

Improving alumina grade from Malaysian bauxite via roasting and magnetic separation prior to the Bayer process

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ABSTRACT Bauxite ore is a sedimentary rock which is known to be the primary ore for alumina (Al_2O_3) production and can be further refined as Aluminum (Al). This element is vital and widely used in transportation, packaging, electrical appliances and household products. The Bayer process is the most common process used for alumina extraction. However, producing a high grade of alumina is challenging due to the presence of impurities. This study investigates the effect of without (Method 1) and with pre-treatments (Method 2) prior to the Bayer process, to produce precipitated alumina trihydrate (ATH) from Malaysian bauxite. In Method 2, the raw bauxite ($-45\ \mu\text{m}$) underwent pre-treatments including roasting at 500°C and a wet magnetic separation at 3.0 A. Whereas, the Bayer process in both methods was performed using 3.0 M NaOH with a liquid to solid ratio of 1:5, stirred at 400 rpm and heated at 90°C for 1 hour. The pregnant solution underwent precipitation by adding 6 g of Al_2O_3 seeds, stirred at 200 rpm at 70°C for 24 hours and left for 5 days. The raw bauxite of Felda Bukit Goh, Kuantan, Pahang, mainly consists of 48.02 wt. % Fe_2O_3 , 31.85 wt. % Al_2O_3 , 14.10 wt. % TiO_2 and 4.92 wt. % SiO_2 . Gibbsite was the predominant mineral. Via AAS analysis, the Al_2O_3 grade detected was 35.2%. After the Bayer process, it was observed that the Al_2O_3 grades of the bauxite residues in methods 1 and 2 were 32.15 % and 28.20 %, respectively. This indicates that there was more dissolution of Al_2O_3 over pre-treatments. The Al_2O_3 grades measured from the precipitated ATH can be achieved up to 77.14% with 7.64% recovery, whereas without pre-treatments, 70.44% Al_2O_3 with 5.72% recovery.

KEYWORDS: Alumina Trihydrate; Bauxite; Bayer process; Magnetic separation; Roasting

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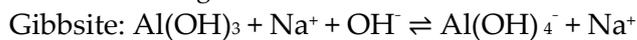
INTRODUCTION

Bauxite is the prime ore for aluminium (Al) production. From beverage cans and smartphones to aircraft and electric vehicles, aluminium touches nearly every aspect of our daily routine, making it essential. In fact, as the global industries continue to transition toward sustainability and electrification, the demand for aluminium is growing promptly, hence the reason this enlists bauxite at the midpoint of the global resource conversation. As of 2024, Australia is the world's main bauxite producer, estimated at 11 billion tons (Arora, 2024). However, Guinea holds the world's largest reserves, valued at over 7.4 billion metric tons (Sistem Al Aluminium, 2024). Meanwhile, China is the world's largest alumina producer with approximately production of 84 million metric tons (Jaganmohan, 2025). In the meantime, the export activity of bauxite in Malaysia has been banned since 2016 and while waiting for the approval of the environmental impact assessment (EIA) report by the government, no active mining has been operating up until now (Majumder, 2024). Hence, careful rules and regulations by the Malaysian government are important and urgent to ensure that the environmental issue of bauxite mining is not a threat to the public. Regardless of that, the Malaysian bauxite is one of the strategic mineral resources gazetted by the Malaysian Government for the economic growth (Kementerian Tenaga dan Sumber Asli, 2021) and this resource is abundantly unexploited in Malaysia.

Generally, four tons of bauxite can produce 2 tons of alumina (Al_2O_3) via the Bayer process. The Bayer process is a well-known process for alumina production invented by Carl Josef Bayer in 1887 and about 90% of global alumina output adopts this method. High impurities, such as iron (Fe) content in bauxite, may interrupt the alumina extraction. Several researchers removed the impurities before the Bayer process was implemented, such as Fe, which can be extracted via magnetic separation. However, not all Fe-based minerals can be separated directly, as the Fe in bauxite can be in the form of goethite ($\alpha\text{-FeOOH}$) or aluminium goethite (Fe, Al)OOH minerals, which is an antiferromagnetic mineral (Rosenblum & Brownfield, 1999). Hematite (Fe_2O_3) is, however, a paramagnetic mineral where a high intensity of magnetic field is needed for extraction compared to ferromagnetic minerals like magnetite (Fe_3O_4), which requires less intensity. To convert this goethite to hematite and magnetite minerals, the pyrolysis process is often used (Joannes *et al.*, 2024; Liu *et al.*, 2023).

The Bayer process comprises three main stages, including (1) extraction or digestion of alumina-bearing minerals from bauxite ore, (2) precipitation or crystallization of aluminium trihydrate (ATH) and (3) calcination to produce the final product, which is the alumina (Ibrahim *et al.*, 2021; Brough & Jouhara, 2020; Popat & Desai, 2013). Usually, during digestion, bauxite ore is mixed with caustic soda or sodium hydroxide (NaOH) at a temperature less than 280°C to attain a soluble anionic complex of tetrahydroaluminate ions (Zhou *et al.*, 2022). This soluble anionic solution then reacted with alumina seeds for crystal growth and can be collected as precipitated ATH or aluminium hydroxide ($\text{Al}(\text{OH})_3$). The precipitated ATH is calcined at high temperature around 1400°C to form alumina. The chemical equation of each stage can be expressed as follows:

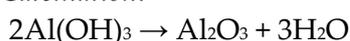
(1) *Extraction or Digestion:*



(2) *Precipitation or Crystallization:*



(3) *Calcination:*



However, the extraction of alumina also depends on the constituents that coexist in the bauxite ore. Therefore, over many years, the Bayer process has been altered to achieve high alumina extraction and recovery. A recent study by Li *et al.* (2025) replaced NaOH with potassium hydroxide (KOH) during the Bayer process to promote an environmentally friendly method for alumina production. The findings revealed that alumina extraction achieved up to 82.52% at optimal conditions of K_2O concentration, digestion temperature, Ca/Si ratio and mixing time of 240 g/L, 260°C , 0.2 and 60 minutes, respectively. The alumina grade reported was as high as 99.4%. Zhou *et al.* (2023) had also performed a two-stage Bayer digestion with glycerol as an additive. In the 1st and 2nd digestions, the temperatures used were 140°C and 270°C , respectively. The alumina recovery and grade attained as high as 99.18% and 1.47%, respectively. Another study by Zhou *et al.* (2022) performed a Bayer digestion of bauxite at 260°C for 60 minutes. About 10.35% alumina with a recovery of 91.50% were achieved. All findings show a promising result on alumina recoveries, but utilizing a digestion temperature above 100°C . Still, the grade alumina needs to be emphasized too.

A previous work by Ibrahim and co-workers (Ibrahim *et al.*, 2021) investigated the effect of several precipitation conditions on precipitated ATH grades at a lower digestion temperature. This includes

the temperature, amount of ATH seed used, pH and precipitation days. Even so, the study only performed dry and wet magnetic separation as the pre-treatments and the particle size of the sample was reduced to less than 600 μm . In this present study, a slight modification has been made by introducing the roasting process before performing the wet magnetic separation, followed by the Bayer process. In addition, the particle size of the sample was reduced to less than 45 μm . Henceforth, the effect of Al_2O_3 grades from the precipitated ATH with and without pre-treatments before the Bayer process was evaluated.

METHODOLOGY

Material and Sample Preparation

The raw bauxite was collected from Felda Bukit Goh, Kuantan, Pahang, Malaysia via grab sampling at approximately 60 cm depth. The sample was sun-dried for 2 to 3 hours and 1 kg of the sample underwent the coning and quartering method (Joannes *et al.*, 2025). Then the sample was ground at 78 rpm for 10 minutes using a grinding mill and underwent wet screening using a 45 μm sieve (ASTM E:11). The process flow chart of ATH production based on methods 1 and 2 is illustrated in Figure 1.

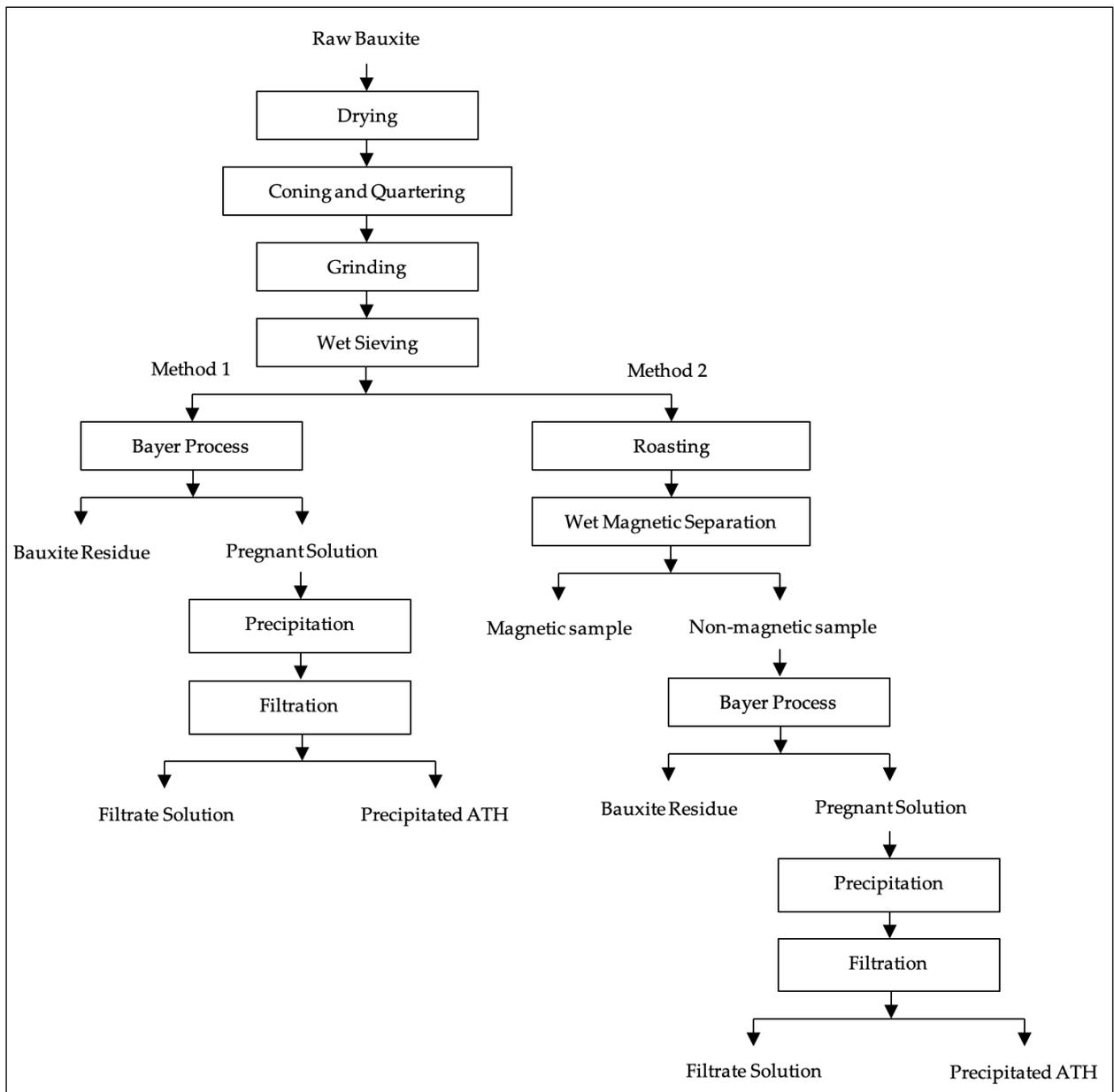


Figure 1. Process flow of alumina trihydrate production based on methods 1 and 2.

Sample Characterization

Prior to processing, the sample was characterized using an X-ray Fluorescence Spectrometer (XRF-1700, Shimadzu, Japan) and X-ray Diffraction (XRD-D8, Bruker, Germany) to determine its chemical compounds and mineral phases. The detailed procedures can be referred to elsewhere (Joannes *et al.*, 2025).

Roasting Process

In method 2, the sample was roasted at 500°C for 1 hour using a furnace (CWF1200, CARBOLITE GERO, Germany) (Joannes *et al.*, 2025).

Magnetic Separation

In method 2, the sample underwent magnetic separation using a wet high-intensity magnetic separator (WHIMS) (BOXMAG RAPID, Ltd, Birmingham, UK). The current was fixed at 3.0 Amperes with three repetitions.

Bayer Process

The Bayer process procedures were adapted from Ibrahim and team (Ibrahim *et al.*, 2021) with a slight modification. The sample underwent the Bayer process, intending to dissolve the alumina minerals into sodium hydroxide (NaOH). In this process, 3.0 M NaOH was used as the leaching agent. The sample mass to NaOH solution volume ratio used was 1:5. Subsequently, the sample was mixed at 400 rpm for 1 hour and heated at $90 \pm 1^\circ\text{C}$ using a hot plate with magnetic stirrer (IKA® RCT Basic C, Germany). While stirring, the pH of the mixture was adjusted to a range from 12.07 to 12.13 using 1% sulfuric acid (H_2SO_4) as the pH regulator and measured using a pH (Thermo Scientific™ Orion Star A121, Fisher Scientific, UK). The sample was filtered using a filter paper (Whatman, ϕ 12 cm, pore size of 2.7 μm) and a vacuum pump (VELP Scientifica, Italy) to separate the pregnant solution and bauxite residue.

Precipitation Process

The sample was mixed at 200 rpm and heated at $70 \pm 1^\circ\text{C}$ for 24 hours. The amount of Al_2O_3 seed used was 6 g for each method. The initial pH of the solution was measured at 13.65 and 11.02 for method 1 and method 2, respectively. After 24 hours of mixing, the solution was left for 5 days at room temperature to allow the crystal growth of ATH. Then the solution and the precipitated ATH were separated using the vacuum pump.

Determination of Alumina (Al_2O_3) Content

The Al content was determined using Atomic Absorption Spectroscopy (AA6800, Shimadzu, Japan) at a wavelength, λ of 396.2 nm. The procedure was based on an in-house method. Between 0.20 and 0.25 g of the sample was used and dissolved in 10 mL of hydrofluoric (HF) solution using a polypropylene beaker. The sample was heated until dry in a steam bath. Then, the residue was washed with distilled water (DW) and placed into a nickel crucible, and the sample was reheated until dry. 2.0 g of potassium hydroxide (KOH) was added, closed with a small glass lid and heated using a Bunsen burner for approximately 5 minutes and left to cool at room temperature. Subsequently, 20 mL of DW was added, closed and heated using a steam bath for 1 hour. The solution inside the crucible was washed using DW and transferred into a 250 mL volumetric flask. 20 mL of hydrochloric acid (HCl) and 50 mL of 10,000 mg/L potassium chloride (KCl) were added, then brought up to 250 mL using DW. The conversion factor of Al to Al_2O_3 was quantified by multiplying the Al value by 1.89.

Recovery of Alumina

The recovery of Al_2O_3 is calculated using Equation 1.

$$R_{\text{Al}_2\text{O}_3} = [(m \times C_{\text{Al}_2\text{O}_3})_{\text{in precipitated ATH}} / (m \times C_{\text{Al}_2\text{O}_3})_{\text{in raw bauxite}}] \times 100\% \quad (1)$$

R is the Al_2O_3 recovery, m is the mass of the respective sample and C is the concentration.

Determination of Iron Oxide (Fe_2O_3) Content

The Fe content was determined based on the titration method as described elsewhere (Joannes *et al.*, 2023). The conversion factor of Fe to Fe_2O_3 was quantified by multiplying the Fe value by 1.43.

RESULT AND DISCUSSION

Chemical Compositions and Mineral Phases of Raw Bauxite

The chemical compositions of the raw bauxite from Felda Bukit Goh, Kuantan, Pahang, were tabulated in Table 1. Note that the bauxite was enriched with iron oxide (Fe_2O_3) content up to 48.02 wt. % followed by 31.85 wt. % Al_2O_3 , 14.10 wt. % TiO_2 and 4.92 wt. % SiO_2 . In addition, the ratio of Al_2O_3 to SiO_2 was less than 8, indicating that pre-treatments before the Bayer process are required (Modi & Dewangan, 2024). Figure 2 illustrates the mineral phases of raw bauxite. Gibbsite, $\text{Al}(\text{OH})_3$, was observed to be the primary mineral. Other alumina minerals, such as diaspore and boehmite, were also detected.

Table 1. Chemical compositions of raw bauxite.

| Composition | wt. (%) | Composition | wt. (%) |
|-------------------------|---------|-------------------------|---------|
| Fe_2O_3 | 48.02 | Cr_2O_3 | 0.20 |
| Al_2O_3 | 31.85 | SO_3 | 0.20 |
| TiO_2 | 14.10 | ZrO_2 | 0.19 |
| SiO_2 | 4.92 | Na_2O | 0.18 |
| MnO | 0.26 | ZnO | 0.08 |

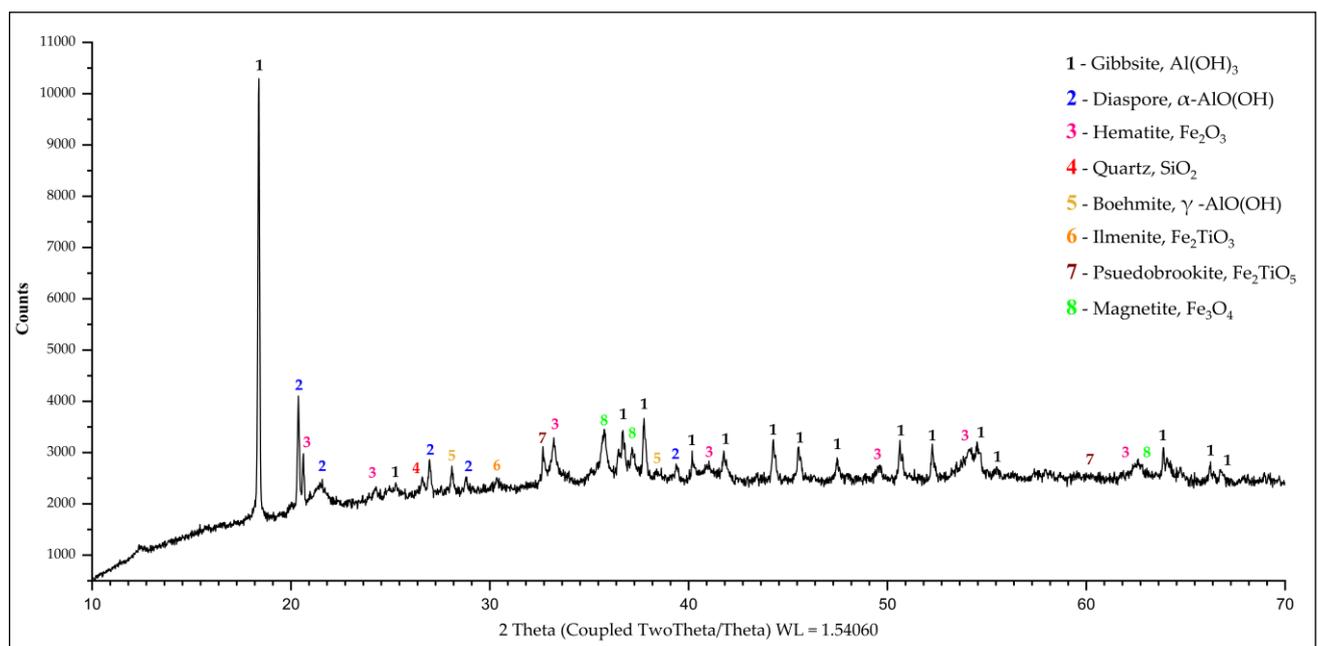


Figure 2. Mineral phases of raw bauxite.

Effect of Pre-treatments

The Al_2O_3 and Fe_2O_3 grades before and after the Bayer process of methods 1 and 2 are displayed in Figures 3 and 4, respectively. With pre-treatments, a higher Al_2O_3 grade in precipitated ATH up to 77.14% indicated enhanced dissolution of Al_2O_3 into the pregnant liquor. Meanwhile, about 28.20% Al_2O_3 remained in the bauxite residue, as shown in Figure 3. By comparing without any pre-treatments, the Al_2O_3 grade in precipitated ATH attained at 70.44%, whereas about 32.15% Al_2O_3 in the bauxite residue, which was almost 4% higher than in method 2. The result attained here was comparable with the study conducted by Ibrahim *et al.* (2021), where, at optimum conditions, grades of 63.88% and 59.00% Al_2O_3 were attained when the precipitated ATH was left for 3 and 5 days, respectively. In Figure 4, after roasting, the Fe_2O_3 grade has increased by about 1.18%. Via wet magnetic separation, the iron content can be separated up to 40.63% Fe_2O_3 however, about 34.51% Fe_2O_3 remained in the non-magnetic sample. This indicates that magnetic minerals can be removed after the non-magnetic minerals are converted to magnetic minerals via roasting (Lui *et al.*, 2023). After the Bayer process, the Fe_2O_3 grades in the bauxite residues with or without pre-treatments in methods 1 and 2 dropped to 27.87% and 26.86%, respectively.

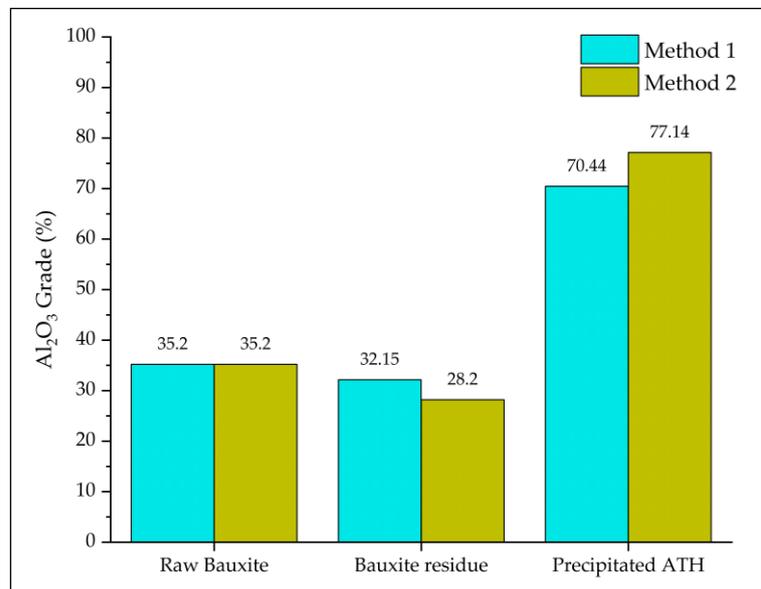


Figure 3. Al_2O_3 grades before and after the Bayer process.

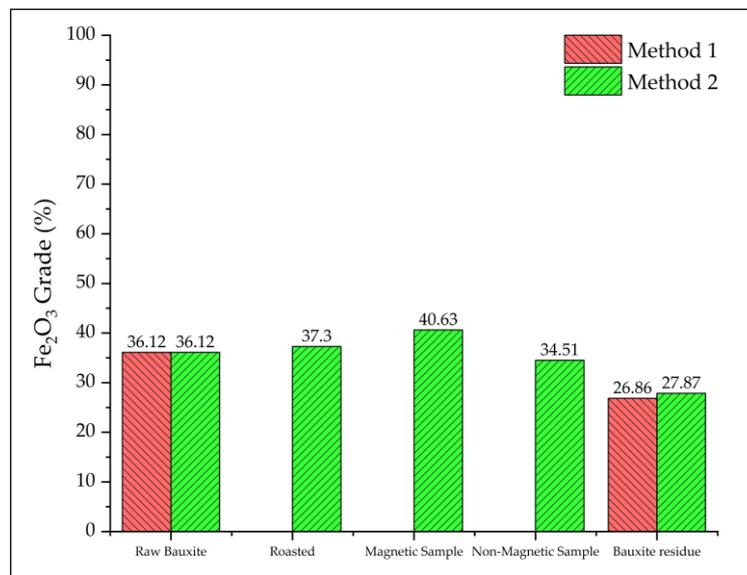


Figure 4. Fe_2O_3 grades before and after the Bayer process.

Recovery of Al₂O₃

The recovery of Al₂O₃ was calculated using Equation 1 and summarized in Table 2. By comparison, the Al₂O₃ recovery in method 2 was higher than in method 1. The Al₂O₃ recovery is another important aspect that needs to be studied and optimized, as it represents the quantity of alumina extracted from the raw ore. In this work, recovery of Al₂O₃ was lower than reported literatures (Li *et al.*, 2025; Zhou *et al.*, 2023).

Table 2. Recovery of Al₂O₃, grades of Al₂O₃ and Fe₂O₃ based on methods 1 and 2.

| | Method 1 | Method 2 |
|--|----------|----------|
| Recovery of Al ₂ O ₃ (%) | 5.72 | 7.64 |
| Grade of Al ₂ O ₃ (precipitated ATH) (%) | 70.44 | 77.14 |
| Grade of Fe ₂ O ₃ (Magnetic sample) (%) | - | 40.63 |

CONCLUSION

The effect of pre-treatments, namely roasting and wet-based magnetic separation before the Bayer process, on alumina grade improvement was investigated. With pre-treatments, it can improve the Al₂O₃ grade of precipitated ATH by ~10% under the conditions investigated and ~21% improvement from the previous study by Ibrahim and co-workers. Nevertheless, the alumina recovery was low, and further work can be done to improve its recovery by optimizing the crystallization period and conditions.

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