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Geochemical and Mineralogical Characterization of Tajimi (Kogi State) Iron Ore and Determination of its Flotability Nature

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ABSTRACT

Iron ore is vital for steel production and manufacturing. The study area shows promise as an iron ore resource but lacks detailed characterization. Hence, there is a need to investigate its properties for sustainable exploitation using froth flotation. A comprehensive analysis of the ore was conducted using techniques such as X-ray Fluorescence (XRF), X-ray Diffraction (XRD), Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM/EDS), and petrographic analysis, followed by beneficiation via froth flotation to enhance the iron concentration. The chemical composition of the crude ore was determined to be 62.166% Fe_2O_3 and 18.568% SiO_2, with other trace elements identified. Mineralogical analysis revealed goethite and cristobalite as the dominant minerals, with significant interlocking in the ore matrix, facilitating comminution. The effective beneficiation process yielded a froth concentrate with 68.260% Fe_2O_3 and a depressed product with 68.006% Fe_2O_3. The recovery rate of iron oxide was 32.941%, with an enrichment ratio of 1.098 and a concentration ratio of 3.333, indicating a successful beneficiation process. The key implication of these findings is that the Tajimi iron ore is a potential constituent for steel reinforcement, offering a high-quality iron source that can enhance the strength and durability of steel products.

INTRODUCTION

The utilization of iron ore in various industrial applications is paramount to promoting economic growth and infrastructure development globally. Iron ore is an essential resource that plays a significant role in various industries, with its primary use in the production of steel. Steel is used in construction, manufacturing, transportation, and many other sectors, making iron ore a critical ingredient for economic development and infrastructure projects worldwide. Several variables influence the global iron ore market, including rising demand from growing nations, production levels, and geopolitical developments. Iron ores can be found in a range of geological contexts, including igneous, metamorphic (transformed), and sedimentary rocks. The Banded Iron Formation (BIF) of Nigeria is typically found in metamorphosed folding bands associated with Precambrian basement complex rocks such as low-grade metasediments, high-grade schist, gneisses and migmatites (Thomas *et al.*, 2019). These include the distinguished Lokoja Okene District (LOK) existences remarkably at Itakpe, Ajabanoko, Kakun, Ochokochoko, Toto Muro and Tajimi, among others. Nigeria as a country possesses approximately three (3) billion tonnes of iron ore deposits in projected reserves, and despite these abundant deposits, the country has little data on the characteristics of these deposits (Thomas *et al.*, 2019). Hence, their exploitation for iron and steel makings is impaired, and much foreign exchange is expended on the importation of iron and steel materials that can be locally sourced and produced in the nation's iron and steel plants (Thomas *et al.*, 2019). As the demand for steel and infrastructure projects continues to rise, exploring untapped regions for iron ore mining becomes essential (Yaro and Thomas, 2009). Understanding the geochemical and mineralogical composition of iron ore deposits is crucial for efficient utilization in various industrial processes (Alabi *et al.*, 2019). This study aimed to conduct a comprehensive geochemical and mineralogical characterization of the Tajimi iron ore deposit in Kogi State, Nigeria. The goal was to determine the flotability nature using the froth flotation method and evaluate the deposit's suitability for industrial purposes. Iron ore characterization involves the systematic analysis of its chemical composition, mineralogy, and physical properties. Such characterization provides valuable insights into the quality, quantity, and processing requirements of the ore (Holman and Ramsay, 2017). By employing advanced analytical techniques, including X-ray fluorescence (XRF), X-ray diffraction (XRD), scanning electron microscopy with energy dispersive X-ray analysis (SEM/EDX), petrological analysis, and sieve analysis, this study seeks to elucidate the elemental composition, mineral phases, and textural features of the Tajimi iron ore (Alabi *et al*., 2019).

Froth flotation involves a physicochemical process capitalizing on the differences in surface characteristics of minerals; hydrophobicity and hydrophilicity – with the use of some chemical reagents to effect separation (Akande *et al*., 2020). Undoubtedly, froth flotation stands as the paramount and adaptable method in mineral processing, particularly for enhancing the quality of iron ore. However, iron ore mining can have environmental impacts, such as deforestation, habitat destruction, air and water pollution, and the generation of large-scale waste. To address these concerns, mining companies are implementing sustainable practices and adopting technologies to minimize their environmental footprint (Wills, 2006).

The Tajimi iron deposit, occurring within the Basement Complex region of Kogi State in North-Central Nigeria represents one such resource with substantial potential and holds significant promise as a valuable resource for iron extraction. The Tajimi iron deposit is notably underlain by metasedimentary and metavolcanic rocks from the Igarra, Kabba, and Jakura areas. The primary lithologic units include regionally emplaced gneisses of migmatite, biotite, and granite, as well as ferruginous quartzites, granites, and pegmatite. The source of iron ore mineralization in the region is ferruginous quartzite (Bayowa *et al*., 2016).

Historically, iron ore mining has been instrumental in the industrial advancement of various nations, significantly contributing to economic growth and the expansion of infrastructure (Ahmad *et al*., 2017). The establishment of iron and steel industries has often depended on the availability of quality iron ore, which has fueled the manufacturing of essential goods, from construction materials to vehicles (Olade, 2019). This mining sector not only creates job opportunities but also stimulates related industries, such as transportation and machinery production (Salawu *et al*., 2015).

To ensure the optimal extraction and utilization of iron ore, it is vital to possess in-depth knowledge of its geochemical and mineralogical characteristics which includes understanding the mineral composition, grade, and geological processes that lead to the formation of iron ore deposits (Agava, 2006). Such expertise enables mining companies to develop effective exploration strategies, implement environmentally sustainable practices, and enhance resource recovery, thereby maximizing economic benefits while minimizing ecological impacts (Alabi, 2016).

MATERIALS AND METHODS

The material used in the course of this research is a 2 kg crude sample of Tajimi iron ore, sourced from the mine deposit located in Kogi State, lying between latitude (8^o 1' N – 8^o 3' N) and longitude (6^o 35' E – 6^o 36' E).

The lump sizes of the ore sample were reduced to 10.0 mm, a size acceptable to the crusher, using sledge hammer. The sample was then crushed using a laboratory jaw crusher to 5.0 mm, and pulverized using a ball mill. Before grinding and pulverization, the steel balls and ball mill compartments were properly cleaned to prevent contamination. The pulverized sample, with a particle size of 90 µm, was homogenized and sampled using the cone and quartering sampling method. This prepared sample underwent further analyses to determine its chemical and mineralogical properties.

Energy Dispersive X-ray Fluorescence (ED-XRFS) was employed to determine the elemental composition. A 20 grams of the ore sample was pelletized using 5 grams of Celleox (a binder) and then analyzed for major and trace elements.

The mineralogical characterization was carried out via X-ray Diffraction (XRD) to identify the mineral phases and their relative abundance in the ore, as presented in Table 2. Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM/EDS) provided insights into the microstructure and chemical composition of the sample, revealing interlocking minerals within the ore matrix, as presented in Plate 1.

Thin sections of the sample were prepared and analyzed using a petrological microscope. This analysis was done to reveal the texture and mineral associations within the ore, as presented in Plate 2.

Froth flotation of Tajimi iron ore was conducted using the Denver D-12 Flotation Cell. A total of 200 grams of pulverized iron ore, with a sieve size of 90 µm (100% passing), was weighed and charged into a 2000 ml capacity froth flotation tank. 1000 ml of distilled water was added, resulting in a slurry with 80% solids by weight. This allowed the solids to remain in suspension while the impeller rotated in the pulp at a speed of 1200 rpm.

To facilitate the separation of iron concentrate from gangue materials, various reagents were introduced, including 0.2 grams of $CuSO_4$ (an activator), 0.2 grams of corn starch (a depressant), 0.2 grams of potassium amyl xanthate (PAX, the collector), and 2 drops of Senfroth (the frother). The resulting products, consisting of froth and depressed samples, were then analyzed to evaluate the efficiency of the process.

RESULTS

Table 1 presents the chemical composition of the crude Tajimi iron ore, as determined through Energy-Dispersive X-ray fluorescence Spectroscopy (ED-XRFS). The table provides a comprehensive breakdown of the ore’s chemical compounds and their corresponding weight percentages. Figure 1 shows the X-ray diffraction (XRD) pattern of the crude Tajimi sample, highlighting the characteristic diffraction peaks of the major minerals present.

Table 2 outlines the phases identified in the Tajimi crude sample, along with their corresponding chemical formulae and figure of merit values, providing a quantitative assessment of the mineralogical composition.

Table 1: Chemical Composition of the crude Tajimi iron ore via ED-XRFS

Sample/ Assay (%)	SiO_2	V_2O_5	MnO	Fe_2O_3	CuO	Nb_2O_5	SO_3
Crude	18.568	0.172	0.047	62.166	0.037	0.130	0.389

Sample/ Assay (%)	CaO	K_2O	Al_2O_3	TiO_2	ZnO	ZrO_2	SnO_2
Crude	0.163	0.145	15.656	1.101	0.045	0.027	BDL

BDL= Below Detectable Level

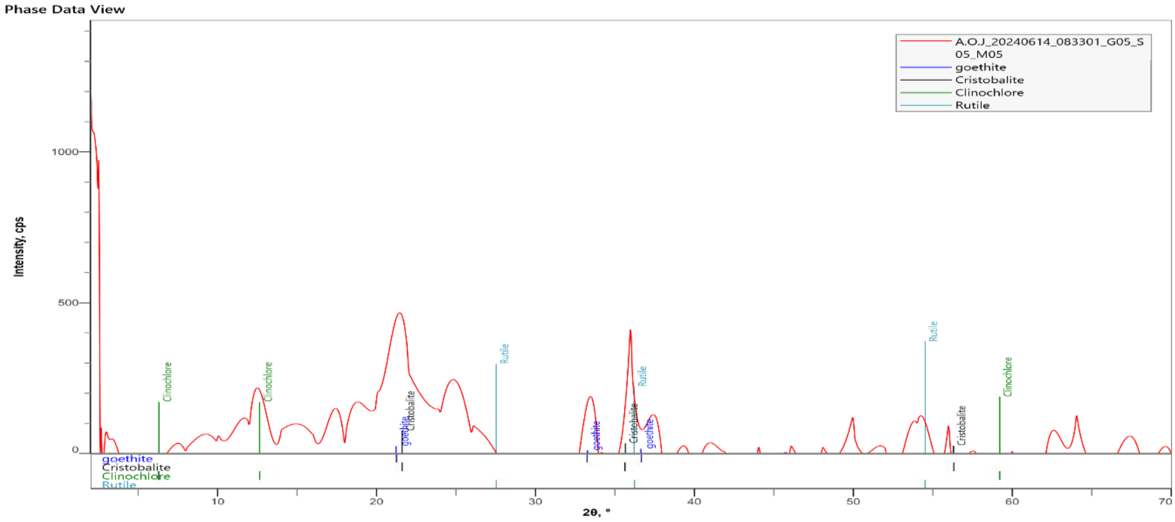


Figure 1: XRD pattern of Tajimi crude sample showing the diffraction peaks of the major minerals present

Table 2: Phases present with their respective chemical formulae and figure of merit

Phase name	**Formula**	**Figure of merit**
Goethite	FeO(OH)	2.912
Cristobalite	SiO_2	2.950
Clinochlore	$AlFeSiO_2OH$	1.827
Rutile	TiO_2	2.850

Figure 2 presents a pie chart illustrating the distribution of major minerals in the Tajimi crude sample, with each segment representing the weight fraction (wt.%) of the corresponding mineral phase. Plate 1 displays Scanning Electron Microscopy (SEM) images of the crude Tajimi iron ore sample, showcasing its morphology at two magnification levels: (a) 500x and (b) 1000x, both at a scale of 100 µm. Table 3 presents the elemental composition of the crude Tajimi iron ore sample, as determined by Scanning Electron Microscopy (SEM) with Energy-Dispersive Spectroscopy (EDS), listing the element number, symbol, name, atomic concentration, and weight concentration of the various elements detected.

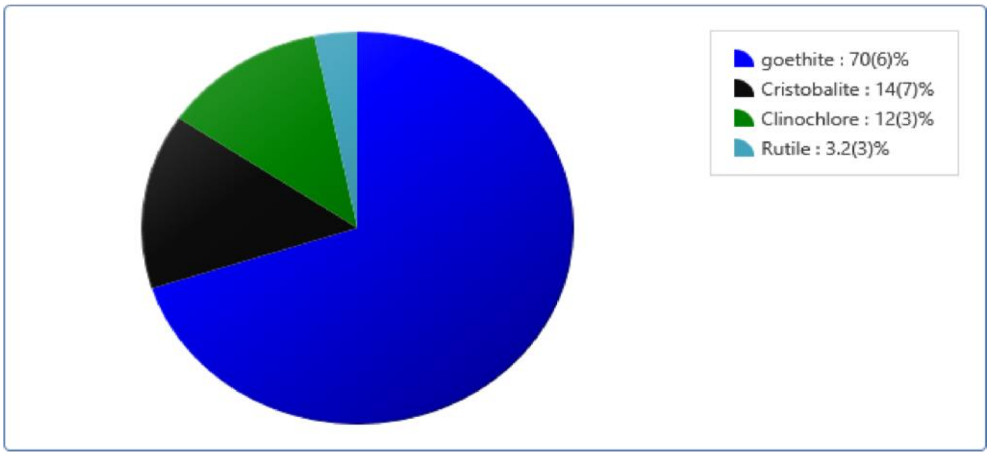
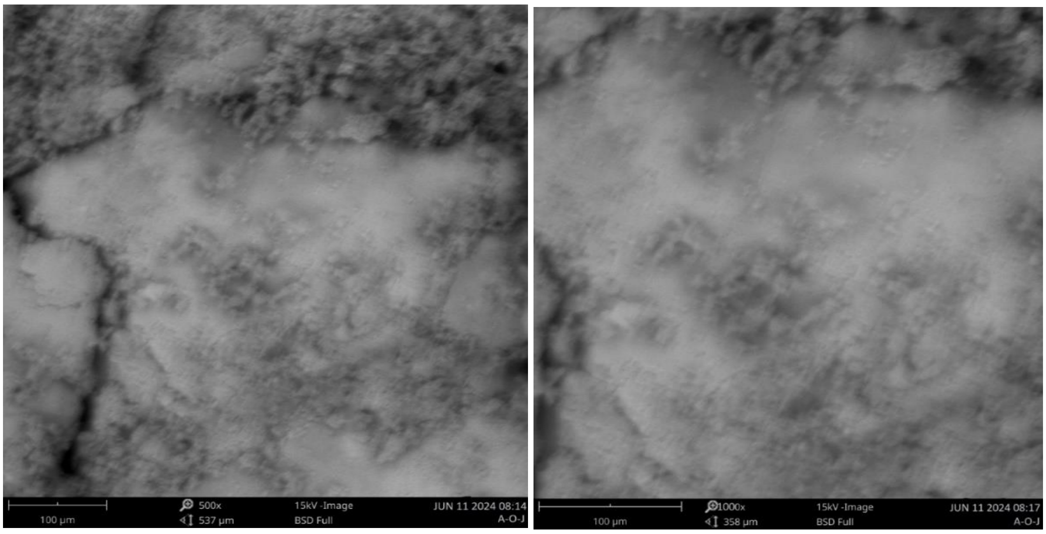


Figure 2: The pie chart of the major minerals present with their respective phase amounts or weight fraction (wt.%)



(a) **(b)**

Plate 1: Scanning Electron Microscopy (SEM) images of the crude sample at 100 µm via (a) 500 magnification, and (b) 1,000 magnification of the homogenized Tajimi iron ore

Table 3: The various elements present in the crude sample SEM Micrograph

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
14	Si	Silicon	17.86	10.05
26	Fe	Iron	58.95	64.26
13	Al	Aluminium	10.81	3.35
16	S	Sulfur	2.83	2.34
19	K	Potassium	1.31	1.32
22	Ti	Titanium	0.99	1.23
12	Mg	Magnesium	1.27	0.80

Figure 3 displays the Energy Dispersive X-ray Spectroscopy (EDS) spectrum of the crude Tajimi iron ore sample, showing the characteristic peaks corresponding to the various elements present, providing a qualitative and quantitative analysis of the elemental composition. Plate 2 presents photomicrographs of polished sections of the Tajimi crude ore, captured under plane-polarized light. The image reveals the ore's mineralogical features, with key minerals labeled, including quartz (Qz) and iron fillings comprising magnetite and iron III (Fe).

Table 4 presents the chemical composition of the froth and depressed samples of the Tajimi iron ore, as determined by Energy-Dispersive X-ray fluorescence Spectroscopy (ED-XRFS), providing a detailed breakdown of the chemical compounds in each sample. Table 5 outlines the metallurgical accounting of the froth flotation process for the Tajimi iron ore, providing a comprehensive summary of the efficiency and performance of the process, including key parameters such as recovery, enrichment ratio, concentration ratio, and grade.

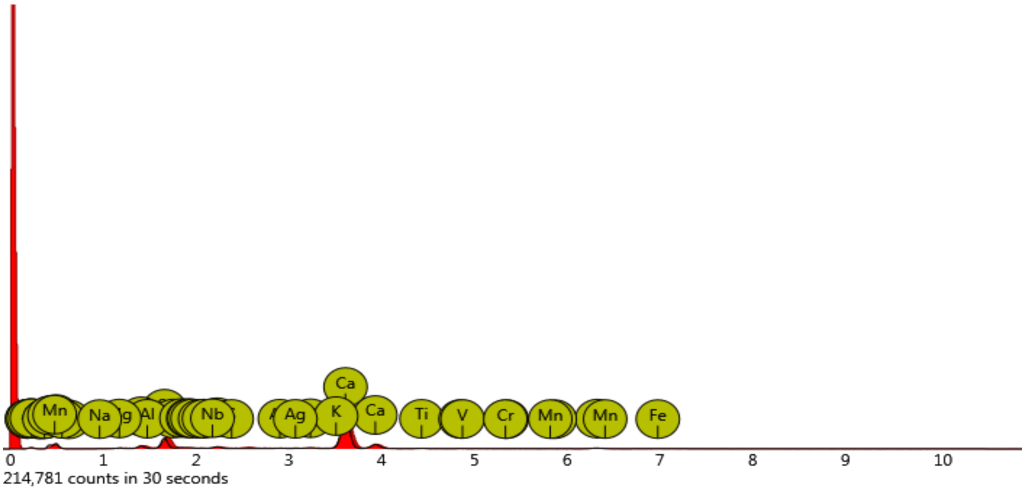


Figure 3: Energy Dispersive X-ray Spectroscopy (EDS) peaks for the various elements present in the crude sample

SEM Micrograph

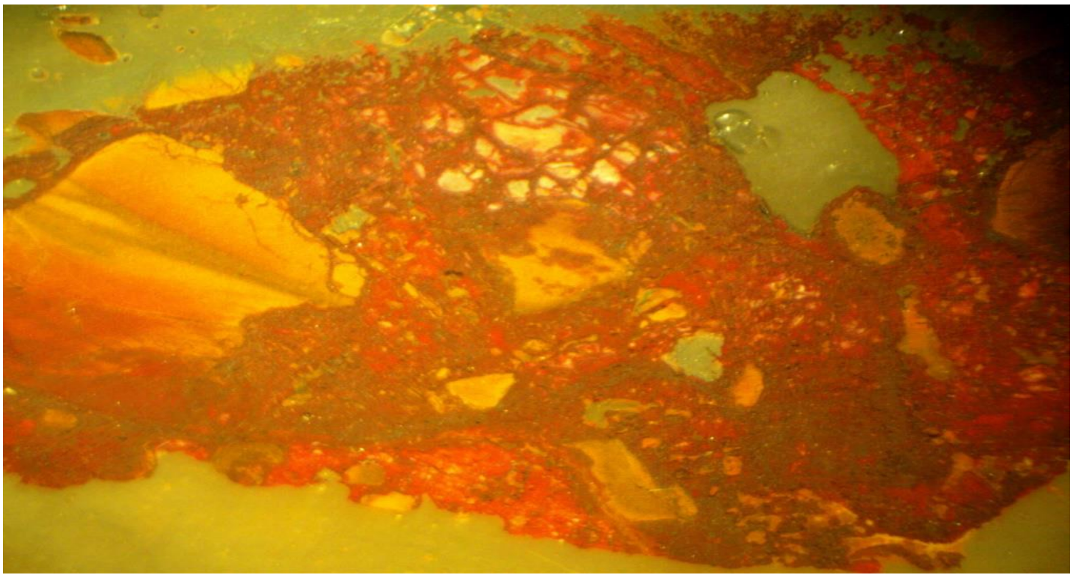


Plate 2: Photomicrographs of Polished Tajimi Crude Ore under plane-polarized light

(Qz = Quartz; Fe = Iron fillings of magnetite and iron III)

Table 4: Chemical composition of Froth and Depressed Samples of Tajimi iron ore via ED-XRFS

Sample/ Assay (%)	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	CaO
Froth	15.312	13.230	68.260	1.027	0.274	0.131
Depressed	16.176	12.160	68.006	1.057	0.258	0.167

Sample/ Assay (%)	K_2O	ZnO	SO_3	V_2O_5	CuO	MnO
Froth	0.135	0.039	0.266	0.166	0.107	0.043
Depressed	0.137	0.028	0.577	0.177	0.105	0.315

Table 5: Metallurgical Accounting of Froth Flotation of Tajimi iron ore

Processed Sample	Recovery (%)	Enrichment Ratio	Concentration Ratio	Grade (%)
Concentrate	32.941	1.098	3.333	68.260
Tailings	76.576	1.094	1.429	68.006

DISCUSSION

Chemical composition of the Tajimi iron ore

Table 1 shows the results obtained from analyzing crude Tajimi iron ore using an energy-dispersive X-ray Fluorescence Spectrometer (ED-XRFS). The analysis revealed that the ore contains various chemical elements in different percentages. These include SiO2 at 18.568%, V2O5 at 0.172%, MnO at 0.047%, Fe2O3 at 62.166%, CuO at 0.037%, Nb2O5 at 0.130%, SO3 at 0.389%, CaO at 0.163%, K2O at 0.145%, Al2O3 at 15.656%, TiO2 at 1.101%, ZnO at 0.045%, ZrO2 at 0.027%, and SnO2 at 0.000%, as well as other trace compounds. It can be concluded from the result that the ore primarily contains iron, aluminium, titanium, and silicon in oxide forms and it exceeds the standard cut-off grade of 1-5% iron requirement in the ore to be identified as an iron-bearing mineral (Salawu *et al.*, 2015; Thomas *et al.*, 2019).

The XRF results from the froth and depressed samples of Tajimi iron ore, as shown in Table 4, reveal significant improvements. The crude ore contains 62.166% Fe2O3 (Table 1), which undergoes a notable increase to 68.260% in the froth concentrate, underscoring the clear effectiveness of the flotation process.

However, the depressed sample also exhibits a high Fe2O3 content of 68.006%, indicating potential loss of iron-rich particles to the tailings. The concentration ratio of 3.333 in the froth (Table 5) portrays the process's efficiency, yet the iron content in the depressed sample calls for enhanced selectivity.

Mineralogical characterization of the Tajimi iron ore

Figure 1 presents the XRD pattern and mineralogical assemblage of Tajimi iron ore as represented by the mineral peaks in the diffractogram. The quantitative analysis report gives the weight fraction (wt.%) of the phase present in the sample, as shown in Figure 2. It can be deduced that goethite is predominant in the ore with a weight fraction of 70(6) wt.%, compared to other minerals which conforms to the results obtained from ED-XRFS and SEM/EDS analyses.

The Scanning Electron Microscopy (SEM) micrograph of the crude sample at 100 µm as shown in Plate 1, reveals the interlocking nature of minerals within the crystal aggregates in the ore matrix. These minerals possess semi-fine grain boundaries and as such facilitate easy liberation via comminution; the more coarsely packed the minerals the easier their liberation (Alabi *et al.*, 2019). Figure 3 displays the Energy-Dispersive X-ray (EDX) analysis spectrum of the ore, featuring prominent peaks corresponding to the various elements present in the crude sample. As observed in the SEM micrograph of Plate 1, the ore's matrix is predominantly silica-based, hosting dispersed grains of sodium aluminium silicate and copper carbonate hydroxide.

The analysis revealed the presence of Si, Fe, Al, S, K, Ti, and Mg, with Iron (Fe) being the principal element having atomic and weight concentrations of 58.95% and 64.26%, respectively as shown in Table 3. Thus, the result obtained conforms with and further complements the ED-XRFS and XRD analyses carried out and as such, the crude sample contains iron as the mineral of interest in association with other minerals that can hinder its processing unless they are reduced to a minimal level by separation techniques to yield a high-grade concentrate while the associated minerals are discarded as tailings (Alabi *et al*., 2019; Gbadamosi *et al*., 2021)

Plate 2 shows the photomicrograph of a polished lump of Tajimi crude ore sample. The results of the petrographic analysis revealed that the sample exhibits a porphyritic texture, characterized by large crystals (phenocrysts) of magnetite and iron III embedded in a finer-grained matrix of quartz and iron oxides. The presence of quartz and iron oxides in the sample indicates that the deposit may have undergone significant alteration and enrichment processes, resulting in the formation of economic iron ore.

CONCLUSION

The Tajimi iron ore has undergone an effective upgrading process, resulting in an iron oxide of 68.260%. This significant enhancement makes the ore viable for use as a reinforcement material in steel production, where high-quality iron sources are essential for improving the overall strength and durability of the finished products. However, while this upgraded ore is suitable for application in blast furnaces, it does contain a relatively high concentration of silica, which can be detrimental to the quality of the steel produced. This presents a valuable opportunity for further processing to improve the ore's overall quality and purity. One effective method for achieving this enhancement is magnetic separation where the purity of the Tajimi iron ore can be significantly increased, thus optimizing its properties for industrial use and contributing to more efficient steel production.

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