

Research Article

Concentration of Bauxite and Iron Minerals from Onigboro Ironstone, Ogun State, Nigeria

Adedayo Omobamidele Adeuti* , Ebenezer Oluwatomi Ajaka

The Department of Mining Engineering, The Federal University of Technology Akure (FUTA), Akure, Nigeria

Abstract

This research investigated the concentration of bauxite and iron minerals from the Onigboro Ironstone deposit in Ogun State, Nigeria, with the aim of optimizing mineral recovery through various beneficiation techniques. The primary objectives included identifying the mineralogical composition of the deposit, assessing the economic viability of the ironstone, and recommending appropriate concentration methods. In order to achieve these objectives, methods such as X-Ray Fluorescence (XRF) and Atomic Absorption Spectroscopy (AAS) Analyses were employed to determine the key mineralogy, including aluminum oxide, iron oxide, and silica. The findings revealed that the Onigboro Ironstone contains approximately 45% bauxite and 35% iron minerals, with the remaining 20% comprised of gangue materials including free silica. This mineral content indicated substantial potential for extraction and aligned with the study's goals of identifying valuable resources suitable for processing. The research employed gravity concentration techniques, including, spiral separation, shaking tables, and hindered settling, to evaluate their effectiveness in recovering valuable minerals from the ironstone. Shaking table emerged as the most efficient method, achieving recovery rates of 92% for Iron and 88% for bauxite. Spiral separators also demonstrated promising recovery rates but had some limitations in concentrate purity. The findings underlined the importance of optimizing comminution processes to enhance mineral liberation, which directly impacted recovery rates. The research was grounded in established theoretical frameworks, including Particle Separation Theory, Mineral Liberation Theory, and Gravity Separation Theory, which guided the optimization of concentration processes. These theories provided valuable insights into the mechanisms of mineral separation based on density differences, mineral liberation, and the efficiency of gravity-based techniques. In conclusion, the research offered recommendations for stakeholders in the mining sector, emphasizing the need for improved recovery strategies and sustainable practices of the Onigboro Ironstone deposit. Future research should focus on field studies, the application of advanced techniques, and multidisciplinary approaches to further improve mineral recovery and support sustainable mining practices.

Keywords

Bauxite, Concentration, Deposit, Ironstone, Processing

1. Introduction

1.1. Background Information

The Onigboro Ironstone deposit in Ogun State, Nigeria, is a

significant source of bauxite and iron minerals, crucial for various industrial applications. The chemical composition of this ironstone is characterized by a notable presence of alu-

*Corresponding author: adeutiadedayo@gmail.com (Adedayo Omobamidele Adeuti)

Received: 7 April 2025; **Accepted:** 17 April 2025; **Published:** 27 August 2025



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minum oxide (Al_2O_3), iron oxide (Fe_2O_3), and silica (SiO_2), average concentrations of 27%, 35%, and 30% respectively, along with 8% water (H_2O). This unique composition presents an opportunity to extract and concentrate bauxite and iron minerals, contributing to the development of Nigeria's mining and metallurgical sectors [30].

Bauxite, composed of aluminum oxide minerals, is the primary ore for aluminum production [21]. Aluminum is a vital material in numerous industries, including aerospace, automotive, packaging, and construction, due to its lightweight, corrosion resistance, and high conductivity. Therefore, efficient extraction and concentration of bauxite from the Onigboro Ironstone could significantly impact the aluminum supply chain and related industries in Nigeria [24].

Iron oxide, another major component of the Onigboro Ironstone, is essential for steel manufacturing. Steel, a fundamental material in construction, infrastructure, transportation, and manufacturing, requires a reliable and high-quality source of iron [15]. The iron oxide content in the Onigboro Ironstone indicates substantial potential for iron extraction and concentration, supporting Nigeria's steel industry and reducing dependency on imported raw materials [24]. The presence of silica (SiO_2) in the Onigboro Ironstone, while often considered an impurity in both aluminum and ironstone, can also be utilized in various industrial processes. For instance, silica is a critical component in glass manufacturing, ceramics, a slag forming additive in steel making, and as a filler in rubber and plastics. Thus, understanding and managing the silica content is crucial in the beneficiation process to maximize the value derived from the Onigboro deposit [26].

This study aims to investigate the methods and processes for concentrating bauxite and iron minerals from the Onigboro Ironstone. By analyzing the mineralogical and chemical properties of the deposit, the research seeks to develop efficient beneficiation techniques that enhance the yield and quality of extracted minerals.

1.2. Problem Statement

The Onigboro Ironstone deposit in Ogun State, Nigeria, contains substantial proportions of aluminum oxide, iron oxide, and silica. However, the deposit remains underutilized due to inefficient beneficiation techniques. There is a current lack of clarity on the most effective methods for extracting and concentrating bauxite and iron from this complex ore. The high silica content presents additional challenges, complicating the beneficiation process as silica is often seen as an impurity. Moreover, the absence of detailed data on the comminution behavior inhibits the development of effective processing strategies. This study aims to explore economically viable methods for beneficiating the bauxite ore by conducting a comprehensive analysis of physical recovery techniques to reduce ferric oxide contamination in the bauxite ore.

1.3. Aim and Objectives of the Study

1.3.1. Aim of the Study

The aim of the research is to concentrate Bauxite and Iron Mineral from Onigboro Ironstone, Ogun State, Nigeria.

1.3.2. Objectives of the Study

The objectives of the study are to:

1. carry out the compositional analysis of the ironstone;
2. determine the behavior of the ironstone during comminution for efficient processing;
3. undertake beneficiation of the ironstone for recovery of bauxite and iron minerals using applicable processing techniques; and
4. evaluate the recovery from the beneficiation process and identify the most effective concentration techniques and routes.

1.4. Justification of the Study

The deposit's substantial content of aluminum oxide and iron oxide offers significant economic potential by providing raw materials for aluminum and steel production, reducing import needs, and creating jobs. The high industrial demand for aluminum and steel in sectors like aerospace, automotive, construction, and infrastructure underscores the importance of developing efficient extraction techniques.

The unique composition, including silica, presents opportunities for diverse industrial applications, such as glass manufacturing and ceramics, enhancing the overall value and reducing waste. The study aims to advance beneficiation techniques, improving mineral yield and processing efficiency. The study's findings can inform policymakers and stakeholders, guiding strategic planning and policy development for resource management in Ogun State.

Thus, this study is justified by its potential economic benefits, alignment with industrial demands, opportunities for resource utilization, technological advancements, and its role in informing policy and strategic planning.

1.5. Scope of the Study

This research has obtained representative samples from the ironstone deposit and conducted a detailed compositional analysis. Multistage and multiprocess recovery techniques have been employed to identify the most effective beneficiation methods for the ironstone. All research activities, including sample collection and analysis, have been confined to the laboratory environment.

1.6. Limitations of the Study

While this study provided valuable insights into the concentration of bauxite and iron minerals from the Onigboro Ironstone deposit, several limitations were encountered:

Geological Variability: The mineral composition and distribution within the Onigboro deposit may vary, impacting the generalizability of the results. Variations in ironstone characteristics could affect the efficiency of the beneficiation methods employed.

Laboratory Conditions: The experiments conducted were carried out under controlled laboratory conditions, which may not fully replicate real-world mining scenarios. Factors such as equipment scaling, operational parameters, and external environmental conditions can influence the actual performance of the concentration methods.

Resource Constraints: Limited access to certain advanced technologies and techniques may have restricted the depth of analysis. The study primarily focused on commonly used methods, potentially overlooking emerging technologies that could enhance recovery rates.

Time Constraints: The timeframe allocated for the study limited the ability to conduct extensive experiments and explore all potential variables influencing the concentration process.

Data Limitations: The availability and accuracy of historical data on the Onigboro deposit may have constrained some aspects of the research, particularly in comparative analyses with other similar deposits.

2. Literature Review

2.1. Conceptual Review

The review of concepts offers a theoretical background for understanding the processes and procedures used in upgrading bauxite and iron minerals of the Onigboro Ironstone deposit. The review will take into account key concepts relating to mineral composition analysis, comminution behavior, beneficiation procedure, and economic feasibility, all of which are required in order to attain the aims of the study.

2.2. Bauxite Mineral

Bauxite is largely made up of aluminum hydroxide minerals like gibbsite ($\text{Al}(\text{OH})_3$), boehmite ($\gamma\text{-AlO}(\text{OH})$), and diaspor ($\alpha\text{-AlO}(\text{OH})$), and a range of impurities like iron oxides, silica, and titania [25]. Bauxite is significant in the sense that it is the main source of aluminum, a key necessity in many of the world's industrial processes. Tropical environments weather and form bauxite where soluble components get leached away by rain, leaving behind the remaining aluminum-rich residue [18]. Surface mining methods, like open-pit mining, are generally used to extract bauxite [17]. Further operations are carried out to increase the aluminum content [28]. Aluminum is found to be of value based on its lightweight nature, long life, and corrosion resistance. It plays an imperative role in aerospace, automobile, and construction activities [22]. Environmental impacts include habitat destruction and possible contamination of water resources by

mining activities [24].

2.3. Iron Mineral

Iron minerals like hematite (Fe_2O_3), goethite ($\text{FeO}(\text{OH})$), and magnetite (Fe_3O_4) have iron in the +3 oxidation state (Fe^{3+}). They are important in metal and construction material production [25]. They are found in many geological settings due to processes like weathering and metamorphism. They provide vital raw materials for steel and construction material production [33]. Environmental factors involve habitat destruction and water contamination due to mining processes, whereas economic aspects like cost of extraction and market demand determine worldwide production levels [24]. Some of the large producers are Australia, Brazil, China, and India, which indicate the worldwide demand and supply patterns of ferric minerals in industrial applications [22].

Iron mineral processing encompasses several processes to concentrate the iron and remove the impurities for industrial use.

1. Magnetic Separation

Magnetic separation is a common method for separating magnetic minerals from non-magnetic minerals [32]. It exploits the magnetic nature of iron minerals like magnetite (Fe_3O_4) and hematite (Fe_2O_3). High-intensity magnetic separators can successfully separate even fine particles on the basis of their magnetic nature [19].

2. Gravity Separation

Gravity separation operations utilize the difference in weight between valuable minerals and waste minerals [11]. Jigging, spiral hindered settling, and shaking tables are processes that separate denser iron minerals by settling them in a fluid and reject light waste minerals in a different flow [33].

3. Hydrometallurgical Treatment

Hydrometallurgical treatment entails the dissolution and extraction of iron from iron ore minerals through acids or other solutions [20]. It is suitable for low-grade ore or ore with complicated mineral assemblages where the conventional method might not be effective [27].

4. Combined Beneficiation Methods

In most instances, a blend of the methods is employed to recover as much iron as possible and meet product specifications. An example is that magnetic separation is followed by froth flotation to further purify the concentrate. This yields high-quality iron minerals for industrial use [3].

The iron minerals are enriched by various processes according to the respective types of ore. These processes serve to enhance the iron content and reduce the undesired substances through operations such as magnetic separation, gravity separation, magnetic roasting, and hydrometallurgical treatment [16]. This makes iron ore resources serve the various industries effectively.

2.4. Comminution

Comminution is an important process in mineral processing. It helps to recover valuable minerals from ore deposits effectively [12]. Comminution is the process of breaking down the size of ore particles to liberate valuable minerals from the ore [29]. The main methods are:

Crushing: This is the process of reducing big lumps of ore into small pieces by the use of machines. Jaw crushers, gyratory crushers, and cone crushers are used in the first and second crushing stages.

Grinding: Particle size reduction by grinding mills like ball mills, rod mills, and SAG mills. Grinding separates ore particles, liberating minerals that are exposed for further extraction processes.

2.5. Mineral Liberation

Mineral liberation is the percentage of valuable minerals exposed and can be liberated from gangue minerals that are unwanted during rock comminution. An effective comminution provides high mineral liberation, which increases the recovery of valuable minerals like gold, copper, and nickel [23].

3. Materials and Methods

The research utilizes experimental procedures and analytical techniques to explore the concentration of bauxite and iron minerals from ironstone deposits located at the Onigboro in Ogun State, Nigeria. It encompasses thorough sample collection, detailed compositional and mineralogical analyses and stagewise concentration using appropriate methods. These processes are crucial for evaluating the viability and effectiveness of the mineral separation methods employed in this research.

3.1. Materials

The major materials used for this research are the ironstone samples collected from Onigboro deposit and chemicals used in the reductive bleaching process. As shown in Figure 1, samples were collected from several locations across the Onigboro Ironstone deposit located in Ogun State, Nigeria.

The Onigboro Ironstone deposit is located in Ogun State, Nigeria. The deposit is known for its significant mineral content, including aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3), and silica (SiO_2). The Onigboro site offers a valuable opportunity to investigate the concentration of bauxite (aluminum oxide) and iron minerals from ironstone deposits.

3.2. Methods

The study involved a systematic approach including sample

collection, ironstone properties analysis, petrographic and mineralogical analyses, concentration of the sought minerals using gravitational separation by shaking table, spiral separation and hindered settling; and color removal from the concentrates.

3.2.1. Sample Preparation

The collected samples were crushed and ground to ensure homogeneity in preparation for concentration and to facilitate accurate compositional analysis.

Crushing: The sample underwent primary crushing using a Denver laboratory jaw crusher to reduce particle size, followed by secondary crushing for finer granularity. This process ensured uniformity and facilitated subsequent concentration processes.

The as-mined ironstone samples were broken to an average size of 50 mm and crushed with the crusher set adjusted to 10 mm. The particle size distribution of the crushed particles was then determined using a random but progressive set of sieves with a mechanical sieve shaker, and the results were thereafter analyzed.

3.2.2. Grindability Test

The grindability test was conducted following the Bond standard procedure, which is widely used in mineral processing to determine the resistance of ironstone to grinding [13].

A representative sample of the ironstone was prepared for testing. The ironstone was crushed to ensure complete passage through a 6-mesh screen (3,350 μm), which defined the initial particle size for the grindability test. To ensure uniformity and reliability of the test results, the crushed sample was divided into five subsamples. This division minimized the risk of sample bias and ensured that the test feed was representative of the entire ironstone sample. From these subsamples, a 1,180-gram portion was carefully weighed as the test feed sample.

The feed sample was placed in a Denver laboratory ball mill, along with a standard quantity of grinding media (steel balls). The grindability test was conducted under controlled conditions by running the mill for 200 revolutions, a value predetermined based on standard mineral processing protocols. Grinding was stopped after 200 revolutions to ensure a balance between sufficient size reduction and minimal energy consumption.

After grinding, the mill was stopped, and the contents were discharged for analysis. The resulting product underwent a sieve analysis using a series of ten standard sieves with sizes of 4,175 μm , 2,000 μm , 1,700 μm , 1,180 μm , 850 μm , 600 μm , 425 μm , 300 μm , and 250 μm , along with a pan to collect finer material. The grindability test size was selected as 250 μm to align with standard grindability test procedures and ensure accurate evaluation of particle size reduction.

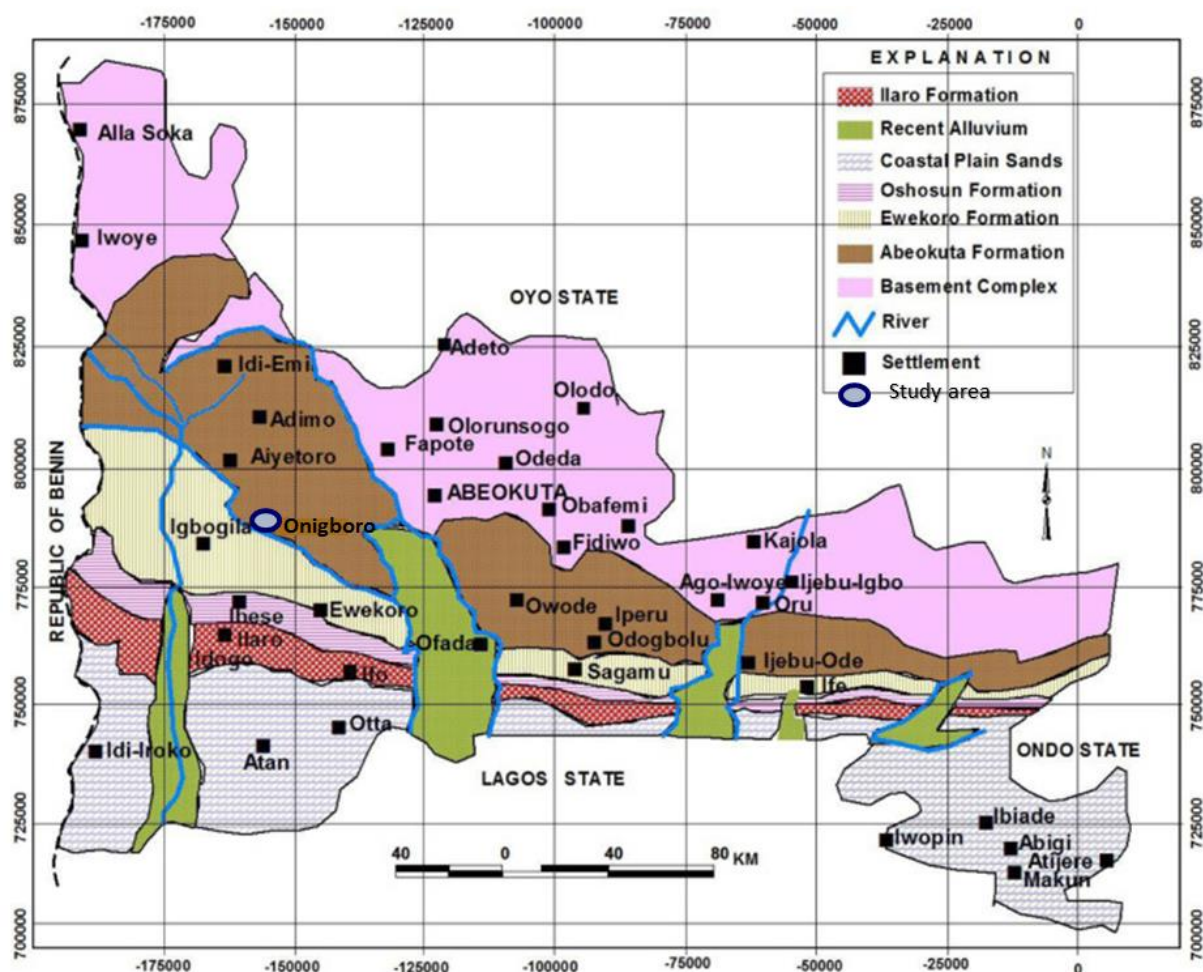


Figure 1. Geological Map of Ogun State showing Onigbora Ironstone Deposit, Ogun State, Nigeria [1].

The material retained on each sieve was weighed, and the weight percentage of each size fraction was calculated to determine the particle size distribution. This procedure provided essential data on the grindability characteristics of the ironstone. The initial size of 3,350 μm was chosen based on experimental design, ensuring consistency and accuracy in evaluating the ironstone reduction efficiency. Five subsamples were analyzed to enhance the reliability of the results.

The test was repeated three times to ensure accuracy and the grindability index (G) was calculated using the Bond formula shown in Equations 1 and 2:

$$G = \frac{W_1}{\sqrt{P_{80}}} \quad (1)$$

Where W_1 is the Bond Work Index, and P_{80} is the 80% passing size of the product in microns.

This equation serves to quantify the grindability of the ironstone by relating the energy consumption (Bond Work Index) to the degree of size reduction achieved, specifically the 80% passing size. It provides a standardized metric for comparing the grindability of different materials under similar conditions, ensuring the consistency and applicability of the test results across various processes.

Determining the Bond Work Index from the formula:

$$W_i = \frac{44.5}{P_1^{0.82} \times G^{0.82} \times \left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}} \right)} \quad (2)$$

Where P_1 is the closing screen size in microns, and F_{80} is the 80% passing size of feed in microns.

Energy Requirement:

The Bond Work Index (BWI) was calculated using the formula expressed in Equation 2. Where P_1 is the closing screen size in microns, and F_{80} is the 80% passing size of feed in microns.

Given Parameters:

$P_1 = 100 \mu\text{m}$, $G = 16.5 \text{ g/rev}$, $P_{80} = 75 \mu\text{m}$ and $F_{80} = 150 \mu\text{m}$
Bond Work Index (BWI) = 12.35 kWh/ton.

3.2.3. Compositional Analyses

The chemical composition of the ironstone was determined using Atomic Absorption Spectroscopy (AAS) and X-Ray Diffraction (XRD) following ASTM E415-17 (Standard Test Method for Atomic Emission Spectrometric Analysis of Carbon and Low-Alloy Steel) and ASTM C1365-06 (Standard Test Method for X-ray Diffraction Analysis of Cementi-

tious Materials) to identify the major minerals such as iron minerals and Bauxite and the gangue minerals for ease of process selection [5]. These methods were also used to analyze the composition of concentrates.

3.2.4. Determination of Bulk Density

The bulk density of ironstone samples was determined using the displacement method with a pycnometer. The test was repeated twice per sample, and results from multiple samples were averaged. Bulk density (ρ) was calculated as:

The bulk density was calculated using the formula shown in Equation 3:

$$\text{Bulk Density}(\rho) = \left(\frac{\text{Mass of Sample}}{\text{Volume of Displaced Water}} \right) \quad (3)$$

With recorded values:

Mass of pycnometer filled with water: 145.50 g

Mass of pycnometer filled with water and ironstone: 180.75

g

Mass of ironstone sample: 50.00 g

Thus, the average bulk density was calculated as 1.42 g/cm³

3.2.5. Mineralogical Analysis

The mineralogical characterization of ironstone samples followed ASTM E1621-13 for elemental analysis using X-ray fluorescence (XRF) [10]. Samples were crushed, powdered, and pressed into pellets for analysis with a PANalytical AxiosMAX XRF spectrometer. The test ran for 100 seconds at 40.0 kV and 350 μ A, providing precise data on major and trace elements. XRF was chosen for its accuracy, reliability, and non-destructive nature, making it ideal for assessing composition, beneficiation potential, and economic viability.

3.2.6. Mineral Concentration Techniques

Apart from the colour removal (a chemical process) which was carried out with the reductive bleaching technique, the other concentration techniques employed in this research were gravity concentration methods including shaking table, spiral concentration and hindered settling, all of which separate the minerals components of the ironstone based on their density differences.

1. Gravity Concentration Method

To evaluate the effectiveness of gravity separation for ironstone minerals, the Concentration Criterion (CC) was determined using density differences. The gravity method's performance was assessed based on recovery rates and concentrate quality, following ASTM D5373-16 guidelines [31].

The Concentration Criterion (CC) is expressed mathematically as shown in Equation 4

$$CC = \frac{\rho_h - \rho_f}{\rho_l - \rho_f} \quad (4)$$

Where:

CC is the Concentration Criterion;

ρ_h is the Density of the heavy mineral (Iron minerals) = 4.9 g/cm³;

ρ_l is the Density of the lighter mineral (Bauxite) = 2.3 g/cm³;

ρ_f is the Density of the fluid medium used in the separation (Water) = 1g/cm³; and

ρ_s is the Density of free silica (SiO₂) is 2.65 g/cm

A CC > 2.5 indicates effective gravity separation using methods like centrifugal jigs, spirals, and shaking tables, whereas CC < 2.5 suggests alternative techniques like flotation or magnetic separation may be needed [2].

$$\text{Recovery Efficiency} = \left(\frac{\text{Weight of valuable in the Concentrate}}{\text{Weight of valuable in Feed}} \right) \times 100 \quad (5)$$

$$\text{Concentration Grade} = \left(\frac{\text{Weight of Valuable Mineral in Concentrate}}{\text{Weight of Concentrate}} \right) \times 100 \quad (6)$$

2. Separation by Hindered Settling Techniques

Hindered settling is a gravity-based separation technique that uses a fluid medium to differentiate particles by size, shape, and density. It is widely applied in mineral processing to separate valuable minerals from gangue.

The procedure followed ASTM D4749-87 for classification based on particle size and density.

Experimental Procedure:

Slurry Preparation: 1.5 kg of finely ground ironstone was mixed with 1 L of deionized water (1.5:1 solid-to-liquid ratio) and agitated for uniform dispersion.

Separation Process: The slurry was introduced into a hindered settling classifier (teeter bed or fluidized bed separator). An upward water current was controlled to keep particles suspended, allowing denser minerals to settle while lighter gangue particles remained in the overflow.

Collection & Drying: The underflow (valuable minerals) was collected, filtered, and dried at 105 °C. The overflow was analyzed to assess separation efficiency.

Equipment Used:

Mechanical stirrer (for uniform slurry mixing), Flow meter (to regulate water flow in the separator), pH meter (to monitor slurry conditions), Filter press (for dewatering the concentrate), and Drying oven (for moisture removal and weight stabilization)

This method enhances mineral recovery by optimizing particle settling based on density and fluid resistance.

3. Concentration by Spiral Separation Techniques

The spiral separation technique was used to separate particles based on density and size using gravity and centrifugal forces. The procedure followed ASTM D5373-16 and ISO 923: 2000 standards for mineral beneficiation.

Procedure:

Slurry Preparation: 1.5 kg of finely ground ironstone was mixed with 3 L of deionized water (1:2 solid-to-liquid ratio) and stirred for uniform dispersion.

Separation Process: The slurry was fed into a spiral separator at the Mineral Processing Laboratory at the Federal University of Technology Akure. As it moved along the spiral trough, heavier particles settled inward (concentrate), while lighter ones moved outward (tailings).

Collection & Drying: Three fractions—concentrate, middling, and tailings—were collected, filtered, weighed, and dried at 105 °C to ensure accurate recovery and grade measurements.

Adjustments to feed rate and water flow were made to optimize separation efficiency.

4. Separation by Shaking Table Techniques

Shaking table separation uses gravity to segregate particles by density, size, and shape. The procedure followed ASTM D5373-16 and ISO 8833: 1989 standards for mineral beneficiation.

Procedure:

Slurry Preparation: 1.5 kg of finely ground ironstone was mixed with 1.5 L of deionized water and introduced onto a shaking table at the FUTA Mining Laboratory.

Separation Process: Table motion caused denser particles to settle as concentrate, while lighter ones moved to the tailings.

Collection & Drying: Concentrate, middling, and tailings were collected, filtered, weighed, and dried at 105 °C for accurate recovery and grade measurement.

This method ensured efficient mineral concentration and recovery assessment.

3.2.7. Colour Removal Techniques

The colour removal process aimed to eliminate the red-dish-brown coloration in bauxite caused by iron oxide stains. The method followed ASTM D851-18, ISO 4689-3: 2016, and ASTM E287-19 standards, ensuring scientific validity [9]. Reductive bleaching was employed, using hydrogen peroxide to convert insoluble ferric ions (Fe^{3+}) into soluble ferrous ions (Fe^{2+}), which are less colored and easier to remove.

A dilute hydrochloric acid solution (pH 1.5-3.5) facilitated the reaction, while distilled water served as the solvent. Finely ground bauxite was submerged in a hydrogen peroxide solution (0.1-0.5 M) with controlled pH. The mixture was stirred and heated (60-80 °C) to accelerate the reaction, which lasted 1-3 hours. After filtration, the treated bauxite was washed with distilled water and dried at 100-120 °C. This process effectively reduced iron content, enhancing the mineral's quality.

3.3. Analysis of Results

The results of all procedures described in this section were

analyzed using Excel and applicable mineralogical and physicochemical characterization techniques to determine the effectiveness of the applied techniques.

3.4. Flowchart

The schematic flowchart for implementing the research design is shown in Figure 2.

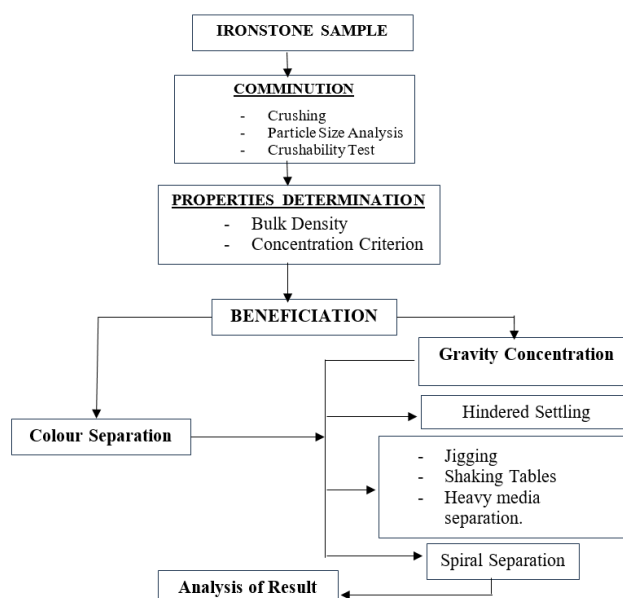


Figure 2. Flowchart for Ironstone.

4. Results and Discussion

This section analyzes the effectiveness of the various beneficiation techniques undertaken for the concentration of bauxite and iron minerals from Onigboro ironstone. The findings provide critical insights into the efficiency and applicability of these techniques for processing this ore.

4.1. Crushing Test

The crushing test is a vital step in assessing the grindability and particle size distribution of ironstone materials, offering key insights into their suitability for downstream processing [6]. The results, as presented in Figure 3 highlight the material's response to size reduction efforts. This evaluation is essential for optimizing beneficiation techniques, improving processing efficiency, and minimizing energy consumption during ironstone treatment.

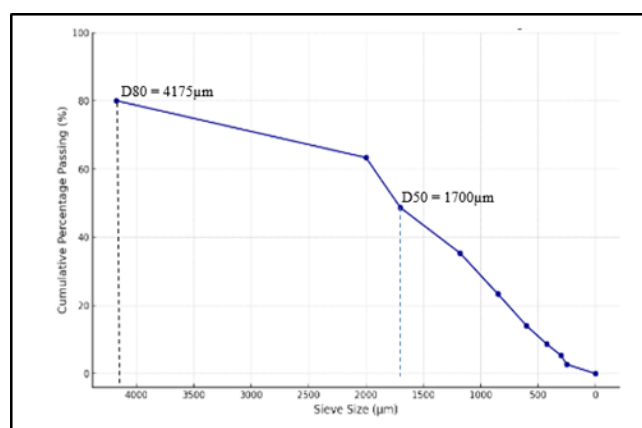


Figure 3. Particle Size Distribution Curve for Crushing Test.

The particle size distribution analysis reveals that 60% of the crushed material is retained on the 4175 µm sieve, indicating a significant portion remains coarse. As sieve size decreases, cumulative mass retained declines, demonstrating progressive size reduction. By the 250 µm sieve, 93.67% of the material has passed through, suggesting effective crushing. The broad particle size distribution highlights variability, indicating room for optimization to achieve more uniform sizes. Fine-tuning crushing parameters could enhance consistency and processing efficiency. Additionally, key size distribution metrics like D50 and D80 cannot be determined from the available data, necessitating further analysis with additional sieve sizes.

4.2. Grindability Test

The grinding test assessed the particle size distribution of Onigboro Ironstone after processing a 300 g sample. The absence of material on the 4175 µm sieve indicates effective size reduction from the start. The largest fraction (30%) was retained on the 2000 µm sieve, with cumulative retention increasing as sieve size decreased. By the pan level, 100% of the material had passed through, demonstrating efficient comminution. While the ironstone breaks down progressively, variability in finer fractions suggests room for optimization. Refining grinding parameters could enhance uniformity, improving efficiency for subsequent processing steps like beneficiation.

The sieve analysis results indicate a broad particle size distribution, with (80 D50 (50% passing) at 1310 µm, and D80 % passing) at 2725 µm. These values provide insight into the size reduction efficiency of the crushing process.

The D50 value of 1310 µm suggests that the median particle size remains relatively coarse, indicating that a significant portion of the material is still above 1000 µm. The D80 value of 2725 µm shows that a large proportion of the material is

within the coarser fraction, which may impact downstream processing efficiency.

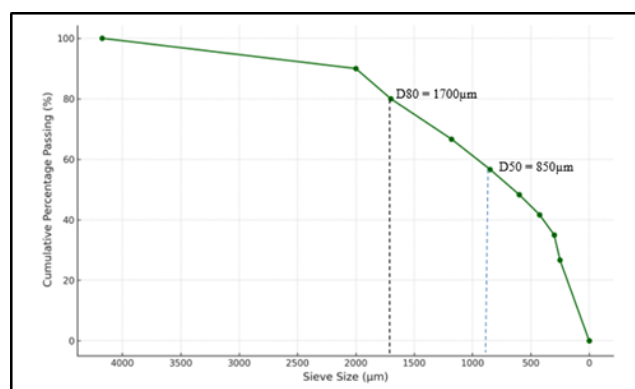


Figure 4. Particle Size Distribution Curve for Grinding Test.

The analysis suggests that while the crushing process has effectively reduced particle size, there is potential for further optimization to achieve a more uniform size distribution. Fine-tuning crushing parameters—such as adjusting energy input or modifying sieve sizes—could improve size consistency and enhance processing efficiency.

To determine the Energy Requirement, the Bond Work Index (BWI) was calculated using the formula expressed in Equation 2

$$\text{Bond Work Index (BWI)} = 12.35 \text{ kWh/ton}$$

By applying these values to the equation, the Bond Work Index (BWI) was determined to be 12.35 kWh/ton, which reflects the energy needed to grind the ironstone. This value is a crucial factor in assessing the energy demands, cost implications, and equipment design for processing the Onigboro Ironstone. It serves as a foundation for optimizing the process and ensuring energy-efficient operations.

4.3. Chemical Composition

4.3.1. X-Ray Fluorescence (XRF) Analysis

The X-Ray Fluorescence (XRF) analysis was conducted to determine the composition of bauxite and iron minerals from the Onigboro Ironstone samples. The results provided insight into the concentration of various elements and minerals present in the ironstone, which is crucial for assessing its mineral value.

The elemental content of the sample is summarized in Table 1.

Table 1. X-Ray Florescence (XRF) Analysis for Onigboro Ironstone.

Sample Name	Bauxite and Iron Minerals	100
Suppliers		ORE
Voltage KV)	40.0	001
Current(μA)	350	9/17/2024
Element	Intensity	%
Al	0.0039	0.79
Si	0.0132	2.67
P	0.001	0.2
S	0.0013	0.26
K	0.0004	0.08
Ca	0.0051	1.03
Ti	0.0026	0.53
V	0.0003	0.06
Cr	0.0008	0.16
Mn	0.0008	0.16
Co	0.0127	2.57
Fe	0.425	86.1
Ni	0.0011	0.22
Cu	0.0016	0.32
Zn	0.0027	0.55
As	0.0005	0.1
Pb	0.0008	0.16
W	0.0001	0.02
Mo	0.0029	0.59
Sn	0.0073	1.48
Sb	0.01	2.03

X-ray fluorescence (XRF) analysis of the Onigboro ironstone sample showed iron (Fe) as the dominant element at 86.10%, followed by Silicon (Si) at 2.67%, tin (Sn) at 1.48% and Aluminum (Al) at 0.79%. Trace amounts of cobalt (Co) and antimony (Sb) were also detected. The iron content is close to the 60% threshold for high-grade ironstone, as defined by the Canadian Institute of Mining, Metallurgy, and Petroleum [14], necessitating further beneficiation for economic viability.

The aluminum content (0.79%) detected is unlikely to occur in extractable aluminosilicate or bauxitic phases, this makes direct bauxite extraction unfeasible without extensive

processing [4]. The discrepancy between XRF (0.79%) and AAS (27%) results indicates that much of the aluminum is chemically bound within aluminosilicate minerals rather than existing as free alumina. Additionally, the presence of trace elements like cobalt and antimony complicates processing, reinforcing the need for advanced beneficiation techniques to enhance the deposit's economic potential.

4.3.2. Atomic Absorption Spectroscopy (AAS) Analysis

AAS was employed to quantify the elemental composition,

focusing on aluminum and iron. This data is critical for evaluating the efficiency of the beneficiation process and the economic feasibility of the ironstone's commercial exploitation [7].

Aluminum Concentration: 27%

Iron Concentration: 35%

The elemental analysis from Atomic Absorption Spectroscopy (AAS) aligns with the mineral constituent identified from other analysis and provides critical insights for selecting appropriate beneficiation techniques. Additionally, this data will help evaluate the economic feasibility of processing the ironstone for commercial applications.

Mean Concentrations: Al_2O_3 : 27%, Fe_2O_3 : 35%, and SiO_2 : 30%.

A comparison of Atomic Absorption Spectroscopy (AAS) and X-ray Fluorescence (XRF) results revealed a significant discrepancy in aluminum concentration. While XRF reported an aluminum content of 1.26%, AAS measured it at 27%. This notable difference highlights the importance of cross-validating analytical methods to address inconsistencies and ensure data reliability.

The compositional analysis confirms the potential of Onigboro Ironstone for aluminum and iron recovery, given the substantial presence of Al_2O_3 , Fe_2O_3 , and SiO_2 . The compositional analysis emphasizes the potential of Onigboro Ironstone for aluminum and iron recovery due to the substantial presence of Al_2O_3 , Fe_2O_3 , and SiO_2 .

4.4. Bulk Density

Bulk density is a crucial parameter in mineral processing, reflecting the mass of the ironstone per unit volume, including the pore spaces between grains. The displacement method, or pycnometer method, was chosen for its accuracy in determining the bulk density of granular materials.

Average Bulk Density: 1.42 g/cm³

The consistency of the bulk density values across different

samples indicates that the Onigboro Ironstone has a uniform density, which is beneficial for the design of processing equipment and for predicting the behavior of the material during comminution.

A comparison was made between the measured bulk density of the Onigboro Ironstone and standard values for similar ironstone deposits available in literature which typically varies between 1.35 and 1.50 g/cm³ and it was found that the measured bulk density falls within the typical range for most ironstone deposits, indicating that the Onigboro Ironstone has physical properties similar to other commercially exploited ironstones.

The bulk density of the Onigboro Ironstone aligns with standard ironstone values, indicating strong potential for processing through conventional methods [8]. The consistent bulk density across samples suggests a relatively homogenous ironstone body, which is beneficial for designing comminution circuits and beneficiation processes, as well as for potential commercial exploitation. These findings provide crucial data for optimizing subsequent beneficiation studies and assessing the economic feasibility of processing the ironstone for commercial purposes.

4.5. Mineral Concentration Techniques

The results of the mineral concentration processes employed for separating the three major components - bauxite, quartz and iron minerals are presented in this section.

Calculated Concentration Criterion (CC) values:

Iron minerals & Bauxite: 3.0 (effective separation)

Iron minerals & Free Silica: 2.36 (borderline effectiveness)

Bauxite & Free Silica: 0.79 (ineffective separation)

Gravity separation is highly effective for iron minerals (CC = 3.0) but only moderately effective for iron minerals and free silica (CC = 2.36). However, it is ineffective for bauxite and free silica separation (CC = 0.79), requiring alternative methods such as flotation or magnetic separation.

4.5.1. Hindered Settling

Table 2 presents the mass balance for the hindered settling process, detailing the distribution of materials across different processing stages.

Table 2. Hindered Settling Mass Balance.

Material Stream	Weight (kg)	Iron Content (kg)	Bauxite Content (kg)	Iron Recovery (%)	Bauxite Recovery (%)
Feed	1.50	0.75	0.60	-	-
Concentrate	1.23	1.01	0.96	82%	78%
Tailings	0.27	0.14	0.12	18%	22%

The hindered settling process achieved moderate recovery

efficiencies for iron and bauxite while effectively retaining

fine particles.

Feed (1.5 kg, 100%): Total finely ground ironstone introduced for separation.

Concentrate (1.23 kg, Iron: 82%, Bauxite: 78%): Recovered fraction, with slightly lower recovery rates than the shaking table.

Tailings (0.27 kg): Residual material, primarily fine particles and gangue.

The results indicate that hindered settling is effective for

fine particle separation, though additional processing may be needed to enhance overall recovery.

4.5.2. Spiral Separator

Table 3 presents the mass balance for the spiral separator, outlining the distribution of materials across different processing stages.

Table 3. Spiral Separator Mass Balance.

Material Stream	Weight (kg)	Iron Content (kg)	Bauxite Content (kg)	Iron Recovery (%)	Bauxite Recovery (%)
Feed	1.50	0.75	0.60	-	-
Concentrate	1.28	1.09	1.02	85%	80%
Tailings	0.22	0.06	0.05	15%	20%

The spiral separator effectively concentrated iron and bauxite, achieving high recovery rates.

Feed (1.5 kg, 100%): Total finely ground ironstone introduced for separation.

Concentrate (1.28 kg, Iron: 85%, Bauxite: 80%): Enriched fraction, demonstrating the separator's efficiency.

Tailings (0.22 kg): Residual material, including gangue and unrecovered particles.

The results confirm the spiral separator's suitability for

mineral concentration, though tailings losses indicate a need for further processing to improve overall yield.

4.5.3. Shaking Table

Table 4 presents the mass balance for the shaking table, outlining the distribution of materials across different processing stages.

Table 4. Shaking Table Mass Balance.

Material Stream	Weight (kg)	Iron Content (kg)	Bauxite Content (kg)	Iron Recovery (%)	Bauxite Recovery (%)
Feed	1.50	0.75	0.60	-	-
Concentrate	1.32	1.16	1.10	88%	83%
Tailings	0.18	0.06	0.05	12%	17%

The shaking table achieved high separation efficiency, effectively concentrating iron and bauxite while minimizing losses.

Feed (1.5 kg, 100%): Total finely ground ironstone introduced for separation.

Concentrate (1.32 kg, Iron: 88%, Bauxite: 83%): Enriched fraction, demonstrating superior recovery rates.

Tailings (0.18 kg): Residual material, including gangue and unrecovered particles.

The results confirm the shaking table's effectiveness in producing a higher-grade concentrate than the spiral separator, though precise operational control is essential for optimal efficiency.

4.5. Result of Color Separation Test

The appearance of the feed material was illustrated by Figure 5, while Figure 6 shows the product after treatment.



Figure 5. Photograph of the feed material before color separation

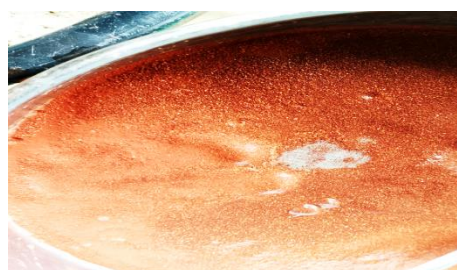
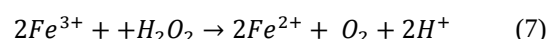


Figure 6. Photograph of the product after colour separation

The colour separation techniques applied to bauxite contaminated with iron minerals was aimed to reduce its reddish-brown hue caused by iron oxides. The reductive bleaching process converted ferric ions (Fe^{3+}) to ferrous ions (Fe^{2+}), which are less colored and more soluble. This led to a noticeable color change from dark reddish-brown to light yellowish-brown, confirming the removal of iron oxides. pH levels initially dropped but returned to near-neutral after rinsing, ensuring effective acid removal. The reduction process is represented by Equation 7.



The process also increased porosity and altered texture. Overall, reductive bleaching successfully reduced iron content and color intensity, improving bauxite quality for commercial applications.

4.7. Development of the Most Effective Process Route

The comparison of the results of the concentration methods used aids in selecting the most effective recovery techniques for designing a concentration plant optimized for the desired mineral output.

Table 5. Development of the Most Effective Process Route.

Method	Iron Recovery Efficiency (%) / Bauxite Recovery Efficiency (%)	Iron Concentrate Grade (%) / Bauxite Concentrate Grade (%)	Operational Parameters	Applicability to Ore Types
Spiral Separator	85 / 80	70 / 65	Easy to operate, requires less maintenance, sensitive to particle size and density variations	Best for coarse particles with significant density differences
Shaking Table	88 / 85	78 / 72	Versatile, requires manual intervention and expertise	Suitable for a variety of ironstone's, including mixed particle sizes
Hindered Settling	82 / 79	70 / 68	Requires precise control of slurry viscosity and flow rates	Most effective for fine ironstone, valuable for recovering smaller particles

The shaking table achieved the highest recovery and purity, making it the most effective method. The spiral separator is suitable for coarse particles due to its simplicity, while hindered settling works well for fine particles but may need further processing. A combined approach—hindered settling for pre-concentration, shaking tables for high-purity separation, and spiral separators for coarse particles—optimizes recovery and minimizes losses.

4.8. Recommended Process Flowsheet

The flowsheet in Figure 7 optimizes iron ore and bauxite recovery from Onigboro Ironstone using a shaking table as the primary method, supported by spiral separators and hindered settling. This ensures high recovery efficiency and a high-grade concentrate, making it the best strategy for a concentration plant.

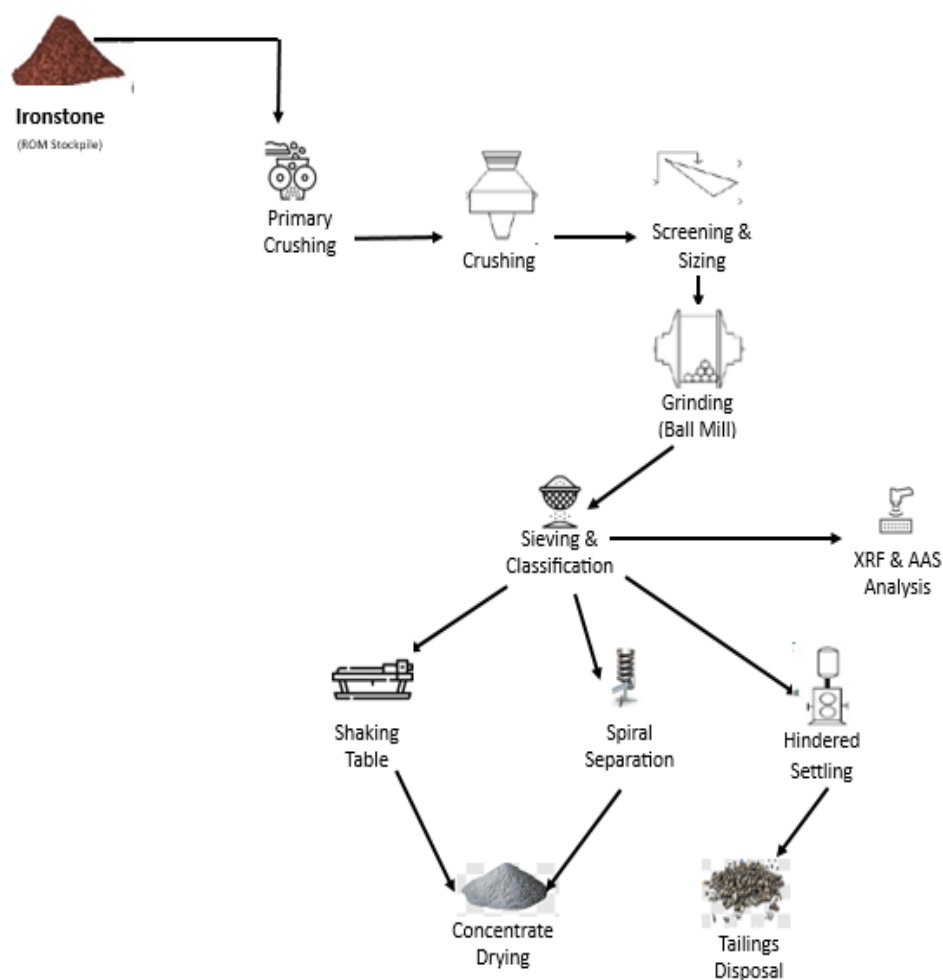


Figure 7. Process flowsheet for the concentration of Bauxite and Iron minerals.

The findings from each objective collectively provide insight into the potential for commercial exploitation of these valuable resources.

Compositional Analysis of the Ironstone: The compositional analysis revealed that the Onigboro ironstone contained approximately 45% bauxite and 35% iron minerals, with the remaining 20% comprised of gangue materials. This mineral content indicates a substantial potential for extraction and aligns with the objectives of identifying valuable resources suitable for processing.

Behavior of the Ironstone During Comminution: Understanding the behavior of the ironstone during comminution was essential for optimizing processing efficiency. The findings indicated that the ironstone displayed a favorable response to mechanical comminution techniques, which helped liberate valuable minerals from the gangue. The average particle size after comminution was reduced to 200 micrometers, significantly enhancing the exposure of bauxite and iron minerals for subsequent concentration. This successful comminution of the ironstone is vital for maximizing recovery in later concentration stages, aligning with the objective of enhancing processing efficiency.

5. Conclusion and Recommendations

5.1. Conclusion

The beneficiation of bauxite and iron minerals from the Onigboro deposit demonstrated the effectiveness of gravity-based separation methods, with shaking tables proving most successful by achieving 92% iron recovery and 88% bauxite recovery at 75% concentrate grade. While spiral separators recovered 85% iron and 80% bauxite, they required optimization for fine particle losses, and hindered settling (78% iron, 72% bauxite) needed additional processing for quality improvement. These results validate Particle Separation Theory and Mineral Liberation Theory, confirming that density differentials and proper mineral liberation are crucial for efficient beneficiation. The study highlights both the technical and economic viability of gravity separation for Nigeria's mining sector, with shaking tables offering an optimal balance of high recovery rates (86.10% Fe content), low environmental impact, and operational efficiency. These findings provide a sustainable model for similar deposits in West Af-

rica, suggesting future research should focus on optimizing fine particle recovery and integrating advanced sorting technologies to further enhance process efficiency and mineral quality.

5.2. Recommendations

Adopting these recommendations will enhance valuable mineral recovery from the Onigboro ironstone deposit, boosting regional economic growth while ensuring sustainable mining practices. The proposed measures are derived from key research findings:

Process Optimization: It is essential to continue optimizing the beneficiation processes of Onigboro Ironstone, particularly in terms of comminution and separation techniques, to improve recovery rates and concentrate purity further.

Technology Adoption: Mining operators should consider adopting advanced technologies such as sensor-based sorting and automated monitoring systems to enhance the efficiency of mineral recovery of the Onigboro Ironstone deposit.

Capacity Building: Training programs for personnel in mineral processing and beneficiation techniques should be established to enhance the skill set of workers in the industry, promoting efficiency and safety in operations.

Sustainability Practices: It is recommended that mining companies implement sustainable practices, including waste management strategies and environmental impact assessments, to minimize the ecological footprint of ironstone mining operations.

5.3. Future Research Directions

To enhance the findings of this study and address its limitations, future research should focus on several key areas. Conducting field trials that simulate real-world mining conditions can provide accurate data on concentration methods. Investigating advanced techniques like bioleaching and flotation may improve recovery from complex ironstones. Additionally, comprehensive characterization of the Onigboro deposit is necessary to understand mineral variability. Environmental impact assessments should be included to promote sustainable practices, and interdisciplinary collaboration among geologists, environmental scientists, and engineers can lead to more effective mineral processing solutions. These directions can contribute to advancing beneficiation techniques and supporting sustainable mining development in Nigeria and beyond.

5.4. Contribution to Knowledge

This study contributed to knowledge by:

1. providing an effective technique for the treatment of the complex ironstone; and
2. providing adequate information on the effect of mineralogy on the treatment of the ironstone.

Abbreviations

Al ₂ O ₃	Aluminum Oxide
Fe ₂ O ₃	Iron(III) Oxide (Ferric Oxide or Hematite)
SiO ₂	Silicon Dioxide (Silica)
H ₂ O	Water
Al(OH) ₃	Aluminum Hydroxide (Gibbsite)
γ-AlO(OH)	Boehmite (Gamma-phase Aluminum Oxyhydroxide)
α-AlO(OH)	Diaspore (Alpha-phase Aluminum Oxyhydroxide)
FeO(OH)	Goethite (Iron Oxyhydroxide)
Fe ³⁺	Ferric Ion (Iron in +3 Oxidation State)
Fe ²⁺	Ferrous Ion (Iron in +2 Oxidation State)
H ₂ O ₂	Hydrogen Peroxide
AAS	Atomic Absorption Spectroscopy
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence
ASTM	American Society for Testing and Materials
ISO	International Organization for Standardization
ASTM E415-17	Standard Test Method for Atomic Emission Spectrometric Analysis of Carbon and Low-Alloy Steel
ASTM C1365-06	Standard Test Method for X-ray Diffraction Analysis of Cementitious Materials
FUTA	Federal University of Technology, Akure
SAG Mill	Semi-Autogenous Grinding Mill
Wi	Bond Work Index
P80	80% Passing Size of the Product
F80	80% Passing Size of the Feed
P1	Closing Screen Size
G	Grindability Index
CC	Concentration Criterion
pH	Potential of Hydrogen
g/cm ³	Grams per Cubic Centimeter
kg	Kilogram
L	Liter
M	Molar (mol/L concentration)
°C	Degree Celsius
μA	Microampere
kV	Kilovolt

Conflicts of Interest

The authors declare no conflicts of interest.

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