International Journal of Engineering Research and Development
e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 22, Issue 1 (January 2026), PP 78-82

Particle Size Effects on Magnetic Separation Efficiency of Ilmenite Ore from Makarfi, Nigeria

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ABSTRACT
Ilmenite ($FeTiO_3$) is a titanium–iron oxide mineral and a major source of titanium, widely used in the production of titanium dioxide (TiO_2) for paints, plastics, paper, and ceramics, as well as titanium metal for aerospace, marine, and medical applications. This study investigates the application of high-intensity magnetic separation (HIMS) for the recovery of ilmenite from Makarfi, Kaduna State, Nigeria. Ore samples were collected, dried, and homogenized using coning and quartering. Mineralogical analysis via X-ray diffraction (XRD) identified four main mineral phases: goethite (44%), ilmenite (38%), quartz (10%), and cuprite (8.1%). Chemical composition determined by X-ray fluorescence (XRF) showed Ti and Fe contents of 33.13% and 33.28%, respectively, with significant silicate gangue. Particle size distribution using 63 µm, 150 µm, and 212 µm fractions indicated that finer particles contained higher TiO_2 (33.90%) and Fe_2O_3 (28.90%) contents. Magnetic separation results showed improved enrichment in coarser fractions, with the 212 µm fraction achieving the highest recovery of ilmenite. The study demonstrates that particle size significantly affects magnetic separation efficiency and that high-intensity magnetic separation is effective for concentrating ilmenite from Makarfi ore. The findings highlight the potential for local beneficiation of titanium-bearing minerals in Nigeria, supporting sustainable resource utilization and value addition.

Date of Submission: 12-01-2026 Date of acceptance: 28-01-2026

I. INTRODUCTION

Ilmenite ($FeTiO_3$) is a titanium–iron oxide mineral and one of the most important sources of titanium in nature. It occurs as a dense, opaque mineral with a black or steel-gray metallic luster and possesses physical properties such as high specific gravity (4.7–4.8), weak magnetic susceptibility, and moderate hardness, making it suitable for beneficiation processes including gravity and magnetic separation (Wills & Finch, 2016). Titanium dioxide (TiO_2), derived from ilmenite, is a widely used white pigment in paints, plastics, paper, ceramics, and cosmetics, while titanium metal is valued for its high strength-to-weight ratio and corrosion resistance, with applications in aerospace, marine, and medical industries (Liu et al., 2011).

In Nigeria, exploration of titanium-bearing minerals, particularly ilmenite, has gained attention due to their economic and strategic potential. Ilmenite occurrences are reported across central and northern regions of the country. Kaduna State, in northwestern Nigeria, is geologically characterized by a mix of basement complex rocks and younger granites known to host mineralized zones. Preliminary surveys and artisanal observations indicate ilmenite-rich sands and rocks in Makarfi Local Government Area, highlighting the area as a prospective site for mineral recovery and beneficiation (Oyinloye & Jegede, 2014).

Efficient recovery of ilmenite depends on beneficiation techniques such as gravity separation, froth flotation, and magnetic separation, which enhance ore quality by exploiting differences in density and magnetic susceptibility. Due to ilmenite's weak magnetic nature, high-intensity magnetic separation (HIMS) is particularly effective, and high-gradient magnetic separation (HGMS), an advanced HIMS method, has been shown to recover fine ilmenite particles efficiently (Tripathy et al., 2013; Chen et al., 2012). Applying these techniques not only improves mineral yield but also reduces environmental waste.

Mineral beneficiation contributes significantly to economic development by adding value to raw ores, promoting local industries, and creating employment opportunities. In Nigeria, the underutilization of ilmenite limits industrial growth and foreign exchange earnings. Despite Makarfi's known ilmenite deposits, systematic beneficiation remains limited, resulting in resource loss and missed economic opportunities. Furthermore, there is scant research on the application of modern recovery techniques, such as magnetic separation, to these deposits.

This study aims to investigate the application of magnetic separation for the recovery of ilmenite from Makarfi, Kaduna State. The specific objectives are: (i) to carry out mineralogical and chemical analyses of Makarfi ilmenite ore, (ii) to test magnetic separation techniques for ore recovery, and (iii) to analyze the resultant products. The study focuses on laboratory-scale beneficiation, including ore sampling, mineralogical and magnetic characterization, and separation using magnetic equipment. It does not extend to downstream titanium extraction or alloy production.

The significance of this research lies in contributing to the knowledge base on ilmenite beneficiation in Nigeria, providing empirical data for future geological and metallurgical studies, and supporting local beneficiation initiatives. Successful application of magnetic separation for Makarfi ilmenite could encourage investment in small- to medium-scale mineral processing, improve domestic resource utilization, and guide policymakers and mining operators toward environmentally sustainable and economically viable beneficiation practices (Wills & Finch, 2016; Liu et al., 2011; Oyinloye & Jegede, 2014; Tripathy et al., 2013; Chen et al., 2012).

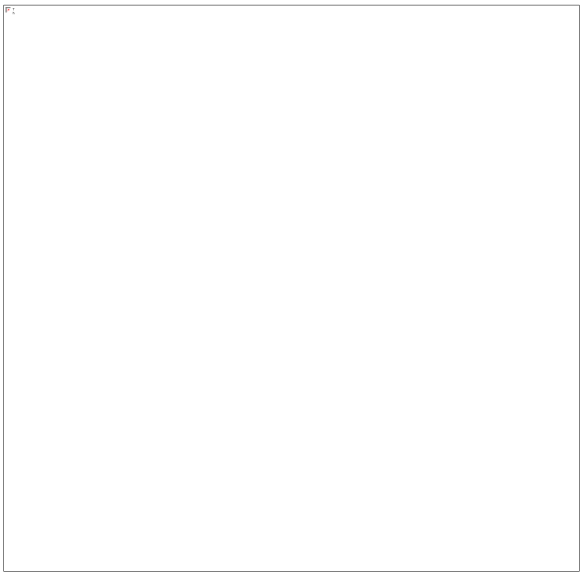

Figure 1: Map of Kaduna Indicating the Study Area

II. MATERIALS AND METHODS

The Makarfi ilmenite ore samples were initially dried in the Mineral Processing Laboratory of Kaduna Polytechnic to remove moisture that could interfere with the magnetic properties of the ore. The dried samples were then thoroughly homogenized using the coning and quartering method to ensure representativeness.

Mineralogical characterization of the head sample was carried out using X-ray Diffraction (XRD). Finely powdered samples were irradiated with a focused X-ray beam to identify the mineral phases present. The XRD results confirmed ilmenite as the dominant mineral, with minor phases including goethite, quartz, hematite, and cuprite, indicating favorable beneficiation potential.

Chemical composition analysis was performed using X-ray Fluorescence (XRF) to determine the elemental constituents of the ore before and after magnetic separation, thereby evaluating the enrichment efficiency. Particle size distribution was determined through sieve analysis using standard mesh sizes of 63 µm, 150 µm, and 212 µm. Each size fraction obtained was used as feed for the magnetic separation process.

High-intensity magnetic separation was conducted by feeding the prepared samples into the magnetic separator, where magnetic minerals were separated from non-magnetic materials. The magnetic (concentrate) and non-magnetic (tailings) fractions were collected separately, weighed, and labeled for further analysis. This procedure was repeated for all particle size fractions to optimize separation efficiency.

Data collection focused on recovery performance by recording the weights of the feed, magnetic fraction, and non-magnetic fraction for each particle size range. These data were used to calculate ilmenite recovery efficiency and assess the overall effectiveness of the magnetic separation process.

III. RESULTS AND ANALYSIS

The X-ray diffraction (XRD) pattern of the Makarfi ilmenite ore (Figure 2) revealed four major mineral phases: goethite ($FeOOH$), ilmenite ($FeTiO_3$), quartz (SiO_2), and cuprite (Cu_2O), with relative abundances of 44%, 38%, 10%, and 8.1%, respectively. The dominance of goethite indicates extensive weathering and a high content of iron oxyhydroxides, which may adversely affect magnetic separation by competing with ilmenite. The significant proportion of ilmenite confirms the economic potential of the deposit as a titanium-bearing resource. Quartz represents non-magnetic silicate gangue that is readily removable during magnetic separation, while cuprite occurs in minor quantities and may influence concentrate purity if not adequately separated.

Figure 2: Mineralogical Analysis of Makarfi Ilmenite Ore

X-ray fluorescence (XRF) analysis of the head sample presented Table 1 shows that the ore is enriched in iron (33.28 wt%) and titanium (33.13 wt%), consistent with the presence of ilmenite as the principal mineral phase. The relatively high silicon content (22.30 wt%) reflects substantial silicate gangue, in agreement with the mineralogical findings. Minor elements such as vanadium, manganese, cobalt, and copper occur in trace amounts and are unlikely to significantly influence beneficiation performance. The low sulfur and phosphorus contents indicate minimal metallurgical penalties, highlighting favorable conditions for titanium dioxide enrichment.

Table 1: Head Sample Makarfi Ilmenite Ore Concentration Wt. (%) (XRF Analysis)

Element	Wt %
Si	22.304
V	0.634
Cr	0.000
MnO	0.638
Fe	33.284
Co	0.142
Ni	0.000
Cu	0.045
Nb	0.020
W	0.021
P	0.259
S	0.588
Ca	1.030
Mg	0.000
K	0.486
Ba	0.072
Al	6.164
Ta	0.021
Ti	33.137
Zn	0.012
Ag	0.010
Cl	0.372
Zr	0.089
Sn	0.000
Pb	0.068
Rb	0.010
Cs	0.585
Sr	0.007

The distribution of TiO_2 and Fe_2O_3 across particle size fractions prior to magnetic separation shows a strong dependence on particle size as shown in Table 2. The finest fraction (63 µm) recorded the highest TiO_2 content (33.90 wt%), indicating preferential concentration of ilmenite in finer particles. In contrast, the 150 µm and 212 µm fractions exhibited lower TiO_2 contents, reflecting increased association with gangue minerals. These results demonstrate that mineral liberation and elemental distribution are strongly controlled by particle size, which directly influences separation efficiency.

Table 2:XRF Results by Particle Size

Particle Size (µm)	Si (wt%)	Fe_2O_3 (wt%)	TiO_2 (wt%)
63	24.69	28.90	33.90
150	35.61	24.63	26.93
212	35.25	25.56	28.37

Magnetic separation results presented in Table demonstrate that recovery improves with increasing particle size. The 63 µm fraction produced the lowest magnetic yield (17 g), likely due to incomplete liberation and particle agglomeration effects. Higher magnetic recoveries were obtained for the 150 µm (27 g) and 212 µm (30 g) fractions, indicating improved liberation of ilmenite from gangue minerals at coarser sizes. This trend highlights the importance of particle size optimization in enhancing separation performance.

Table 3: Magnetic Separation Recovery

S/N	Particle Size (µm)	Feed Weight (g)	Magnetic Fraction (g)	Non-Magnetic Fraction (g)
1	63	80	17	63
2	150	80	27	53
3	212	80	30	49

Post-separation XRF analysis further confirms the influence of particle size on enrichment behavior as presented in Table 4. Titanium enrichment in the magnetic concentrate was marginal for the 63 µm fraction, whereas the 150 µm and 212 µm fractions showed improved titanium concentration and more effective separation from iron-rich gangue. These results indicate that high-intensity magnetic separation is most effective within the 150–212 µm particle size range, where optimal liberation and selective recovery of ilmenite are achieved. Overall, the findings demonstrate that the beneficiation efficiency of the Makarfi ilmenite ore is governed by its mineralogical composition and particle size, providing a basis for process optimization in titanium mineral recovery.

Table 4:Magnetic Separation Analysis of Makarfi Ilmenite Ore (XRF Results)

Element	Head Sample (%)	63 µm Concentrate	63 µm Tailings	150 µm Concentrate	150 µm Tailings	212 µm Concentrate	212 µm Tailings
Fe	33.28	28.90	40.33	24.63	44.22	25.56	40.33
Ti	33.13	33.89	31.72	26.93	35.69	28.37	35.34

The overall recovery efficiency of the magnetic separation process was calculated using the ratio of magnetic fraction weight to feed weight. The 63 µm fraction showed a recovery of 21.3%, while the 150 µm and 212 µm fractions achieved higher recoveries of 33.8% and 37.5%, respectively. These results confirm that coarser particles provide better liberation and higher ilmenite recovery. Combined with the enrichment data, the findings indicate that high-intensity magnetic separation is most efficient for the 150–212 µm particle size range, yielding both higher TiO_2 concentration and improved recovery while minimizing gangue contamination.

IV. CONCLUSION AND RECOMMENDATION

The study demonstrates that Makarfi ilmenite ore is rich in titanium and iron, with ilmenite as the dominant mineral, confirming its economic potential for titanium dioxide production. High-intensity magnetic separation proved effective in enriching Ti and Fe, with coarser particle size fractions (150–212 µm) exhibiting higher recovery than the finer fraction (63 µm). These results highlight the significant influence of particle size on separation efficiency, emphasizing the need for careful control of particle size during beneficiation.

It is recommended that multi-stage magnetic separation be implemented to further enhance recovery, and that local processing facilities be established to add value to the ore. The findings provide a solid foundation for future research aimed at optimizing beneficiation techniques and supporting sustainable exploitation of ilmenite resources in Nigeria.

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