)

Nickel selectivity = \( \frac{\text{Ni/Fe in the aqueous}}{\text{Ni/Fe in the raw ore}} \)  \hspace{1cm} (2)

![Figure 1. Experiment setup for nickel leaching.](image-url)
3. Results and Discussion

3.1. Roasting (No Alkali) Pretreatment

X-ray diffractograms in Figure 2 identify the crystalline phases present in the raw limonite ore, the conventionally roasted ore and the solid residue remaining after the leaching process. The raw limonite nickel ore consists of magnetite (Fe$_3$O$_4$) and goethite (FeOOH) as the major mineral phases. Goethite is assumed to have small nickel content in it with the formula of (Fe,Ni,Al)OOH. Upon roasting, hematite appears as a major phase. It is postulated that at a temperature of 650 °C, the hematite (Fe$_2$O$_3$) phase is formed due to the dehydroxylation of goethite [19], thus potentially liberating Ni from goethite. The residue from the leaching process shows enstatite (MgSiO$_3$), quartz (SiO$_2$), olivine (Mg$_2$SiO$_4$) and hematite (Fe$_2$O$_3$).

![Figure 2. X-ray diffraction analysis of raw limonite ore, roasted ore and residue after leaching.](image)

Figure 3 indicates nickel and iron recoveries as a function of time in various pH and temperature from the results of leaching of the conventionally roasted ore. The highest nickel recovery of 14.80% was obtained at pH 1 and temperature 80 °C after 180 min. In the early duration of the leaching process, 8.71% nickel was recovered from the ore at pH 1 and temperature of 80 °C; this result is higher than the nickel recovery in other conditions (Figure 3a). Leaching of iron decreases at increasing leaching time, with the recovery of 0.22% at 180 minutes at pH 1 and a temperature of 80 °C. Thus, the leaching process using SO$_2$-dissolved air indicates high Ni/Fe selectivity.

![Figure 3. Recovery of nickel and iron using conventional roasting pretreatment and leaching using SO$_2$-dissolved air. (a) nickel recovery; (b) iron recovery.](image)
3.2. Alkali Roasting Pretreatment

The diffractograms in Figure 4 compares the effect of conventional and alkali roasting on phase changes of the limonite ore. Several different phases form after the alkali roasting pretreatment step. Ore treated with Na₂CO₃ shows sodium iron silicon oxide [Na(FeSi)O₂], quartz (SiO₂), hematite and magnesium iron oxide (MgFeO). It is postulated that Na₂CO₃ decomposes into Na₂O and CO₂ during the roasting as indicated by Equation (3) [18]. Then, Na₂O possibly reacts with iron, silicate, chrome and other minerals in the ore (Equations (4)–(6)).

\[
\begin{align*}
\text{Na}_2\text{CO}_3 & = \text{Na}_2\text{O} + \text{CO}_2 \\
\text{Na}_2\text{O} + \text{Fe}_2\text{O}_3 & = 2\text{NaFeO}_2 \\
\text{Na}_2\text{O} + \text{Cr}_2\text{O}_3 & = 2\text{NaCrO}_2 \\
\text{Na}_2\text{O} + \text{SiO}_2 & = \text{Na}_2\text{SiO}_3
\end{align*}
\]

![Figure 4](image)

Figure 4. XRD pattern of limonite ore after roasting and alkali roasting. G—goethite; M—magnetite; H—hematite; Ss—sodium iron silicon oxide; Q—quartz; Mg—magnesium iron oxide; T—thenardite; Ns—sodium sulfate; Mn—manganese cyanide.

The XRD of pretreated ore with Na₂SO₄ contains hematite as the major mineral as well as thenardite (Na₂SO₄). In a study that used reducing atmosphere [20], Na₂SO₄ is decomposed to form Na₂O, Na₂S and S; whereas it is claimed that Na₂S and S are beneficial for nickel recovery through a magnetic separation due to the FeS formation. The present study shows that Na₂SO₄ is not decomposed into Na₂O. For the XRD of pretreated ore with NaOH, the identified major mineral is sodium iron silicon oxide. The absence of goethite (Fe,Ni)(OOH) in the original ore has transformed to other major minerals, speculating to destruct the Ni that is bound in the limonite ore.

Figure 5 displays TGA/DSC thermograms of the raw limonite, limonite + Na₂CO₃ and limonite + Na₂SO₄ blends. All thermograms indicate an endothermic reaction at approximately 250–350 °C, which is due to the dehydroxylation of goethite to hematite [19].

X-ray diffractograms of the raw ore, after alkali roasting and after leaching are also shown in Figure 6a–c for alkali roasting with Na₂CO₃, Na₂SO₄ and NaOH, respectively. As can be seen in those figures, the goethite phase becomes diminished after alkali roasting. After leaching with SO₂-dissolved air, the residue with Na₂CO₃ and Na₂SO₄ are dominated by the hematite phase. This condition may
After leaching, the TGA/DSC patterns indicate that the iron in the ore is not dissolved in the leaching process due to its stability as the hematite phase. This may be advantageous in increasing the Ni/Fe selectivity. Zinc chromium iron oxide is present in the residue after leaching of NaOH-roasted limonite (Figure 6c).

![Figure 5](image1.png)

**Figure 5.** TGA/DSC patterns of (a) Limonite ore, (b) ore + Na₂CO₃ and (c) ore + Na₂SO₄ alkali roasting.

![Figure 6](image2.png)

**Figure 6.** Cont.
After roasting without alkali. Figure 7a, b present the Ni and Fe recoveries at pH 1 and temperature 80 °C with Na₂CO₃ addition, which reached 23.99% and 4.39%, respectively. In this condition, the nickel recovery was influenced by the leaching time. However, at pH 3 the nickel recovery was not affected by leaching time. Figure 7c, d present Ni and Fe recoveries with Na₂SO₄ roasting, which reached about 28.15% and 3.85%, respectively. Overall, the highest Ni and Fe recoveries were achieved by the addition of NaOH, which reached 39.22% and 18.60%, respectively (see Figure 7e, f).

However, these graphs also indicate that the recovery of unwanted Fe increases with the increasing leaching time. While alkali roasting activation pretreatment breaks the mineral lattices of laterites and increases the surface area of the raw ore, not only Ni and Co are exposed to the solvent, but also Fe.
In the SCM model, the core model (SCM) approach for experimental data at pH 1 and temperature of 80 °C was investigated. This condition is unfavorable since it reduces the selectivity of the SO$_2$–dissolved air in water. The Ni/Fe selectivity was also investigated to determine the effectiveness of utilization of SO$_2$–air in the leaching process. The summarized nickel selectivity presented in Table 2. The highest nickel selectivity of approximately 24,947 was obtained at pH 3 and temperature 80 °C for conventionally roasted ore. The second-highest selectivity of 16,172 was produced by alkali roasting using Na$_2$SO$_4$ followed by extraction at pH 3 and temperature of 55 °C. The alkali roasting pretreatment with NaOH and Na$_2$CO$_3$ generated low nickel selectivity as the Fe also was leached at prolonged leaching time. The higher basicity of NaOH is hypothesized to increase the extent of silicate structure disruption in the ore. This condition is unfavorable since it reduces the selectivity of the SO$_2$–air extraction step.

![Graphs showing Ni recovery and Fe recovery vs. leaching time for different conditions](image)

**Figure 7.** Recovery of nickel and iron using alkali roasting pretreatment and leaching using SO$_2$-dissolved air in water: (a,b) Ore + Na$_2$SO$_4$; (c,d) Ore + Na$_2$SO$_4$; (e,f) Ore + NaOH.

| Ni/Fe Selectivity          | Operating Condition |
|----------------------------|---------------------|
|                            | pH | T (°C) | Roasting | Na$_2$CO$_3$ Roasting | Na$_2$SO$_4$ Roasting | NaOH Roasting |
|                            |    |        |          |                       |                        |               |
|                            | 1   | 55     | 3.02     | 0.71                  | 56.66                   | 1.25          |
|                            |     | 80     | 66.71    | 5.47                  | 7.31                    | 2.11          |
|                            | 3   | 55     | 10,539   | 0.61                  | 16,172.38               | 2.32          |
|                            |     | 80     | 24,946   | 0.48                  | 7024.42                 | 1.12          |

3.3. Kinetic Analysis

The kinetics of nickel leaching from limonite at all method was investigated using the shrinking core model (SCM) approach for experimental data at pH 1 and temperature of 80 °C. This analysis aims to determine the leaching rate-controlling step in the nickel leaching process. In the SCM model, the leaching is described as involving three processes: surface diffusion, interface chemical reaction and...
diffusion of reactants or products. All standard kinetic equations derived from the SCM model were tested [15,21]. It is found that Equations (7) and (8), which describes the interface chemical reaction and diffusion of reactants or products, respectively, gives an excellent fit to the experimental data.

\[
1 - (1 - X)^{1/3} = \frac{t}{\tau} \tag{7}
\]

\[
1 - 3(1 - X)^{2/3} + 2(1 - X) = \frac{t}{\tau} \tag{8}
\]

where \(X\) = conversion, \(t\) = time and \(\tau\) = completing reaction time (min).

Figure 8a,b describe the fitting of two equations of the SCM model. Equations (7) and (8) provide a very good fit for the leaching of alkali-roasted ores, with coefficients of determination \(R^2\) higher than 0.96. However, the kinetics of leaching of conventionally roasted ores cannot be fit by both models. The Equation (7) assumes that the leaching rate-controlling step is the chemical reaction occurring on the mineral particle surface while Equation (8) assumes the rate-controlling step to be the diffusion of leaching reagent through the product layer on the mineral particle surface [22]. Thus, the nickel leaching kinetics of alkali roasted limonite ore using \(\text{SO}_2\)-dissolved air may be represented by two mechanisms simultaneously.

![Graphs showing nickel leaching kinetics](image)

**Figure 8.** A linear fit of the nickel leaching kinetics at pH 1 and a temperature of 80 °C for (a) interface chemical reaction and (b) diffusion of reactants or products.

Table 3 summarizes key operating conditions and extraction yields from several published literatures on the recovery of nickel from limonite ores. These works mostly employ sulfuric acid, sodium sulfite, chlorination or hydrochloric acid. Nickel recovery varies from 82.3% to 93.1%.

| Reaction | R^2 | Recovery (%) |
|----------|-----|--------------|
| \(\text{Ore + Na}_2\text{CO}_3\) | 0.5234 | 82.3% |
| \(\text{Ore + Na}_2\text{SO}_4\) | 0.9679 | 93.1% |
| \(\text{Ore + NaOH}\) | 0.9992 | 87.3% |

Compared to this range, the recovery obtained using dissolved \(\text{SO}_2\)-air is considerably lower, i.e., 23.33–39.22%. This may be due to the nature of \(\text{SO}_2\) gas which is a much milder reductant compared to sulfuric acid or hydrochloric acid. Previous research on the \(\text{SO}_2\)-air leaching method also indicates a nickel recovery of only 21%, but with a very high nickel selectivity [17]. A higher leaching temperature of 80 °C causes insufficient nickel leaching by \(\text{SO}_2\)/air due to the low solubility of \(\text{SO}_2\) at elevated temperatures [15]. Another phenomenon that may hinder the recovery is the inclusion of nickel in the recrystallized iron oxide [23].

The overall results also show that alkali roasting has effect to increase the nickel recovery; however, it lowers the selectivity of nickel over iron. Adding alkali in the pretreatment process will also increase the operating cost of the overall hydrometallurgical process. While the recovery values summarized in Table 3 give the impression that the dissolved \(\text{SO}_2\)-air to be not very promising, an economic assessment may nevertheless be needed to verify the overall economics of the processes in Table 3.
During the leaching process, there are proposed mechanism reaction of SO$_2$ occurred in the solution [27] (Equations (9)–(14)). The formation of a peroxo–monosulfate species (SO$_5^{−}$ or HSO$_5^{−}$) is responsible for the fast oxidation. The final product of SO$_3^{−}$ is sulfate via intermediate product HSO$_5^{−}$ or FeSO$_5^{+}$. However, the radical SO$_3^{−}$ and SO$_5^{−}$ also terminate by self-reaction to produce dithionate [26].

$$\text{SO}_2 \cdot \text{H}_2\text{O} \rightleftharpoons \text{HSO}_3^{−} + \text{H}^{+} \quad (9)$$

$$\text{HSO}_3^{−} \rightleftharpoons \text{SO}_3^{2−} + \text{H}^{+} \quad (10)$$

$$\text{Fe}^{3+} + \text{SO}_3^{2−} \rightleftharpoons \text{FeSO}_3^{+} \quad (11)$$

$$\text{FeSO}_3^{+} \rightarrow \text{Fe}^{2+} + \text{SO}_3^{−} \quad (12)$$

$$\text{SO}_3^{−} + \text{O}_2 \rightarrow \text{SO}_5^{−} \quad (13)$$

$$\text{SO}_5^{−} + \text{HSO}_3^{−} \rightarrow \text{SO}_3^{−} + \text{H}_2\text{SO}_5^{−} \quad (14)$$

The SO$_4^{−}$ radical is known to be a very strong oxidant with a standard reduction potential of 2.43 V vs. SHE and is expected to rapidly oxidize sulfite and transition metal ions. (Equation (15)) [16].

$$\text{SO}_3^{−} + \text{H}_2\text{SO}_5^{−} \rightarrow \text{SO}_4^{−} + \text{HSO}_4^{−} \quad (15)$$

The process may be improved by investigating the leaching mechanism; from dissolving SO$_2$ gas and air, its reaction with water to form sulfite acid ions and the contact of the sulfite ions with the nickel-bearing ore. In addition, the roasting condition should be investigated to determine the optimum roasting temperature that yields the highest nickel recovery.

### 4. Conclusions

Nickel leaching from low-grade limonite ore using SO$_2$-dissolved air with roasting and alkali roasting pretreatment has been carried out in this study. XRD results from roasting pretreatment indicate the formation of hematite due to the dehydroxylation of goethite, while those from alkali pretreatment indicate the formation of different mineral phases such as sodium iron silicon oxide [Na(FeSi)O$_4$], quartz (SiO$_2$), hematite and magnesium iron oxide (MgFeO) (for ore roasted with Na$_2$CO$_3$), hematite and thenardite (for ore roasted with Na$_2$SO$_4$) and sodium iron silicon oxide (for ore roasted with NaOH). The result shows that the highest nickel recovery of 39.22% was obtained by extraction at pH 1 and temperature of 80 °C with alkali roasting pretreatment using NaOH. The leaching kinetics of alkali roasted ore can be represented by interface chemical reaction and diffusion models. However, the nickel selectivity still low due to extensive breakup of the silica structure in the ore,
which leads to increasing recovery of iron. The highest nickel selectivity of 24,946 was obtained by extraction limonite ore at pH 3 and temperature of 80 °C with no alkali roasting pretreatment, with the nickel recovery of 14.80%. While alkali roasting pretreatment increases the recovery of nickel, it also increases the recovery of iron, thereby decreasing the selectivity of nickel over iron.

**Author Contributions:** Conceptualization, W.W. and T.W.S.; methodology, M.M.K.; experimental work: M.M.K.; formal analysis: M.M.K., W.W. and R.M.; Writing—Original draft preparation, M.M.K. and R.M.; Writing—Review and editing: W.W. and T.W.S.; funding acquisition, W.W. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Program Penelitian, Pengabdian Masyarakat, dan Inovasi (P3MI) (Research, Community Service and Innovation Program Grant) Institut Teknologi Bandung 2020.

**Acknowledgments:** We would like to thank PT. Bhumi Karya Utama for providing the ore samples.

**Conflicts of Interest:** The authors declare no conflicts of interest.

**References**

1. Mudd, G.M.; Jowitt, S.M. A Detailed Assessment of Global Nickel Resource Trends and Endowments. *Econ. Geol.* **2014**, *109*, 1813–1841. [CrossRef]
2. Fan, R.; Gerson, A.R. Mineralogical characterisation of Indonesian laterites prior to and post atmospheric leaching. *Hydrometallurgy* **2013**, *134*, 102–109. [CrossRef]
3. U.S. Geological Survey. *Mineral Commodity Summaries 2019*; U.S. Geological Survey: Hunter Mill, VA, USA, 2019.
4. Zhu, D.; Cui, Y.; Hapugoda, S.; Vining, K.; Pan, J. Mineralogy and crystal chemistry of a low grade nickel laterite ore. *Trans. Nonferrous Met. Soc. China* **2012**, *22*, 907–916. [CrossRef]
5. Guo, Q.; Qu, J.K.; Han, B.B.; Wei, G.Y.; Zhang, P.Y.; Qi, T. Dechromization and dealumination kinetics in process of Na$_2$CO$_3$-roasting pretreatment of laterite ores. *Trans. Nonferrous Met. Soc. China* **2014**, *24*, 3979–3986. [CrossRef]
6. Shibayama, K.; Yokogawa, T.; Sato, H.; Enomoto, M.; Nakai, O.; Ito, T.; Mizuno, F.; Hattori, Y. Taganito HPAL Plant Project. *Miner. Eng.* **2016**, *88*, 61–65. [CrossRef]
7. McDonald, R.G.; Whittington, B.I. Atmospheric acid leaching of nickel laterites review: Part II. Chloride and bio-technologies. *Hydrometallurgy* **2008**, *91*, 56–59. [CrossRef]
8. McDonald, R.G.; Whittington, B.I. Atmospheric acid leaching of nickel laterites review: Part I. Sulphuric acid technologies. *Hydrometallurgy* **2008**, *91*, 35–55. [CrossRef]
9. Jang, H.-C.; Valix, M. Overcoming the bacteriostatic effects of heavy metals on Acidithiobacillus thiooxidans for direct bioleaching of saprolitic Ni laterite ores. *Hydrometallurgy* **2017**, *168*, 21–25. [CrossRef]
10. Oxley, A.; Smith, M.E.; Caceres, O. Why heap leach nickel laterites? *Miner. Eng.* **2016**, *88*, 53–60. [CrossRef]
11. Astuti, W.; Hirajima, T.; Sasaki, K.; Okibe, N. Comparison of atmospheric citric acid leaching kinetics of nickel from different Indonesian saprolitic ores. *Hydrometallurgy* **2016**, *161*, 138–151. [CrossRef]
12. Luo, J.; Li, G.; Rao, M.; Peng, Z.; Zhang, Y.; Jiang, T. Atmospheric leaching characteristics of nickel and iron in limonitic laterite with sulfuric acid in the presence of sodium sulfite. *Miner. Eng.* **2015**, *78*, 38–44. [CrossRef]
13. Wang, K.; Li, J.; Mcdonald, R.G.; Browner, R.E. Iron, aluminium and chromium co-removal from atmospheric nickel laterite leach solutions. *Miner. Eng.* **2018**, *116*, 35–45. [CrossRef]
14. Wulandari, W.; Soerawidjaja, T.H.; Alifiani, D.; Rangga, D.A. The effect of pre-treatments to the nickel limonite leaching using dissolved gaseous SO$_2$-air. *IOP Conf. Ser. Mat. Sci. Eng.* **2018**, *285*. [CrossRef]
15. Gbor, P.K.; Ahmed, I.B.; Jia, C.Q. Behaviour of Co and Ni during aqueous sulphur dioxide leaching of nickel smelter slag. *Hydrometallurgy* **2000**, *57*, 57–62. [CrossRef]
16. Mulaudzi, N.; Mahlungu, T. Oxidative precipitation of Mn(II) from cobalt leach solutions using dilute SO$_2$/air mixture. *J. South. Afr. Inst. Min. Metall.* **2009**, *109*, 375–382.
17. Wulandari, W.; Soerawidjaja, T.H.; Joshua, S.; Isradi, H.R. Extraction of nickel from nickel limonite ore using dissolved gaseous SO$_2$-Air. *AIP Conf. Proc.* **2017**, *1805*, 070004. [CrossRef]
18. Guo, Q.; Qu, J.; Qi, T.; Wei, G.; Han, B. Activation pretreatment of limonitic laterite ores. *Miner. Eng.* **2011**, *24*, 825–832. [CrossRef]
19. Li, J.; Li, X.; Hu, Q.; Wang, Z.; Zhou, Y.; Zheng, J.; Liu, W.; Li, L. Effect of pre-roasting on leaching of laterite. *Hydrometallurgy* 2009, 99, 84–88. [CrossRef]

20. Jiang, M.; Sun, T.; Liu, Z.; Kou, J.; Liu, N.; Zhang, S. Mechanism of sodium sulfate in promoting selective reduction of nickel laterite ore during reduction roasting process. *Int. J. Miner. Process.* 2013, 123, 32–38. [CrossRef]

21. Levenspiel, O. Chemical Reaction Engineering. In *Chemical Reaction Engineering*, 3rd ed.; John Wiley & Sons: Hoboken, NJ, USA, 1998; pp. 569–576.

22. Thubakgale, C.K.; Mbaya, R.K.K.; Kabongo, K. A study of atmospheric acid leaching of a south african nickel laterite. *Miner. Eng.* 2013, 123, 32–38. [CrossRef]

23. O’Connor, F.; Cheung, W.H.; Valix, M. Reduction roasting of limonite ores: Effect of dehydroxylation. *Int. J. Miner. Process.* 2006, 80, 88–99. [CrossRef]

24. Li, J.; Li, Y.; Gao, Y.; Zhang, Y.; Chen, Z. Chlorination roasting of laterite using salt chloride. *Int. J. Miner. Process.* 2016, 148, 23–31. [CrossRef]

25. Ma, B.; Yang, W.; Pei, Y.; Wang, C.; Jin, B. Effect of activation pretreatment of limonitic laterite ores using sodium fluoride and sulfuric acid on water leaching of nickel and cobalt. *Hydrometallurgy* 2017, 169, 411–417. [CrossRef]

26. Li, G.; Shi, T.; Rao, M.; Jiang, T.; Zhang, Y. Beneficiation of nickeliferous laterite by reduction roasting in the presence of sodium sulfate. *Miner. Eng.* 2012, 32, 19–26. [CrossRef]

27. Zhang, W.; Singh, P.; Muir, D. Iron(II)/oxidation by SO2/O2 in acidic media: Part I. Kinetics and mechanism. *Hydrometallurgy* 2000, 55, 229–245. [CrossRef]

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