Published by
NIGERIAN SOCIETY OF PHYSICAL SCIENCES
Available online @ https://asr.nsps.org.ng/index.php/asr

African Scientific Reports 4 (2025) 260

African Scientific Reports

Physicochemical analysis and dissolution kinetics of Itakpe iron ore in acid, base and aqueous media

A. U. Atumeyi[a,b,*], A. U. Itodo[c,d], R. Sha'Ato[a], R. A. Wuana[a]

[a]*Department of Chemistry, Joseph Sarwuan Tarka University Makurdi, Nigeria*
[b]*Department of Chemistry, Federal University Lokoja, Nigeria*
[c]*Department of Industrial Chemistry, Joseph Sarwuan Tarka University Makurdi, Nigeria*
[d]*Department of Chemistry, Confluence University of Science and Technology, Osara, Nigeria*

Abstract

This work examines the physicochemical properties and dissolution kinetics of Itakpe iron ore, Nigeria, to provide insight into its industrial and environmental applications. The iron ore had a bulk density of 4.22 g/cm^3, an apparent density of 3.33 g/cm^3, and a pH of 8.3, hence showing potential in adsorption and environmental remediation. Conductivity of 138.7 μS/cm and specific surface area of 146.81 m^2/g showed potential in catalytic and adsorptive applications. The dissolution rates were significantly higher in acidic media, with a maximum weight loss of 5.65% at 360 minutes compared to 4.38% in basic media and 0.45% in neutral conditions. The zero-order kinetic model, $R^2 = 0.8819$, showed that the dissolution process was surface-controlled in acidic media, while the Higuchi model, $R^2 = 0.8797$, confirmed dissolution driven by diffusion. These findings emphasize the need to apply zero-order and Higuchi models in the dissolution kinetics of Itakpe iron ore. This work presents a clear quantitative comparison across media that was not developed earlier. These results support the optimized utilization of Itakpe iron ore in steel production and environmental remediation, hence indicating compatibility with various chemical conditions and that sustainable mining will help reduce harmful environmental impacts.

DOI:10.46481/asr.2025.4.1.260

Keywords: Dissolution, Environment, Iron ore, Kinetics, Physicochemical

Article History :
Received: 13 November 2024
Received in revised form: 20 January 2025
Accepted for publication: 28 January 2025
Published: 16 March 2025

© 2025 The Author(s). Published by the Nigerian Society of Physical Sciences under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

1. Introduction

Data recently made available have indicated that Nigeria now has about 2.5 billion metric tonnes of iron ore reserves, making Nigeria the 12th largest iron ore resource country in the world and the second largest in Africa. About 70 percent of these deposits are yet to be proven [1]. It is mainly located in the Itakpe Hill, Kogi State, Nigeria, with a geological proven reserve estimated at about 200 million tonnes [2]. The estimate of the reserves was made by wide grid 100 m pre-exploitation drillings; hence, continuous exploration will be required for the economic exploitation of the deposit [3, 4]. A further deposit of more than 6 million tonnes has been found in Ajabanoko, about 4 km northwest of Itakpe [5]. Itakpe iron ore, in Kogi State of Nigeria, is one of the peculiar

*Corresponding author Tel. No.: +234-806-467-2026.
Email address: anthony.atumeyi@fulokoja.edu.ng (A. U. Atumeyi)

deposits that is high in grades of hematite intergrown with magnetite and silica as major impurities. These unique characteristics make it worth studying in depth for reactivity and versatility under different chemical conditions.

Iron formations tend to occur with many other types of sedimentary rocks which include dolomite, quartz-rich sandstone, and black shale, and may locally grade into chert or dolomite [6]. These various types of textures are found in limestone which include micritic, pelleted, intraclastic, peloidal, oolitic, pisolitic, and stromatolitic structures [7]. Low-grade iron formation might contain various dominant minerals depending on the facies. The oxide facies are dominated by magnetite and hematite, whereas silicate facies are made up of greenalite, minnesotaite, and glauconite. The carbonate facies are generally siderite, while the sulfide facies are pyrite [8]. Due to their Precambrian age, most iron formations have undergone either deformation or metamorphism; the chemical makeup of these iron formations, however, is remarkably distinct even within high metamorphic grades [9, 10]. The higher the grade, the more metamorphosed the ore becomes; low-grade rocks may show only compaction while high-grade rocks may be undistinguishable. Itakpe iron ore is a rich hematite ore, some hematite being intergrown with magnetite was obtained from Ref. [11]. The main impurity is silica, which could easily be removed after liberation by mechanical crushing and physical separation. It makes the Itakpe ore suitable feedstock material for the direct reduction methods of ironmaking, characterizing ores resulting from magmatic segregation [12].

The early application of iron for manufacturing tools and weapons was favoured by the widespread distribution of iron ores and by the facility with which iron compounds may be reduced by carbon. In steelmaking, most of the iron produced is refined and transformed into steel-a uniquely versatile material exhibiting a wide composition and property range [13, 14].

Rates of mineral dissolution control a wide range of geochemical processes, including soil fertility, aquifer porosity, the transport and sequestration of contaminants and CO_2, metal cycling, and ore deposit genesis [15, 16].

Such dissolution kinetics strongly impact both the chemical and physical characteristics of landscapes and the availability and quality of potable water and fertile soil to support ecosystems. Iron ore mining activities also result in widespread soil contamination. This can have an adverse impact on the agricultural sectors of the surrounding areas [17]. In iron ore mining, toxic constituents such as arsenic, selenium, and other metals can also experience leaching even if acidic conditions are not present [18]. Contents of cyanide, and nitrogen compounds, like ammonia and nitrate and nitrite, are also reported to be higher in waters around mines due to heap leaching and blasting processes [19]. Acid drainage and contaminant leaching have been two of the major sources of water quality degradation associated with metallic ore mining [20]. These dissolution rates control the residence times of minerals in the soil environment, and thus, the understanding of the rates is essential to the quantitative prediction of the environmental evolution. Mineral dissolution rate can be influenced by various factors, including chemical composition, temperature, particle size, acid concentration, pH, and solid-to-liquid ratio [21, 22]. In general, dissolution rates increase with increased temperature and acid concentration but decrease with larger sizes of particles, increased pH, and solid-to-liquid ratios.

The novelty of this study is that zero-order and Higuchi kinetic models were employed to analyze the dissolution of Itakpe iron ore. In general, such models provide the full meaning of dissolution mechanisms, wherein the zero-order model describes a surface-controlled process, while the Higuchi model presents diffusion-driven kinetics. While earlier studies were all about the characterization of minerals, this work will relate the dissolution behavior to its industrial and environmental implications.

This work, therefore, aims at studying the physicochemical properties and dissolution kinetics of Itakpe iron ore in acidic, basic, and neutral media as an approach to understanding its impacts on the environment and possibly realizing its industrial applications in steel production and environmental remediation. Iron ore mining is often associated with environmental degradation, such as pollution of soil and water by toxic elements like arsenic and selenium. These contaminants degrade the quality of water through leaching during mining and ore processing, thus adversely affecting the ecosystems. Thus, this work is done to examine the dissolution kinetics of Itakpe iron ore in acidic, basic, and neutral media for its optimum utilization toward sustainable mining practice and environmental remediation. Therefore, the study will be useful in integrating quantitative data with environmental impact assessment for the development of clean and efficient extraction methods that assure minimum ecological disruption with full industrial benefit.

This involves the determination of some physicochemical characteristics of the iron ore sample, such as bulk density, apparent density, pH, conductivity, and specific surface area. Dissolution experiments in various media allow the comparison of dissolution rates under different conditions, while zero-order and Higuchi models apply in analyzing the kinetics of dissolution, with a focus on the influence of diffusion in each medium. In brief, the final results obtained would serve in useful ways for the optimization of the utilization of Itakpe iron ore amidst or complementary to a sustainable mining method that will reduce environmental hazards.

2. Study area

he sampling area for iron ore is Itakpe iron ore depot of the Nigeria Iron Ore Mining Company located in Okehi Local Government Area of Kogi States. Itakpe is on the Latitude of 7°36′ North; Longitude of 6°16′ East, as shown by the GPS map of Itakpe iron ore mining site in Figure 1. The people living in these areas are engaged in mining activities due to the existence of the ores at their disposal. Mining operational mode explored by these inhabitants is not a healthy type but rather at the expense of the environment.

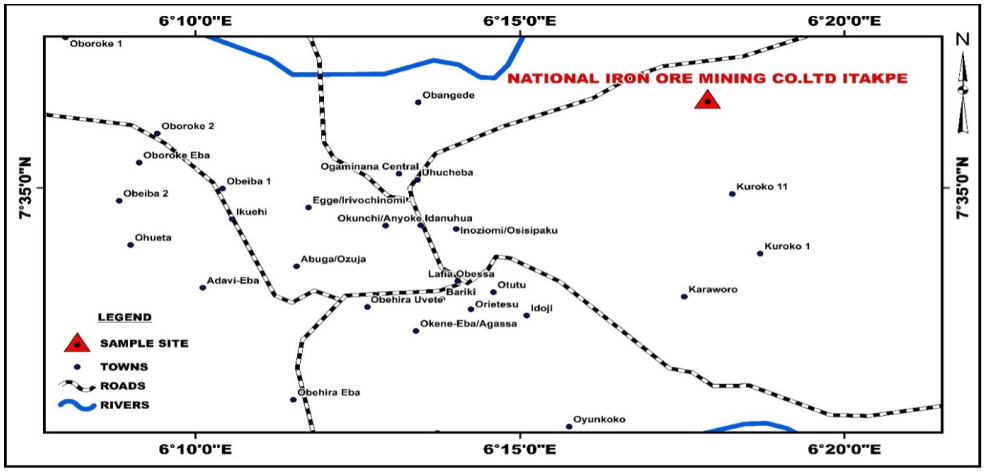


Figure 1: GPS map of Itakpe iron ore mining site.

3. Materials and methods

The materials involved include thermometer, masking tape, digital pH meter (model PHS-25), conductivity meter (model DDS-307A Philips conductivity meter), crusher, plastic container with a screw tap, hand gloves and drying oven. Apparatus used include routine laboratory glassware such as beakers, volumetric flask, test tubes, measuring cylinders, conical flask, pipettes, funnel, hot plates, weighing balance and filter paper.

3.1. Sampling

The mineral sample was handpicked randomly from the depots and stored, well labeled, and then taken to the laboratory and store under ambient condition.

3.2. Methods

3.2.1. Iron ore sample pre-treatment

The iron ore sample was washed, air dried, pulverized and sieved into target particle sizes [23, 24] and then labeled with masking tape for laboratory analysis.

3.2.2. Physicochemical analysis

a. Bulk density: A 10 cm^3 Cylinder was filled to 8 cm^3 with the grinded powder of coal, iron ore and limestone samples. The weight in gram (g) of the sample was recorded from weighing balance. The bulk Density was calculated as in the formula in equation (1) [25]:

$$Bulk\ Density\ (g/cm^3) = \frac{Mass\ (g)}{Volume\ (cm^3)}. \tag{1}$$

b. Apparent density: A 25 cm^3 cylinder was filled with distilled water up to its 15 cm^3 marked point after which 5 g of the samples was weighed and added into the cylinder containing the distilled water. The change in volume of the content was recorded from the cylinder. The apparent density was calculated using the formula below [25]:

$$Apparent\ Density\ (g/cm^3) = \frac{Mass\ (g)}{Apparent\ Volume\ (cm^3)}. \tag{2}$$

c. pH: For the pH determination, 1 g of each of the samples (Coal, Iron Ore and Limestone) was weighed and dissolved in 20 cm^3 of deionized water, then warmed and allowed to cool. The pH electrode was dipped into the solution and the value read from the meter until a desirable pH is reached [25, 26].

d. Conductivity: For conductivity test, 1 g of the samples each was weighed and dissolved in 20 cm^3 of de-ionized water. The samples warmed each and the conductivity electrode dipped into the mixture and the readings were taken from the meter [25, 26].



Figure 2: Pulverized Itakpe iron ore from Itakpe mining site.

e. Specific surface area: Saers' method was used for the determination of porosity/surface area. A sample of each of coal, iron ore and limestone of 0.5 g was acidified with 0.1M HCl to pH 3-3.5; the volume was made up to 50 cm^3 with de-ionized water after addition of 10.0 g of NaCl. The titration was carried out with standard 0.1M NaOH in a thermostatic bath at 298±0.5 K to pH 4.0, and then to pH 9.0. The volume V required to raise the pH from 4.0 to 9.0 was noted and the surface area was computed from the following equation [27]:

$$S(m^2/g) = 32V - 25. \tag{3}$$

3.2.3. *Dissolution studies (Gravimetry)*

The dissolution kinetics of modified iron ore (as shown in Figure 2) in acid and base was studied. One g amount of iron ore sample was added to the 5 reactor vessels containing 100 mL 0.1 M HCl and 0.1 M NaOH separately. The temperature, solid-to-liquid ratio, particle size and pH were kept at constant at stirring speed of 200 rpm for 1, 2, 3, 4 and 5 hours. This was done using a temperature controlled magnetic stirrer. The sample was removed, filtered and dried in the oven and weighed till constant weight was obtained. Dissolution in distilled water was set as control experiment [28].

3.2.4. *Experimental conditions*

The dissolution experiments were performed under controlled laboratory conditions in order to ensure that the experiments would be reproducible and identical. The temperature was kept constant at 298 ± 0.5 K using a thermostatically controlled magnetic stirrer, which ensured uniform heat distribution throughout the reaction mixture. All experiments were conducted in a sealed system to prevent contamination or evaporation of the reactants. During the different experiments, the solid-to-liquid ratio was the same, as was the similar particle size with a stirring speed of 200 rpm. All experimental conditions were run with their own replicates for confirming the reliability of the obtained results.

3.2.5. *Dissolution kinetics models*

The kinetic models adopted will be the zero-order and Higuchi kinetic models, because usually mineral dissolution includes surface-controlled and diffusion-driven processes. A zero-order model was selected for test conditions whereby the rate of dissolution is independent of concentration and as such will represent a surface reaction [29]. On the other hand, a Higuchi model was selected to test dissolution that is controlled by diffusion, more relevant in systems that contain complex matrices, like iron ore [30]. Other alternative models, such as first-order or pseudo-second-order kinetics, were not considered appropriate since they describe mainly adsorption phenomena or chemical reactions, while the process studied here was physical and limited by diffusion. The selected models provided a robust framework for understanding the dissolution behavior under the experimental conditions.

i. Zero-order model: Solid dissolution from dosage forms that do not disaggregate and release the substance slowly can be represented by the equation:

$$Q_0 - Q_t = K_0 t. \tag{4}$$

Rearrangement of equation above yields:

$$Q_t + Q_0 = K_0 t, \tag{5}$$

where Q_t is the amount of solid dissolved in time t, Q_0 is the initial amount of the substance in the solution (most of the times, $Q_0 = 0$) and K_0 is the zero order release constant expressed in units of concentration per time [29].

ii. Higuchi model: Higuchi developed models to study the release of water soluble and low soluble substances incorporated in semi-solid and solid matrices. To study the dissolution from a planer system having a homogeneous matrix, the relation obtained is shown in equation below [30].

$$Q = [D(2C - C_s)C_s t]^{1/2}, \tag{6}$$

where Q is the amount of substance released in time t per unit area, C is the initial substance concentration, C_s is the substance solubility in the matrix media and D is the diffusivity of substance molecules in the matrix substance.

In general Higuchi model can be simplified as,

$$Q = K_H t^{1/2}, \tag{7}$$

where, K_H is the Higuchi dissolution constant [29]. Higuchi describes substances release as a diffusion process based in the Fick's law, square root time dependent. For diffusion-controlled process a plot of Q versus square root of time is linear. The integral form of Higuchi equation is employed in seeking to establish whether mixed order release kinetics exists: In general Higuchi model can be simplified as,

$$LogQ = logK_H + \frac{1}{2}\ log\ t. \tag{8}$$

A confirmation of Higuchi diffusion is provided by the equation above; diffusion-controlled process dominates when the logarithm plot approaches 0.5 [30].

3.2.6. Statistical analysis of kinetic models

In order to validate the kinetic models (Zero-Order and Higuchi) and assess the significance of differences in dissolution kinetics across media (acid, base and water) using ANOVA, the following hypotheses were defined:

i. Null Hypothesis (H_0): There is no significant difference in the kinetic constants (k_0 for zero-order and k_H for Higuchi) across the media (acid, base, and water).

ii. Alternative Hypothesis (H_a): There is a significant difference in the kinetic constants across the media.

The One-Way ANOVA formula for validating kinetic models across the media in the context of this investigation compares variations in dissolution rates and constants under different chemical environments (acidic, basic, and aqueous). It employs the following general formula:

$$\frac{MST}{MSE}, \tag{9}$$

where:

- MST (Mean Square Between Groups): Measures variance between media (acid, base, water).
- MSE (Mean Square Within Groups): Measures variance within the same medium across experimental conditions (e.g., temperature, time).

This allows assessment of whether the variations in dissolution rates are statistically significant across the different media. For this study, the kinetics models (zero-order and Higuchi) involve constants (k_0 and k_H) and regression values (R^2) that serve as input data for ANOVA to determine the influence of the media.

4. Results and discussion

4.1. Physicochemical analysis

4.1.1. Bulk density

The bulk density value of 4.22 g/cm^3 in Table 1, is an indication that the Itakpe iron ore is quite dense and probably would be relevant for a wide variety of industries, especially in areas where high structural integrity and possibly very high adsorption capacity are required. High bulk density is a characteristic of materials whose particles are closely packed. A high bulk density enhances the mechanical strength and stability, hence advantageously influences adsorption efficiency due to smaller pore spaces with higher mass per unit volume. Hence, such characteristics facilitate their application in, say, water treatment processes due to the fact that density

Table 1: Physico-chemical parameters of iron ore samples from Itakpe.

Parameters	Values
Bulk density (g/cm^3)	4.22±0.01
Apparent density (g/cm^3)	3.33±0.00
pH	8.3±0.00
Conductivity (µs/cm)	138.7±0.16
Specific surface area (m^2/g)	146.81±0.01

ensures a good rate of adsorption. Further, durability and long-term stability are ensured, especially where operations are required to run at high throughputs [31, 32].

In adsorption studies, denser materials are preferred since they can handle larger pollutant loads with minimal volume expansion. This high density further makes Itakpe iron ore suitable for heavy-duty applications in steel production, where dense ore is beneficial for attaining high iron yields during its reduction processes. Similar studies carried out on similar high-density ores, like hematite and magnetite, have shown that the higher the bulk density of any such ores, the higher their reduction efficiency, since the fact is that denser materials are more likely to contain a more concentrated iron content, hence reducing use in iron-making furnaces [23].

Furthermore, the obtained bulk density of greater than 4 g/cm^3 is within acceptable limits, based on the industrial requirements for adsorbents. More so, densities falling in this range were observed with commercial adsorbents, like activated carbon and various mineral-based adsorbents. A high bulk density of 4.22 g/cm^3 is promising for mechanical stability, hence applicable in maintaining structural integrity for adsorbent beds in various water treatment processes.

A comparison with global iron ore deposits will place it in a wider perspective. Brazilian hematite, with a bulk density of about 5.0 g/cm^3, shows better efficiency in direct steelmaking because of its higher density. However, the fact that Itakpe has a lower density and higher specific surface area makes it more suitable for adsorption-based applications, especially in environmental remediation [23].

It has also been reported that adsorbents of higher bulk density tend to work more effectively during contaminant treatments applied to water and air due to a higher amount of adsorptive material being involved per unit volume, thereby enabling longer practical lives with reduced frequencies of replacements [31].

4.1.2. Apparent density

An apparent density value of 3.33 g/cm^3 in Table 1, represents an important characteristic of Itakpe iron ore, helpful in assessing its suitability for industrial and environmental use with respect to adsorption and heavy metal removal. While apparent density reflects the stability of an adsorbent, meaning thereby not porous and leading to breakdowns, the Itakpe iron ore could, on many counts, prove suitable for applications that need a robust adsorbent which should be long-lasting. Studies undertaken on dense materials, including mineral ores and activated carbon, reveal the apparent density of adsorbents with higher apparent density usually exhibits more physical stability-an important component in repetitive cycles of adsorption-desorption when the use is for environmental remediation [32].

Apparent density relates to adsorption in water treatment because it gives an indication of the settling rate that will take place and provides an overall insight into filtration efficiency. More dense materials exhibit quicker rates of settling and, therefore, are less likely to form suspensions, thereby affecting the clarity of the treated water. This is indicative of the fact that apparent density tends to be inversely proportional to leaching, allowing for a more predictable and controlled process of adsorption, hence possibly relating to heavy metals and other contaminants' removal in water treatment. The same can be said for Itodo *et al*. [32].

In contrast, South African magnetite, with its somewhat higher apparent density of 3.8 g/cm^3 and more neutral pH, will not be as versatile in adsorption processes compared to Itakpe's mildly alkaline profile, which thus favors heavy metal removal [33–35].

Apparent density in this case also speaks to the fact that for industrial use, Itakpe iron ore tends to have a relatively higher mineral content with respect to volume, hence its usefulness in such processes as metal extraction. In general, higher apparent density means a higher purity level mineral ore, therefore more efficient in metallurgical applications such as in a blast furnace or reduction process. Such high densities support efficient reduction and melting due to a higher content of iron, which would reduce the volume of waste and increase yields when smelted.

Another typical characteristic of materials with higher apparent density is that their compactness often allows for better mechanical properties-resistance to abrasion and crushing are among the key features for industrial reactors or adsorptive columns. In this regard, such durability would allow multiple uses of Itakpe iron ore without losing structural integrity, especially under conditions of high stress. Studies have found that materials of the same apparent densities are more resistant under mechanical stress, hence best suitable for continuous flow systems as well as for industrial processes wherein adsorbents or reactants are subjected to strenuous physical conditions [31].

4.1.3. pH

The pH of 8.3 in Table 1, which means a mild alkaline, further underlines the suitability of Itakpe iron ore for environmental applications, especially in water treatments and pollutant removal. Generally, adsorbents that have alkaline pH values are favoured for the removal of acid contaminants due to the buffering effect and the neutralization they would exert on the acid solutions to facilitate the adsorption processes. Indeed, research studies have proved that a mildly alkaline pH material, of characteristics similar to the Itakpe iron ore material, is quite effective in adsorbing heavy metals and other impurities from wastewater since these conditions favor increased electrostatic attraction between the negatively charged surface of the adsorbent and positively charged metal ions.

Besides that, the fact that the ore pH was mildly alkaline would imply that for the most part, the material could be quite stable and resilient to different environmental conditions without altering the pH of water systems greatly; hence, it may work well for long-term applications. One of the key added advantages of alkaline adsorbents is preventing the acidification of treated water, an important ecological balance in natural water bodies. This has been quite significant in regions so far affected by mining, considering that their acid leachates are common and the existence of such alkaline adsorbents can help mitigate the impacts of acid drainage [26], among other areas, corroborate this assertion.

In terms of industrial applicability, a pH near neutral or slightly alkaline, about 8.3, is considered optimal because the ore reacts well with acids in certain processes, like acid leaching. This condition optimizes dissolution of metals, given that the acid environment ensures adequate deconstruction of the ore structure without being at much resistance from the material. Slightly alkaline pH of 8.3 supports electrostatic attraction between the negatively charged ore surface and positively charged ions, hence favors the removal of positively charged contaminants. Such conditions have been observed to facilitate higher extraction efficiencies in leaching studies of metal ores, especially in processes in which a controlled alkaline environment is imposed to prevent premature precipitation of dissolved ions [33].

4.1.4. Conductivity

esults from the conductivity measurement for Itakpe iron ore (as shown in Table 1) gave a value of 138.7 μS/cm, indicating high free ions and, therefore, a high ionic exchange potential. This, therefore, improves this ore in its ability with regard to adsorption, catalytic applications, and environmental remediation purposes. High values of conductivity in materials suggest that their contents include free-moving ions such as iron, silica, and other trace metals that contribute to their potential engagement in ionic reactions. In environmental applications, more conductive materials are helpful in the adsorption of pollutants during water treatment. This is because free ions can participate in ion exchange mechanisms where effective inhibition of contaminants from solution occurs by binding [26].

More so, conductive materials find an excellent application in catalysis, where ion availability enhances the rate of chemical reactions. Research has indicated that adsorbents exhibiting increased conductivity tend to be more efficient in the decontamination of heavy metal-laden water due to the fact that the heightened levels of ionic content tend to support mechanisms of electron transfer involved in the processes of adsorption and oxidation-reduction reactions. This attribute is, therefore, vital in such industrial applications as acid leaching, where the dissolution of certain minerals such as iron results from increased ionic mobility that aids in the extraction of metals from ore [33].

Apart from that, the high conductivity value in Itakpe iron ore would enhance its potential in industrial processing, such as steel production, wherein it is more general to work with ores containing high ionic levels and conductivity. These ores offer smoother electron flow during the reduction process, hence giving better overall efficiency and lowering energy costs. High conductivity of 138.7 μS/cm shows the existence of free ions, facilitating ionic interaction in leaching and enhancing it with regard to extraction [33]. Conductivity also extends to the activities of electrometallurgical treatment, whereby ores with electric conductivity give some advantages in running the smelting and refining works efficiently.

4.1.5. Specific surface area (SSA)

The result obtained in Table 1, is therefore an indication of the high adsorption capacity thus efficiency in the industrial and environmental applications as depicted by the value of specific surface area obtained for Itakpe iron ore to be 145.81 m^2/g. Specific surface area is generally the most important parameter governing the adsorptive properties of a material, giving detailed information on the amount of surface that can be engaged in interactions with other materials. The SSA of 145.81 m^2/g is an indication of high surface area, hence increasing the adsorption capacity of the ore. This property facilitates efficient interaction with pollutants like heavy metals in water treatment. Consequently, materials with high SSA, such as activated carbon, have over the years found wide applications in pollution control due to their larger surfaces that provide higher adsorption of contaminants [31].

A high SSA in water treatment will increase the capacity of iron ore to adsorb all forms of pollutants including heavy metals by mechanisms involving direct contact with the surface. Larger SSA provides sites for adsorption at which efficient adsorption occurs in environmental applications, including those involving rapid removal of contaminants. It has been determined that high SSA adsorbents can effectively decrease pollutant levels in wastewater because of the high degree of interaction between the adsorbate and the adsorbent surface provided [31].

It is also believed that the high SSA could enhance the catalytic performance of Itakpe iron ore because the large surface area increases the availability of reactive sites in catalytic processes. This, therefore, makes the ore particularly useful in areas such as

Table 2: Dissolution of iron ore in different media (acid, base and water).

Time (min)								
Media/Weight (g)		60	120	180	240	300	360	Mean ± SD
Acid	Wt_{Ai}	1.0040	1.0022	1.0010	1.0011	1.0007	1.0013	1.0017±0.001
	Wt_{Af}	0.9761	0.9701	0.9691	0.9623	0.9575	0.9447	0.9633±0.011
	Wt_{Ad}	0.0279	0.0321	0.0319	0.0388	0.0432	0.0566	0.0384±0.010
% diss A		2.7788	3.2029	3.1829	3.8757	4.3169	5.6527	3.8349±1.05
Base	Wt_{Bi}	1.0031	1.0025	1.0012	1.0010	1.0008	1.0030	1.0019±0.001
	Wt_{Bf}	0.9628	0.9686	0.9669	0.9572	0.9641	0.9606	0.9633±0.004
	Wt_{Bd}	0.0403	0.0339	0.0343	0.0438	0.0367	0.0424	0.0386±0.004
% diss B		4.0175	3.3815	3.4259	4.3758	3.6671	4.2273	3.8492±0.42
Water	Wt_{Wi}	1.0011	1.0020	1.0005	1.0014	1.0024	1.0009	1.0014±0.0007
	Wt_{Wf}	1.0001	0.9981	0.9976	0.9995	0.9989	0.9964	0.9984±0.001
	Wt_{Wd}	0.0010	0.0039	0.0029	0.0019	0.0035	0.0045	0.00295±0.001
% diss W		0.09989	0.3892	0.2898	0.1897	0.3492	0.4496	0.2946±0.13

Key: Wt A = Weight of Iron Ore in Acid, Wt B = Weight of Iron Ore in Base, Wt W = Weight of Iron Ore in Water, Wt $_{Xi}$ = initial weights, Wt_{Xf} = Final weights and Wt_{Xd} = Difference in Weight between Initial and Final, % diss X = Percentage Weight Dissolved

Table 3: Experimental constants and parameters for the dissolution of Itakpe iron ore.

Dissolution model	Constants	Medium		
		A	B	W
Zero Order	R^2	0.8819	0.1301	0.3927
	k_0 (g/min)	9.0×10^{-5}	1.09×10^{-5}	7.0×10^{-6}
Higuchi Model	R^2	0.8797	1.50×10^{-5}	7.0×10^{-6}
	k_H (g/min)	8.0×10^{-5}	1.10×10^{-5}	7.0×10^{-6}

Key: A = Acid, B = Base and W = Water

acid leaching, in which an increase in surface contact increases the rate and extent of dissolution of metals in order to maximize metal recoveries.

In industrial applications of steelmaking, the ores with higher SSA are more reactive. This means they provide faster reduction reactions during smelting. This results in savings in energy costs and optimization of reaction conditions in the blast furnace hence more efficient processing with higher yields. Similar studies dealing with materials possessing similar SSA values, for example, modified adsorbents, have reported enormous advantages in industrial applications, and hence Itakpe iron ore is considered an effective raw material for high-demanding processes [34].

4.2. Dissolution studies in different media

1. Acidic Medium (A): In the case of acidic media (as revealed in Table 2 and Figure 3), the increased dissolution rate could be related to more availability of hydrogen ions, which help in the breakdown of minerals. Ghosh *et al.* [35] reported that the acid media cause dissolution of iron-bearing minerals through ion exchange and hydrolysis, which increases the % of iron solubilized from the neutral and basic media. This is further ascertained by a high zero-order rate constant in this study, $k_0 = 9.0 \times 10^{-5}$ g/min, which indicates that the dissolution process is very rapid.
   Kinetic analyses indicate that Australian deposits exhibit faster dissolution rates in neutral conditions due to the higher reactive mineral content, whereas the significant dissolution of Itakpe in acidic media underscores its suitability for applications like acid leaching and pollutant neutralization [19, 36].
2. Basic Medium (B): The reduction of dissolution rate in basic medium can (as shown in Table 2 and Figure 3) perhaps be explained by the precipitation of hydroxide complexes which may stabilize iron and impede its dissolution; Li *et al.* [36] noted that alkaline conditions may precipitate iron hydroxides that block further dissolution pathways, hence accounting for a lower R^2 value in basic conditions of 0.1301 in the zero-order plot.
3. Water (for control experiment): The recorded results show slight dissolution in water (as shown in Figure 3), with ko = 7.0×10^{-6} g/min (Table 3). This is in good agreement with the results obtained by Sarma *et al.* [37], who observed that water has a very limited capability to solubilize iron minerals because of its neutral pH value, which cannot provide the right ionic environment for better mineral dissolution. This enhances the need for acid or base conditions for better dissolution.

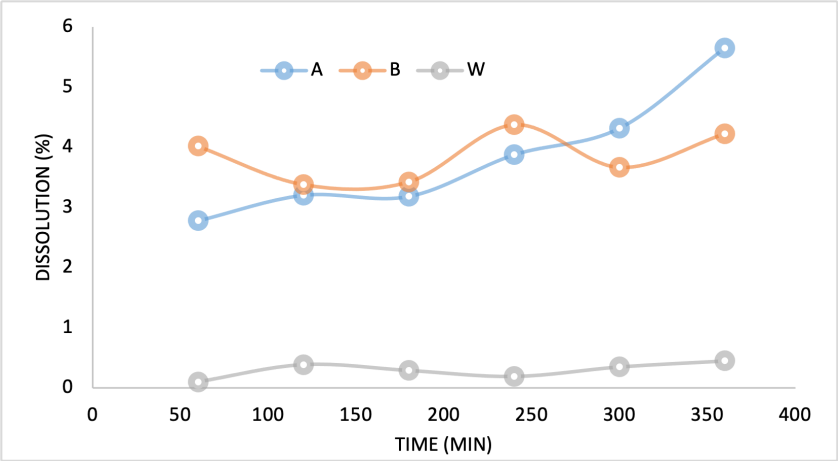


Figure 3: Dissolution profile of Itakpe iron ore in acid and base using water as control.

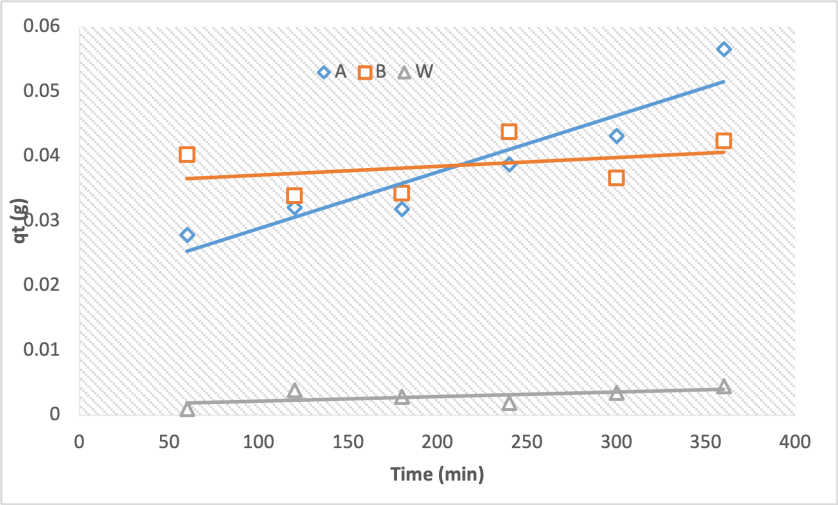


Figure 4: Zero order plots for dissolution of Itakpe iron ore in Acid (A), Base (B) and Water (W).

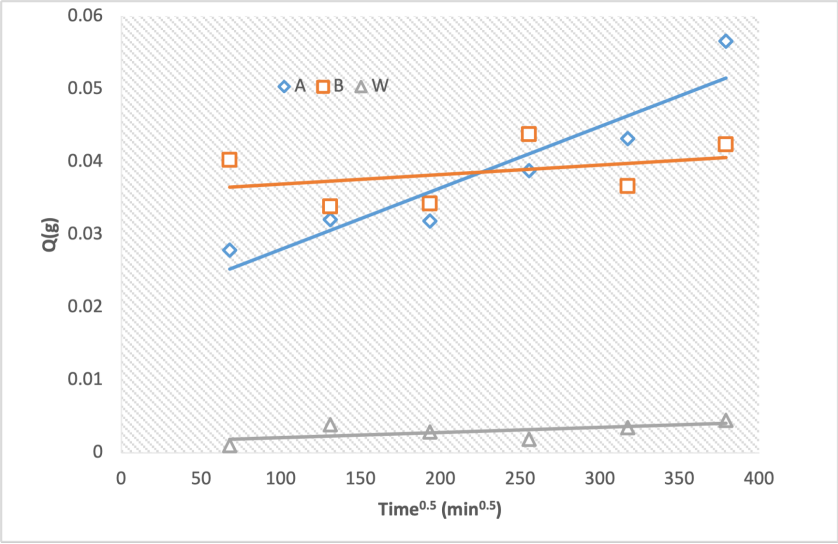


Figure 5: Higuchi plots for dissolution kinetics of Itakpe iron ore in Acid (A), Base (B) and Water (W).

4.3. Dissolution kinetic modelling

4.3.1. Zero-order

The zero-order kinetics obtained in the acidic medium (with R^2 of 0.8819 and k_o of 9.0×10^{-5} k_o g/min) in Table 3 and Figure 4, shows that the dissolution rate is independent of the concentration of dissolved iron. This usually characterizes surface-controlled reactions. According to Faraji *et al*. [38], in this type of kinetics, the dissolution of solids-liquid usually takes place when the surface area controls the reaction kinetics rather than the concentration of the reactant. In this respect, this behavior confirms the results of this study, indicating that dissolution in acid media is a surface-controlled process.

4.3.2. Higuchi model

The dissolution data in Table 3 and Figure 5 obtained in the acidic medium (R^2 = 0.8797 and $k_o = 8.0 \times 10^{-5}$ g/min) suggests applicability for the Higuchi model and indicates that the process is highly controlled by diffusion. As stated by Siepmann and Peppas [39], the model "represents dissolution processes from when the rate-controlling mechanism of the process is the phenomenon of diffusion." It means that ion migration through the liquid medium plays a key role in determining the overall dissolution rate of the precipitate.

4.3.3. Comparison of constants

Large variations in dissolution rates and constants among the three media (Table 3) indicate that the chemical environment is a very major factor in dissolution kinetics. According to Das *et al*. [40], acid can be highly enriched with reactive ions, which is responsible for a sharp increase in the minerals' solubility. On the other hand, in neutral water, the availability of reactive ions is less; hence, dissolution rates are significantly lower.

4.3.4. Statistical analysis and interpretation of kinetic models

i. Zero-Order model (k_o)

F – statistic = 870.53

P – statistic = 1.03×10^{-13}

ii Higuchi model (k_H)

F – statistic = 750.12

P – statistic = 2.50×10^{-13}

Interpretation

The p – value for both models is significantly less than 0.05, indicating that there are statistically significant differences in the kinetic constants (k_o and k_H) across the media (acid, base and water). This supports the hypothesis that the chemical environment (medium) significantly impacts the dissolution kinetics of Itakpe iron ore [41].

5. Conclusion

The present work provide insight into dissolution kinetics, an important aspect when considering industrial applications and environmental behaviour of Itakpe iron ore. The study has shown clearly that the rates increase reasonably at low pH of the solution to allow the ore be useful in applications like steel and environment decontamination among others. A zero-order model as well as the Higuchi model described surface-controlled and diffusion-driven kinetic processes, respectively. These models allow for a quantitative basis in view of optimizing ore use under different chemical conditions. This is nevertheless a limited laboratory study that might not take into consideration specific complexities that occur at the natural field environment. Narrow attention was possible on other kinetic models than zero-order and Higuchi to the detriment of considering other relevant kinetic frameworks. Further research is needed to determine the effectiveness of these results under practical conditions, like field-scale mining or industrial operation. The ore applicability could be further increased by studying it for a broader range of environmental remediation activities, such as heavy metal adsorption and wastewater treatment. Besides this, long-term environmental impacts of mining and ore processing under various different chemical conditions would also extend the concept of sustainable mining.

Data availability

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Acknowledgment

We dearly acknowledge the effort of laboratory technologists of Departments of Chemistry, Federal University, Lokoja and Joseph Sarwuan Tarka University, Makurdi for providing apparatus and support. We are equally grateful to the staff of National Iron Ore Mining Company Limited (NIOMCO), Itakpe for their cooperation.

References

[1] Nigerian Geological Survey Agency, "Nigeria's iron ore reserves", 2020. https://ngsa.gov.ng/wp-content/uploads/2020/06/Iron-Ore.pdf.
[2] O. A. Adekola, "Mineralogy of iron ores in Nigeria", Journal of Mining and Geology **56** (2020) 151. https://nmgs-journal.org/journal/details.php?jn=9.
[3] K. A. Alabi, "Iron ore deposits in Nigeria: an overview", African Journal of Science, Technology, Innovation and Development **12** (2020) 433. http://dx.doi.org/10.1080/20421338.2019.1624008.
[4] A. R. Adeshina & F. A. Olaniyi, "Geochemical evaluation of Itakpe iron ore mine tailings, Itakpe, Nigeria", Journal of Research in Environmental and Earth Sciences **10** (2024) 55. https://dx.doi.org/10.35629/2532-10085571.
[5] J. O. Oke, A. O. Akande & M. I. Aremu, "Exploration and exploitation of iron ore resources in Nigeria", Nigerian Journal of Mining and Geology **56** (2020) 23. https://nmgs-journal.org/journal/details.php?jn=64.
[6] F. B. Fatoye, "Geology and mineral resources of Kogi State, Nigeria", International Journal of Multidisciplinary Sciences and Engineering **9** (2018) 7. https://www.researchgate.net/publication/376263250.
[7] T. O. I. Olatunji, "Mineralogical variations in iron ores", Journal of Environmental and Earth Sciences **12** (2020) 52. http://dx.doi.org/10.1016/j.jseaes.2020.104554.
[8] S. Akande, E. O. Ajaka, O. O. Alabi & T. A. Olatunji, "Effects of varied process parameters on froth flotation efficiency: a case study of Itakpe iron ore", Nigerian Journal of Technology (NIJOTECH) **39** (2020) 807. https://dx.doi.org/10.4314/njt.v39i3.21.
[9] A. A. Arowolo, "Hematite-Magnetite intergrowths in Nigerian iron ores", Minerals Engineering **139** (2020) 105. http://dx.doi.org/10.1016/j.mineng.2019.105865.
[10] B. S. Choi, J. H. Lee & S. H. Kim, "Steelmaking from iron ores: a review", Journal of Cleaner Production **235** (2019) 275. http://dx.doi.org/10.1016/j.jclepro.2019.06.029.
[11] A. A. Tella & N. D. Danjibo, "The environmental impact of mining activities in the local community: a structural equation modelling approach", International Journal of Social Work **11** (2024) 44. https://dx.doi.org/10.5296/ijsw.v11i1.21747.
[12] G. Onyedika, C. Nwoko, A. Oguarah & M. Ogwuegbu, "Comparative kinetics of iron ore dissolution in aqueous HCl-HNO_3 system", Journal of Minerals and Materials Characterization and Engineering **1** (2013) 153. http://dx.doi.org/10.4236/jmmce.2013.14026.
[13] C. A. T. Wong, R. A. Hamzah & L. H. Tan, "Leaching of toxic elements from iron mining", Environmental Pollution **247** (2019) 1025. http://dx.doi.org/10.1016/j.envpol.2018.12.043.
[14] T. A. N. Baker, J. K. Smith & A. L. Martinez, "Acid mine drainage: environmental risks", Journal of Environmental Quality **48** (2019) 793. http://dx.doi.org/10.2134/jeq2018.09.0330.
[15] S. D. B. Ali, M. A. Khan & N. K. Jha, "Sustainable mining practices", Resources Policy **61** (2019) 178. http://dx.doi.org/10.1016/j.resourpol.2018.11.001.
[16] A. A. Temuujin, M. M. Ulziibayar & H. P. Jin, "Factors affecting mineral dissolution rates", Geochimica et Cosmochimica Acta **242** (2018) 232. http://dx.doi.org/10.1016/j.gca.2018.08.015.
[17] Y. Barakat, Y. -J. Cui, N. Mokni, P. Delage & F. Bernier, 'Effects of pH and exposure time to alkaline solutions on the mineralogy of the Opalinus clay from the lower sandy facies of Mont Terri site", Engineering Geology **306** (2022) 106766. https://dx.doi.org/10.1016/j.enggeo.2022.106766.
[18] G. Onyedika, C. Ikpe & A. Nwoko, "Comparative kinetics of iron ore dissolution in aqueous HCl-HNO3 System", Journal of Minerals and Materials Characterization and Engineering **1** (2013) 153. https://dx.doi.org/10.4236/jmmce.2013.14026.
[19] A. O. Oke, S. A. Oni & B. O. Nwankwo, "Modeling of dissolution kinetics of iron ore", Journal of Chemical Engineering and Applications **10** (2019) 39. https://www.researchgate.net/publication/335678901_Modeling_of_Dissolution_Kinetics_of_Iron_Ore.
[20] A. A. Arowolo, "Toxicity of mining activities on agricultural practices", Journal of Environmental Management **237** (2019) 301. http://dx.doi.org/10.1016/j.jenvman.2019.02.097.
[21] P. H. Statham, L. J. F. Kelsey & R. M. Hinton, "Environmental evolution and mineral dissolution", Earth and Planetary Science Letters **470** (2017) 158. http://dx.doi.org/10.1016/j.epsl.2017.04.033.
[22] J. Cama, V. Metz & J. Ganor, "The effect of pH and temperature on kaolinite dissolution rate under acidic conditions", Geochimica et Cosmochimica Acta **66** (2002) 3913. https://dx.doi.org/10.1016/S0016-7037(02)00966-3.
[23] K. I. Ayinla, A. A. Baba, S. Girigisu, O. S. Bamigboye, B. C. Tripathy, A. S. Ibrahim & S. O. Azeez, "Acidic leaching of iron from kaoje goethite ore by hydrochloric acid: kinetics modelling", Nigerian Journal of Technology **39** (2020) 800. http://dx.doi.org/10.4314/njt.v39i3.29.
[24] R. O. Ajemba & O. D. Onukwuli, "Kinetic model for Ukpor clay dissolution in hydrochloric acid solution", Journal of Emerging Trends in Engineering and Applied Sciences **3** (2012) 448. https://hdl.handle.net/10520/EJC137036.
[25] A. U. Itodo, I S. Eneji, B. O. Mnengan & M. A. Tseen, "Chemical characterization and leaching kinetics of metals from iron ores", Academic Journal of Chemistry **4** (2019) 69. http://dx.doi.org/10.32861/ajc.49.69.80.
[26] A. U. Itodo, F. W. Abdulrahman, L. G. Hassan, S. A. Maigandi & H. U. Itodo, "Physicochemical parameters of adsorbents from locally sorted H_3PO_4 and $ZnCl_2$ modified agricultural wastes", New York Science Journal **3** (2010) 17. https://www.researchgate.net/publication/204581247.
[27] A. O. Dada, A. P. Olalekan, A. M. Olatunya & O. Dada, "Langmuir, Freundlich, Temkin and Dubinin–Radushkevich isotherms studies of equilibrium sorption of Zn^2? onto phosphoric acid modified rice husk", Journal of Applied Chemistry **3** (2012) 38. http://dx.doi.org/10.9790/5736-0313845.
[28] K. Ray E. Lawrence, N. Hein & R. Hilary, "Dissolution kinetics of South African coal fly ash and the development of a semi-empirical model to predict dissolution", Chemical Industry and Chemical Engineering Quarterly **21** (2015) 319. http://dx.doi.org/10.2298/CICEQ140423032K.
[29] L. Hussain, D. Ashwini & D. Shirish, "Kinetic modeling and dissolution profiles comparison: an overview", International Journal of Pharmaceutical and Biological Science **4** (2013) 728. https://www.ijpbs.net/details.php?article=2021.
[30] S. A. Chime, G. C. Onunkwo & I. I. Onyishi, "Kinetics and mechanisms of drug release from swellable and non swellable matrices: a review", Research Journal of Pharmaceutical, Biological and Chemical Sciences **4** (2013) 97. https://www.researchgate.net/publication/286596213.
[31] K. O. Boadu, O. F. Joel, D. K. Essumang & B. O. Evbuomwan, "Comparative studies of the physicochemical properties and heavy metals adsorption capacity of chemical activated carbon from palm kernel, coconut and groundnut shells", Journal of Applied Science Environment Management **22** (2018) 1833. http://dx.doi.org/10.4314/jasem.v22i12.15.
[32] A. U. Itodo, L. Egbegbedia, I. S. Eneji & A. Asan, "Iron ore deposit and its tailing impact on the toxic metal level of neighboring agricultural soils", Asian Journal of Environment and Ecology **2** (2017) 1. https://doi.org/10.9734/AJEE/2017/32900.

[33] A. A. Baba, F. A. Adekola & A. O. Folashade, "Quantitative leaching of a Nigerian iron ore in hydrochloric acid", Journal of Applied Science and Environmental Management **9** (2005) 15. http://dx.doi.org/10.4314/jasem.v9i3.17362.
[34] R. H. Khuluk, R. Ali, B. Buhani & S. Suharso, "Removal of methylene blue by adsorption onto activated carbon from coconut shell (Cocous Nucifera L.)", Indonesian Journal of Science and Technology **4** (2019) 229. https://ejournal.upi.edu/index.php/ijost/article/view/18179.
[35] A. Ghosh, A. Nanda & S. Ranjan, "Acidic and basic dissolution of iron ore: effects on surface morphology and kinetics", Minerals Engineering **50** (2013) 43. http://dx.doi.org/10.1016/j.mineng.2013.06.007.
[36] H. Li, Y. Liu & H. Wang, "The effect of alkaline environment on the dissolution of iron ore in aqueous solutions", Hydrometallurgy **147** (2014) 81. http://dx.doi.org/10.1016/j.hydromet.2014.04.003.
[37] S. Samal, "The dissolution of iron in the hydrochloric acid leach of titania slag obtained from plasma melt separation of metalized ilmenite", Chemical Engineering Research and Design **89** (2011) 2190. https://dx.doi.org/10.1016/j.cherd.2011.01.026.
[38] F. Faraji, A. Alizadeh, F. Rashchi & N. Mostoufi, "Kinetics of leaching: a review", Reviews in Chemical Engineering **38** (2020) 113. http://dx.doi.org/10.1515/revce-2019-0073.
[39] J. Siepmann & N. A. Peppas, "Higuchi equation: derivation, applications, use and misuse", International Journal of Pharmaceutics **418** (2011) 6. http://dx.doi.org/10.1016/j.ijpharm.2011.03.051.
[40] K. Huang, K. Inoue, H. Harada & H. Kawakita, "Leaching behavior of heavy metals with hydrochloric acid from fly ash generated in municipal waste incineration plants", Transactions of Nonferrous Metals Society of China **21** (2011) 1422. https://dx.doi.org/10.1016/S1003-6326(11)60876-5.
[41] A. A. Baba, F. A. Adekola, O. I. Dele-Ige & R. B. Bale, "Investigation of dissolution kinetics of a Nigerian tantalite ore in nitric acid", Journal of Minerals & Materials Characterization & Engineering **7** (2007) 83. https://www.researchgate.net/publication/242150835.