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# The Effect of Alkali Roasting Pretreatment on Nickel Extraction from Limonite Ore by Using Dissolved $SO_2$-Air

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**Abstract:** Extraction of limonite ore using dissolved $SO_2$–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, $Na_2CO_3$ and $Na_2SO_4$). 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 $Na_2CO_3$, $Na_2SO_4$ 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; $SO_2$; 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 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 $Na_2CO_3$. Alkali roasting activation pretreatment was thought to breaks 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 $Na_2CO_3$, $Na_2SO_4$ 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 | $SiO_2$ | CaO | MgO | MnO | $Cr_2O_3$ | $Al_2O_3$ | $P_2O_5$ | $TiO_2$ | $SO_3$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 ($Na_2CO_3$, $Na_2SO_4$, 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 $SO_2$ (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 Diffrraction (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:

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

$$\text{Nickel selectivity} = \frac{Ni/Fe\ in\ the\ aquoeus}{Ni/Fe\ in\ the\ raw\ ore} \tag{2}$$

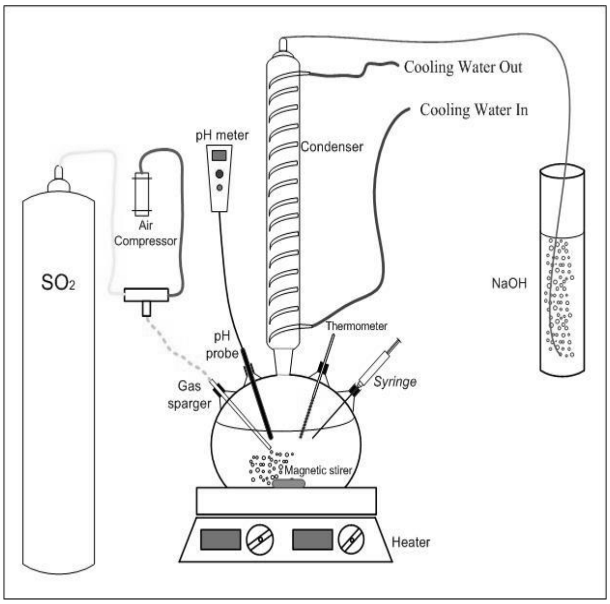



**Figure 1.** Experiment setup for nickel leaching.

## 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 composes of magnetite ($Fe_3O_4$) 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 ($Fe_2O_3$) 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 ($Mg_2SiO_4$) and hematite ($Fe_2O_3$).

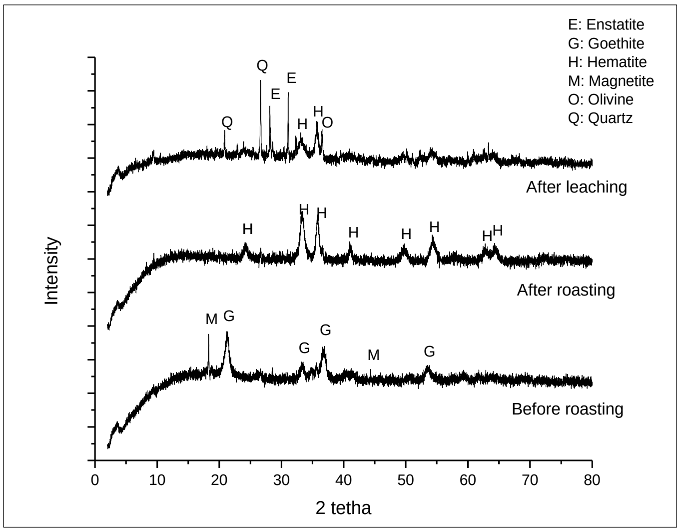
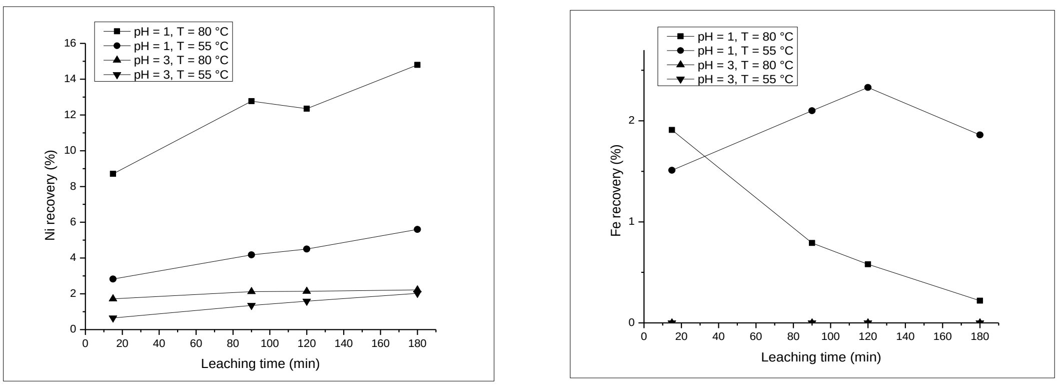



**Figure 2.** X-ray diffraction analysis of raw limonite ore, roasted ore and residue after leaching.

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.




(**a**) (**b**)

**Figure 3.** Recovery of nickel and iron using conventional roasting pretreatment and leaching using $SO_2$-dissolved air. (**a**) nickel recovery; (**b**) iron recovery.

### 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 $Na_2CO_3$ shows sodium iron silicon oxide [$Na(FeSi)O_2$], quartz ($SiO_2$), hematite and magnesium iron oxide (MgFeO). It is postulated that $Na_2CO_3$ decomposes into $Na_2O$ and $CO_2$ during the roasting as indicated by Equation (3) [18]. Then, $Na_2O$ possibly reacts with iron, silicate, chrome and other minerals in the ore (Equations (4)–(6)).

$$Na_2CO_3 = Na_2O + CO_2 \quad (3)$$

$$Na_2O + Fe_2O_3 = 2NaFeO_2 \quad (4)$$

$$Na_2O + Cr_2O_3 = 2NaCrO_2 \quad (5)$$

$$Na_2O + SiO_2 = Na_2SiO_3 \quad (6)$$

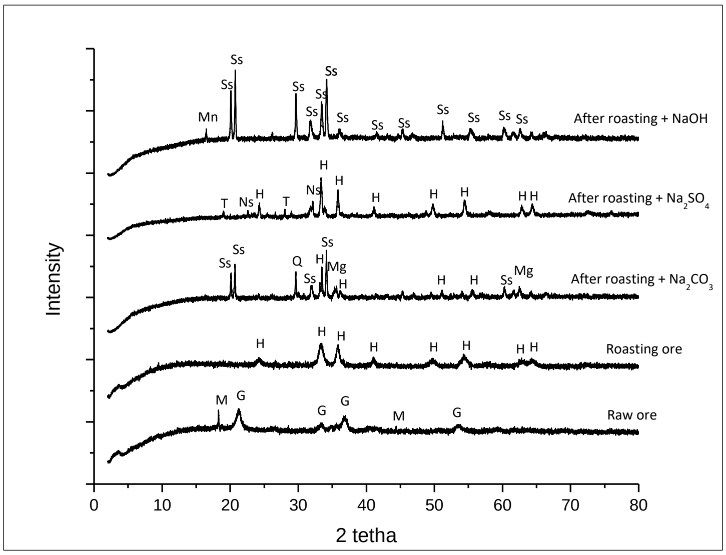
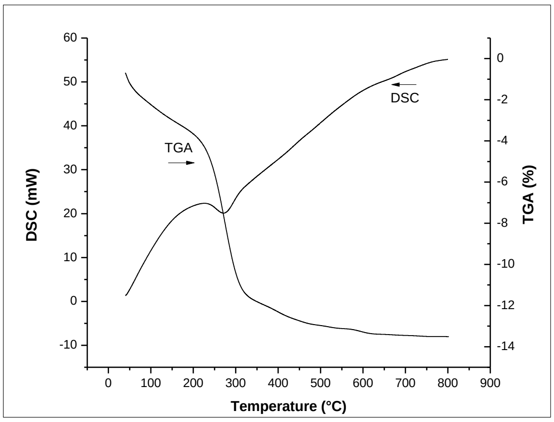



**Figure 4.** XRD pattern of limonite ore after roasting and alkali roasting. G—goethite; M—magnetite; H—hematite; Ss—sodium iron silicon oxide; Q—quartz; Mg—magnesium iron oxide; T—thenardite; Ns—sodium sulfate; Mn—manganese cyanide.

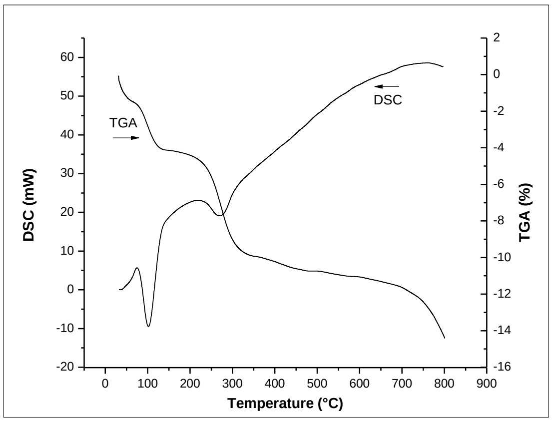
The XRD of pretreated ore with $Na_2SO_4$ contains hematite as the major mineral as well as thenardite ($Na_2SO_4$). In a study that used reducing atmosphere [20], $Na_2SO_4$ is decomposed to form $Na_2O$, $Na_2S$ and S; whereas it is claimed that $Na_2S$ and S are beneficial for nickel recovery through a magnetic separation due to the FeS formation. The present study shows that $Na_2SO_4$ is not decomposed into $Na_2O$. 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 those XRD spectra indicates that the goethite 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 + $Na_2CO_3$ and limonite + $Na_2SO_4$ 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 $Na_2CO_3$, $Na_2SO_4$ and NaOH, respectively. As can be seen in those figures, the goethite phase becomes diminished after alkali roasting. After leaching with $SO_2$-dissolved air, the residue with $Na_2CO_3$ and $Na_2SO_4$ are dominated by the hematite phase. This condition may 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).




(**a**)

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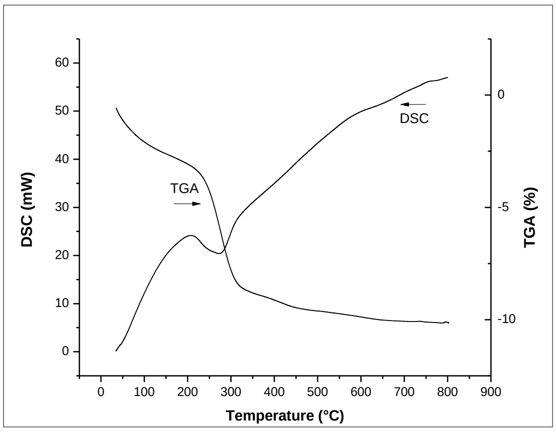
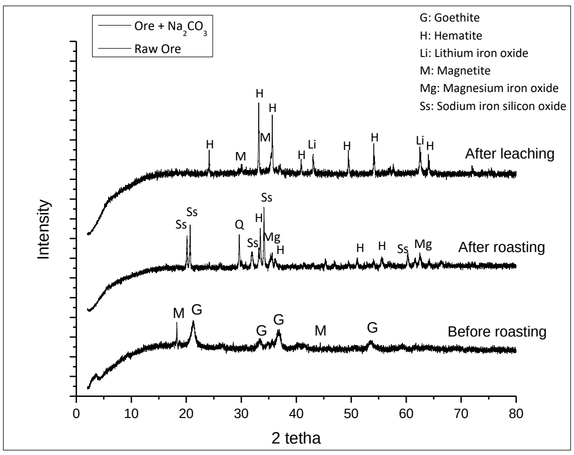
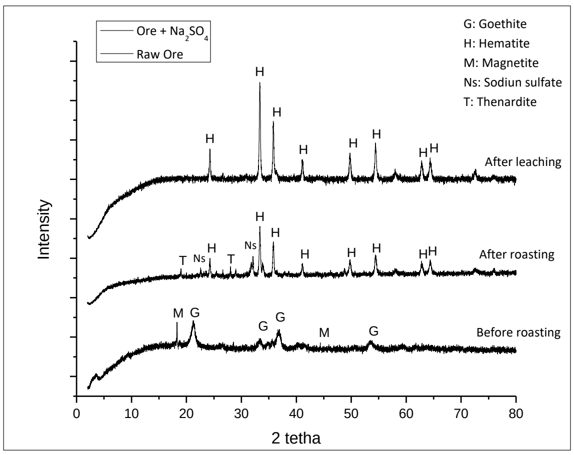



**(c)**

**Figure 5.** TGA/DSC patterns of (**a**) Limonite ore, (**b**) ore + $Na_2CO_3$ and (**c**) ore + $Na_2SO_4$ alkali roasting.

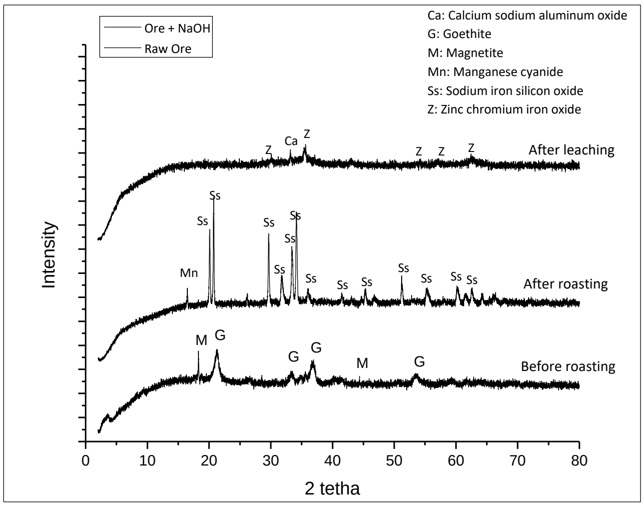



(**a**)




(**b**)

**Figure 6.** *Cont*.

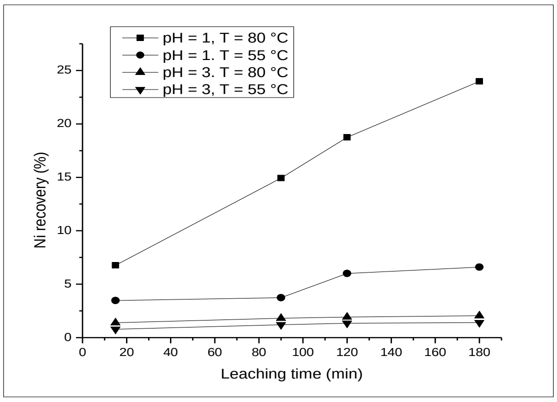



**(c)**

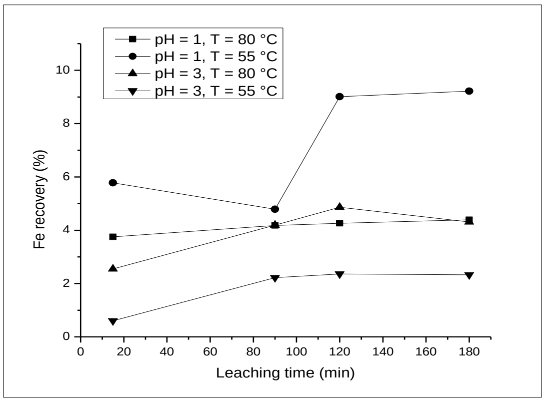
**Figure 6.** XRD patterns of (**a**) Ore + $Na_2CO_3$, (**b**) ore + $Na_2SO_4$ and (**c**) ore + NaOH after roasting and leaching with $SO_2$–air.

Figure 7a–f show the recovery of nickel and iron after leaching with $SO_2$-dissolved air. The increase in nickel recovery was observed at pH = 1 and temperature 80 °C in all pretreated ore. This result shows that the utilization of alkali roasting pretreatment enhances the recovery of nickel compared to roasting without alkali. Figure 7a,b present the Ni and Fe recoveries at pH 1 and temperature 80 °C with $Na_2CO_3$ 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 $Na_2SO_4$ 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.

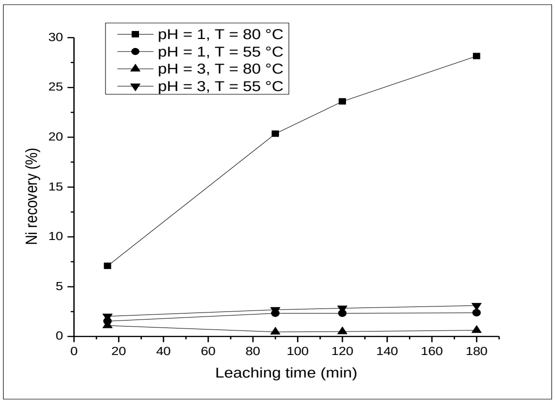



**(a)**




**(b)**

**Figure 7.** *Cont.*

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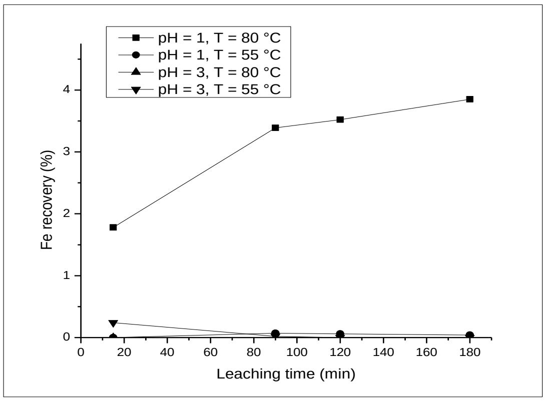


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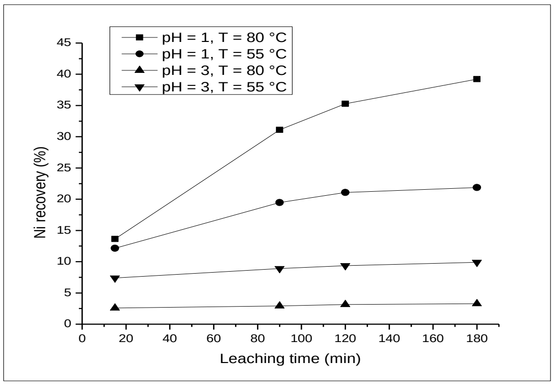
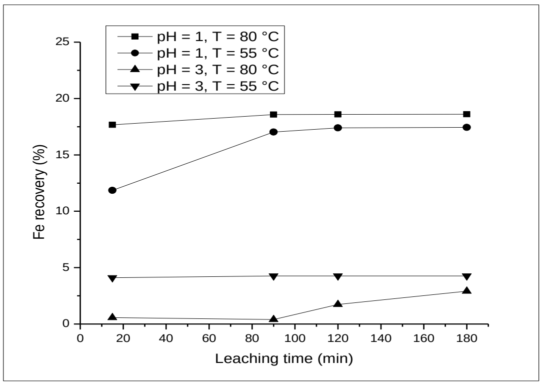



**(e)**




**(f)**

**Figure 7.** Recovery of nickel and iron using alkali roasting pretreatment and leaching using $SO_2$-dissolved air in water: (**a**,**b**) Ore + $Na_2SO_4$; (**c**,**d**) Ore + $Na_2SO_4$; (**e**,**f**) Ore + NaOH.

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 $Na_2SO_4$ followed by extraction at pH 3 and temperature of 55 °C. The alkali roasting pretreatment with NaOH and $Na_2CO_3$ 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.

**Table 2.** The selectivity of nickel over iron in various pH and temperature.

| **Operating Condition** | | **Ni/Fe Selectivity** | | | |
|---|---|---|---|---|---|
| **pH** | **T (°C)** | **Roasting** | **$Na_2CO_3$ Roasting** | **$Na_2SO_4$ 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.

$$1-(1-X)^{1/3}=\frac{t}{\tau} \quad (7)$$

$$1-3(1-X)^{2/3}+2(1-X)=\frac{t}{\tau} \quad (8)$$

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 $SO_2$-dissolved air may be represented by two mechanisms simultaneously.

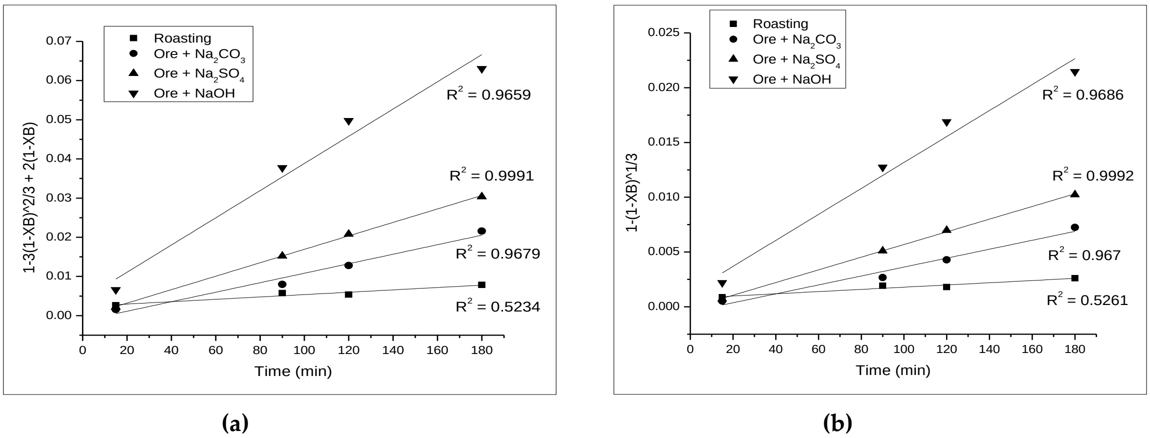



**Figure 8.** A linear fit of the nickel leaching kinetics at pH 1 and a temperature of 80 °C for (**a**) interface chemical reaction and (**b**) diffusion of reactants or products.

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%. Compared to this range, the recovery obtained using dissolved $SO_2$–air is considerably lower, i.e., 23.33–39.22%. This may be due to the nature of $SO_2$ gas which is a much milder reductant compared to sulfuric acid or hydrochloric acid. Previous research on the $SO_2$–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 $SO_2$/air due to the low solubility of $SO_2$ 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 $SO_2$–air to be not very promising, an economic assessment may nevertheless be needed to verify the overall economics of the processes in Table 3.

**Table 3.** Summary of leaching process of limonite ores literatures.

| No. | Method | Type of Ore | Experiment Parameters | Ni Recovery (%) | Reference |
|---|---|---|---|---|---|
| 1 | Atmospheric leaching | Indonesian laterite | T = 90 °C, 30-g/L $Na_2SO_3$, t = 6 h, L/S ratio: 10:1. | 82.3 | [12] |
| 2 | Atmospheric leaching | West Papua limonite and saprolite | T = 100 °C, $H_2SO_4$/ore ratio = 1.4:1, t (limonite) = 3 h. t (saprolite) = 11 h | Limonite: 85 Saprolite: 50 | [2] |
| 4 | Chlorination roasting and water leaching | Limonite | Roasting T = 1173 K, t = 1.5 h, Chloride agent = NaCl + $MgCl_2.6H_2O$ (mass ratio of 0.4) | 87 | [24] |
| 5 | Activation pretreatment and NaF and $H_2SO_4$ leaching | Philippines limonite | Activation T = 400 °C, t = 60 min, $H_2SO_4$ dosage = 500 kg/ton, NaF dosage = 3% | 85.3 | [25] |
| 6 | Pre-roasting and leaching | Yunan, China laterite | T roasting = 300 °C, Ore + 4-mol/L HCl; S/L ratio = 1:6; T = 50 °C; t = 1 h | 93.1 | [19] |
| 7 | Reduction roasting | Sulawesi, Indonesia laterite | Reduction roasting T = 1100 °C, t = 60 min, sodium sulfate = 20 wt% | 83.01 | [26] |
| 8 | Alkali roasting, $SO_2$–air leaching | Indonesia, limonitic | T = 55–80 °C, pH: 1 and 3; t = 3 h | 23.99–39.22 | Current work |

T—temperature; t—time; No.—number.

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 ($SO_5^{\cdot-}$ or $HSO_5^-$) is responsible for the fast oxidation. The final product of $SO_5^{\cdot-}$ is sulfate via intermediate product $HSO_5^-$ or $FeSO_5^+$. However, the radical $SO_3^{\cdot-}$ and $SO_5^{\cdot-}$ also terminate by self-reaction to produce dithionate [26].

$$SO_2{\cdot}H_2O \rightleftharpoons HSO_3^- + H^+ \tag{9}$$

$$HSO_3^- \rightleftharpoons SO_3^{2-} + H^+ \tag{10}$$

$$Fe^{3+} + SO_3^{2-} \rightleftharpoons FeSO_3^+ \tag{11}$$

$$FeSO_3^+ \rightarrow Fe^{2+} + SO_3^{\cdot-} \tag{12}$$

$$SO_3^{\cdot-} + O_2 \rightarrow SO_5^{\cdot-} \tag{13}$$

$$SO_5^{\cdot-} + HSO_3^- \rightarrow SO_3^{\cdot-} + HSO_5^- \tag{14}$$

The $SO_4^{\cdot-}$ 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].

$$SO_5^{\cdot-} + HSO_3^- \rightarrow SO_4^{\cdot-} + HSO_4^- \tag{15}$$

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 [$Na(FeSi)O_2$], quartz ($SiO_2$), hematite and magnesium iron oxide (MgFeO) (for ore roasted with $Na_2CO_3$), hematite and thenardite (for ore roasted with $Na_2SO_4$) 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.

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