

Optimization and Dissolution Kinetics of a Nigerian Monazite Ore Using H₂SO₄

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Abstract

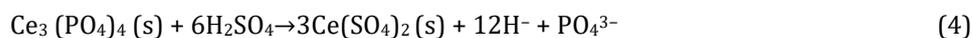
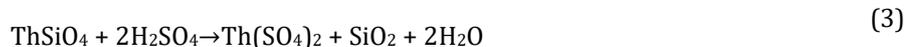
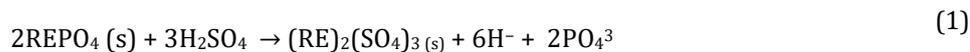
This study presents the optimization and kinetic evaluation of thorium recovery from monazite ore sourced from Plateau State, Nigeria with the use of sulphuric acid as a leaching agent. The study aims to ascertain the optimal conditions for thorium recovery and to understand the kinetics involved in the process. A central composite design (CCD) under response surface methodology (RSM) was utilized to evaluate the effects of acid concentration, reaction temperature and leaching time on thorium extraction. The results showed that the leaching efficiency was significantly impacted by the acid concentration, reaction temperature and the leaching time. The RSM-derived quadratic model predicted optimal conditions for maximum thorium recovery achieved at 3.1M, 196°C, and 237.5 min sulphuric acid concentration, reaction temperature and leaching time respectively to give 79.56% leaching efficiency. The kinetic studies showed that the leaching process followed a shrinking core model with diffusion as the rate controlling step. These findings demonstrate the viability of thorium recovery with sulphuric acid from Nigerian monazite and provide a good basis to scale up the process for nuclear fuel material development.

1. Introduction

Thorium as a naturally occurring radioactive material (NORM) has gained renewed attention by different countries as a potential alternative nuclear fuel due to its abundance, favourable nuclear properties and relative proliferation resistance compared to uranium and plutonium fuels. Thorium-based nuclear systems have been proposed as safer and more sustainable options for future energy generation, particularly with molten salt reactor technologies gaining momentum globally [1-3].

Monazite, a phosphate mineral rich in rare earth elements (REEs), is one of the primary thorium-bearing minerals with minimal uranium in some cases and is typically found in placer deposits. Nigeria, particularly Plateau State is endowed with substantial monazite reserves as part of its extensive mineral resources [4, 5]. Despite the potential for Nigeria, beneficiation technologies are still not well explored in the Country. Recovery of thorium from monazite ore needs effective leaching techniques and these are influenced by combining chemical, thermal and time-dependent parameters. Monazite is widely distributed throughout the world as a minor accessory mineral in intermediate and high-rank metamorphic rocks derived from argillaceous sediments with thorium having the potential to contribute towards a more sustainable nuclear industry, including lower lifecycle emissions and more efficient resource utilization [2-4].

Monazite lattice is made of strong bonds between rare earth elements (REEs) and oxygen and are therefore not soluble in water. The digestion process can be carried out either in acid (like H_2SO_4) or base [6]. In acidic digestion process, the strong bonds are broken down and soluble REEs' sulphates are formed. The following reactions occur during the process [6,7]:



Critical to improving thorium recovery rates while minimizing reagent use and environmental impact is optimization of the leaching process. Previous studies have employed various acids and complexing agents, including sulphuric acid, hydrochloric acid and ammonium hydroxide, under elevated temperature conditions to facilitate the breakdown of monazite matrix [7-9]. Furthermore, kinetic modeling of the leaching process is essential for understanding the reaction mechanisms and identifying rate controlling steps, which can guide scale up and industrial application [10].

In kinetic studies one experimental factor is altered, while other factors are kept constant, to analyze their impact on mineral leaching. Statistical experimental design maximizes variable values to optimize the leaching procedure, allowing simultaneous alteration of experimental parameters [11]. This approach yields valuable insights while minimizing the number of experimental runs, making experimental design a valuable and powerful tool for observing variable interactions [12].

In this study, monazite ore sourced from Plateau State, Nigeria, is used as the material for thorium recovery. The focus of the work is on optimizing the leaching conditions utilizing response surface methodology (RSM) and examining the kinetics of the extraction process with varying acid concentration, temperature and time. In their work Farzaneh et al. [13] used RSM to optimize the leaching of Th, Ce, La and Nd in an Iranian monazite concentrate with leaching efficiency of thorium at 88.94%. The findings in this study will contribute to the development of an efficient and scalable thorium recovery process tailored to Nigerian ore.

2. Materials and Methods

2.1 Materials

The monazite ore was provided by Department of Geology, Ahmadu Bello University, Zaria, Nigeria. The ore was sourced from a deposit in Plateau State, Northern Nigeria. The fraction used for the experiment was 125 μm . Sulphuric acid with purity of 95% (Sigma-Aldrich) was used for the digestion, while deionized water was used for the preparation of the different acid concentrations.

2.2 Methods

2.2.1 Isotopic Neutron Activation Analysis of Thorium in Monazite

An Americium-Beryllium (Am-Be) neutron source was utilized for the quantification of thorium in the monazite. In order to validate the method, $\text{Th}(\text{NO}_3)_4 \cdot 5\text{H}_2\text{O}$ (British Drug House, BDH) was used as standard and exposed to the neutron source for 72 hours in the Am-Be neutron source set up. Radioactivity measurement of the induced thorium as a radionuclide was performed by the PC-based gamma-ray spectrometry set up which consists of a horizontal dip-stick High Purity Germanium (HPGe) detector and the MAESTRO acquisition software compatible with the ADCAM^(R) multichannel analyzer (MCA) card, and associated electronic modules [14].

2.3 Experimental Design

To investigate the effects of process parameters on thorium recovery from monazite ore, a Central Composite Design (CCD) was employed as part of a Response Surface Methodology (RSM). For its efficiency in fitting a second order (quadratic) model, CCD was chosen. It facilitates the exploration of linear, interaction and quadratic effects of the selected variables on the response. Three independent variables were considered which included: acid concentration (X_1), reaction temperature (X_2) and leaching time (X_3). Each factor was studied at five levels: $-\alpha$, -1 , 0 , $+1$ and $+\alpha$ in order to ensure rotatability of the design. Table 1 presents the experimental template showing the actual (un-coded) values corresponding to each coded level [15]. This experimental design made it possible for

the development of a predictive model for thorium recovery, giving account for both individual and interactive effects of the parameters. The Centre points (coded as 0) were replicated to estimate experimental error and assess model adequacy.

Table 1 Experimental template for un-coded factor levels

Process parameters	Acronym	Units	Factor level range				
			$-\alpha$	-1	0	+1	$+\alpha$
Acid Concentration	(X ₁) (A)	M	0.6251	2.5	5.25	8	9.87
Reaction Temperature	(X ₂) (B)	°C	126.14	150	185	220	243.86
Leaching Time	(X ₃) (C)	Min	38.87	90	165	240	291.13

The factorial points -1 and +1 represent the low and high levels of the variables as established from literature, while 0 is the centre point or the average of the low and high values. $-\alpha$ and $+\alpha$ are extensions by RSM beyond the factorial design to estimate curvature (quadratic effects).

2.4 RSM – Statistical Analysis Modeling

The data from the leaching experiment was analyzed statistically using Response Surface Methodology (RSM). The correlation between the response – Leaching Efficiency and the process parameters – acid concentration, reaction temperature and leaching time was established using regression modeling. A model equation was generated to show how the experimental data impacted the response. Analysis of Variance (ANOVA) was applied to establish the model's extent of fitness by making use of p-values to pinpoint the variables' significance on the system and fisher value to identify the quantum of influence of process parameters on the response [15,16].

2.5 Kinetic Studies

5g of monazite ore (125 μ m) was weighed and transferred into a 500ml beaker, followed by the addition of 100ml of acid (H₂SO₄) of 3.10 M (optimum) concentration and placed on a hot plate with magnetic stirrer at a set temperature of 196°C (optimum) and stirring speed of 200rpm. The reaction was monitored with samples taken at intervals of 30 min, 60 min, 90 min, 120 min and 150 min. The samples were filtered in a filtration unit coupled to a vacuum pump. Each precipitate on filter was allowed to dry at room temperature for 3 days and thereafter were taken for thorium content analysis via the Am-Be neutron source and with neutron activation analysis (NAA) the concentration of thorium that reacted (denoted as α) was determined as the reaction progressed at different time intervals.

The equations for three shrinking core models that the leaching results were subjected to are as in equations 5-7 [16-18].

$$1 - (1 - \alpha)^{2/3} = Kct \text{ for chemically controlled process} \quad (5)$$

$$1 - \frac{2}{3}\alpha - (1 - \alpha)^{2/3} = Kpt \text{ for diffusion controlled process} \quad (6)$$

$$1 - \frac{2}{3}\alpha - (1 - \alpha)^{2/3} + \frac{1}{6}(1 - \alpha)^{1/3} + 1 - 2(1 - \alpha)^{2/3} = Kmt \text{ for mixed process} \quad (7)$$

Here, α is the fraction of thorium that reacted and it was determined by subtracting the concentration of thorium in the precipitate on filter from the initial concentration of the thorium in the ore (4.68%), t is the time of the reaction (min).

The various plots necessary were plotted: $\ln C_{(t)}$ against time (min) – for 1st order reaction, $1 - (1 - \alpha)^{2/3}$ against time (min) – for chemically controlled process, $1 - \frac{2}{3}\alpha - (1 - \alpha)^{2/3}$ against time (min) – for diffusion controlled process and $1 - \frac{2}{3}\alpha - (1 - \alpha)^{2/3} + \frac{1}{6}(1 - \alpha)^{1/3} + 1 - 2(1 - \alpha)^{2/3}$ against time (min.) – for mixed controlled process.

The temperature of the reaction was also varied with acid concentration and reaction time kept constant to determine the rate constant and the activation energy (E_a) was determined with the use of Arrhenius equation in its linear form,

$$\ln k = -Ea \frac{1}{T} + \ln A \tag{7}$$

Where, *k* is the rate constant (frequency of collisions resulting in a reaction) [16].

3. Results and Discussion

3.1 Am-Be Source Neutron Activation Analysis

The quantification of thorium in the monazite ore was carried out using Isotopic (Am-Be) neutron activation analysis which gave 4.68% thorium. This procedure was preceded by validating the method and measuring thorium in the compound Th(NO₃)₄.5H₂O as an unknown sample. Table 2 shows the result as actual concentration vs. measured concentration and it compares well. This comparison validates the method as suitable for thorium determination. The concentration of thorium in the monazite ore was measured as 4.68% in this work and it is higher than in a work which reported thorium concentration at 2.15% in a monazite ore from Malasia [10] and 2.75% thorium was reported for the work done on monazite from South Dakota, USA [19]. The high concentration of thorium as a rare earth element in the studied ore is indicative of its high grade, bearing in mind its nuclear energy potential. Monazite from granitic or pegmatic sources as the case in Nigeria often contain high thorium compared to in placer deposits as in Malaysia and USA [22]. Although, high thorium concentration can heighten radiological concern protective measures can be taken to avoid exposure to undue radioactivity.

Table 2 Actual vs. measured thorium concentration in Th(NO₃)₄.5H₂O using isotopic (Am-Be) neutron activation analysis

Actual Concentration	Measured Concentration
48.33 (%)	48.77 (%)

3.2 Statistical Optimization Using Response Surface Methodology

A Central Composite Design under Response Surface Methodology (RSM) was implemented to optimize thorium leaching. The model fitting gave a quadratic response surface. The analysis of variance (ANOVA) (table 4) showed the model as significant with p-value of 0.001 (p<0.05) and table 3 shows the fit statistics with R² value of 0.9757 indicating that 97.57% of the variability in the response is explained by the model. The adjusted R² (0.9538) and predicted R² (0.8658) are reasonably in agreement showing that the model is statistically sound and has predictive capabilities.

In addition, with adequate precision value at 22.45, far more than the minimum threshold of 4.0 confirms a strong signal-to-noise ratio, demonstrating that the model can be reliably deployed to explore and carryout optimization of the response. A good regression model requires not more than a difference of ±0.2 between predicted and R² values with a signal-to-noise ratio greater than 4 [16].

Table 3 Fit statistics

Parameter	Value
Std. Dev.	2.92
Mean	77.50
C.V. %	3.76
R ²	0.9757
Adjusted R ²	0.9538
Predicted R ²	0.8658
Adeq Precision	22.4507

From the presentation in table 4, among the linear terms: acid concentration (A), temperature (B) and time (C) has significant effects on leaching efficiency of the thorium from monazite ore. Concentration had the highest influence with an F-value of 139.79 and p< 0.0001, followed by temperature and time with equal F-values of 66.66 and p< 0.0001. These results confirm that acid concentration, reaction temperature and leaching time individually play critical roles in the leaching process. However, the interaction terms AB, BC and AC are statistically insignificant (p value >0.05). This indicates that the combined effects of any two variables are not greater than the sum of their individual effects, and response surface is not strongly influenced by interaction between variables.

The quadratic terms A^2 , B^2 and C^2 are all statistically significant, confirming the presence of curvature in the response surface. This validates the use of a quadratic model, as the relationship between the factors and leaching efficiency are not linear. The lack of fit test showed a p-value of 0.2432, which is not significant. This suggests that the model does not suffer from poor fit and can reliably be used for prediction.

Table 4 ANOVA for quadratic model for Response 1: Leaching

Source	Sum of Squares	df	Mean Square	F-value	p-value	Remark
Model	3413.53	9	379.28	44.54	< 0.0001	significant
A-Conc	1190.32	1	1190.32	139.79	< 0.0001	
B-Temp	567.62	1	567.62	66.66	< 0.0001	
C-Time	567.62	1	567.62	66.66	< 0.0001	
AB	4.50	1	4.50	0.5285	0.4839	
AC	0.5000	1	0.5000	0.0587	0.8134	
BC	8.00	1	8.00	0.9395	0.3553	
A^2	988.28	1	988.28	116.07	< 0.0001	
B^2	99.25	1	99.25	11.66	0.0066	
C^2	99.25	1	99.25	11.66	0.0066	
Residual	85.15	10	8.51			
Lack of Fit	56.13	5	11.23	1.93	0.2432	Not significant
Pure Error	29.01	5	5.80			
Cor Total	3498.68	19				

From Table 5 which is a display of coefficients in terms of coded factors, the final equation is response (Y) = $86.74 + 9.34A + 6.45B + 6.45C - 0.75AB + 0.25AC - 1BC - 8.28A^2 - 2.62B^2 - 2.62C^2$. This equation can be used to predict the response (Y) at any combination of A, B and C within the experimental range and also understand the relationship between variables with the response as well as optimize the process by identifying the best values of A, B and C for maximum or minimum efficiency.

Table 5 Coefficients in terms of coded factors

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	86.74	1	1.19	84.09	89.39	
A-Conc	9.34	1	0.7896	7.58	11.10	1.0000
B-Temp	6.45	1	0.7896	4.69	8.21	1.0000
C-Time	6.45	1	0.7896	4.69	8.21	1.0000
AB	-0.7500	1	1.03	-3.05	1.55	1.0000
AC	0.2500	1	1.03	-2.05	2.55	1.0000
BC	-1.0000	1	1.03	-3.30	1.30	1.0000
A^2	-8.28	1	0.7687	-9.99	-6.57	1.02
B^2	-2.62	1	0.7687	-4.34	-0.9116	1.02
C^2	-2.62	1	0.7687	-4.34	-0.9116	1.02

3.3 Effect of Process Parameters on Thorium Dissolution

With increasing acid concentration, the leaching efficiency was generally enhanced. This is explained by the fact that at lower concentrations, the limited availability of protons may hinder the breakdown of the phosphate matrix [19]. As the acid concentration increases from 2.5 M to about 5.5 M, the leaching efficiency also increases significantly. Beyond 5.5 M the leaching efficiency appears to peak or decline slightly, showing diminishing returns at very high concentration. Also, the results show that leaching improves with increasing temperature as it enhances reaction kinetics, reduces viscosity and improves mass transfer. However, the curve flattens beyond a temperature range of 200°C suggesting an optimal temperature for maximum recovery. As for the effect of time, it shows a nonlinear effect. While longer time is initially desirable, too long a time may lead to side reactions, re-precipitation or equilibrium, thereby reducing efficiency.

Fig. 1 to Fig. 3 are response surface plots illustrating the interactive effects of sulphuric acid concentration, temperature and leaching time.

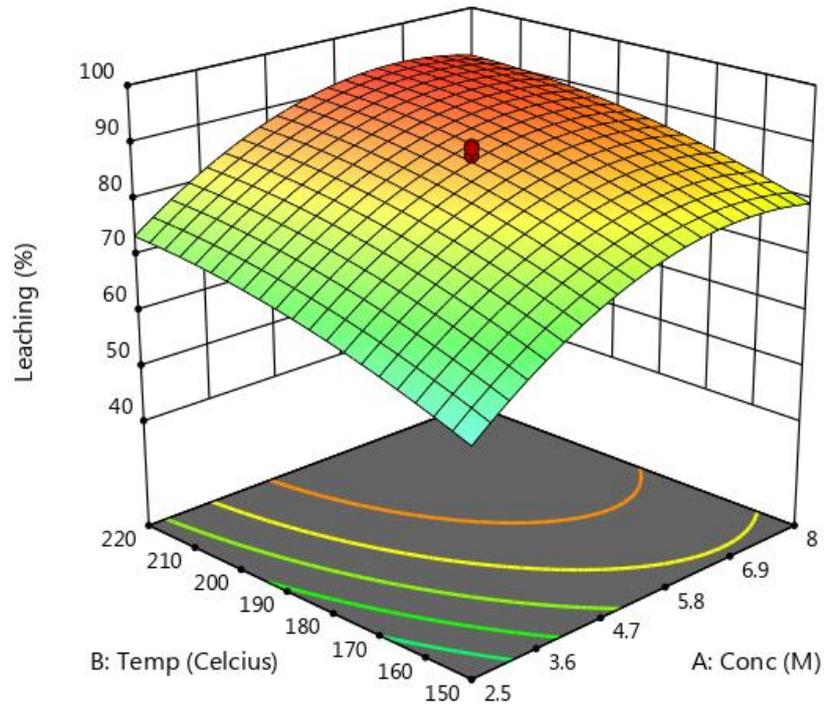


Fig. 1 Response surface plot showing the interaction between acid concentration and temperature on Th recovery

Fig 1 is useful in identifying the optimal combination of acid concentration and temperature to maximize thorium extraction from the ore. It suggests that both factors positively influence leaching efficiency to a point, beyond which the combined effects wane or slightly decrease.

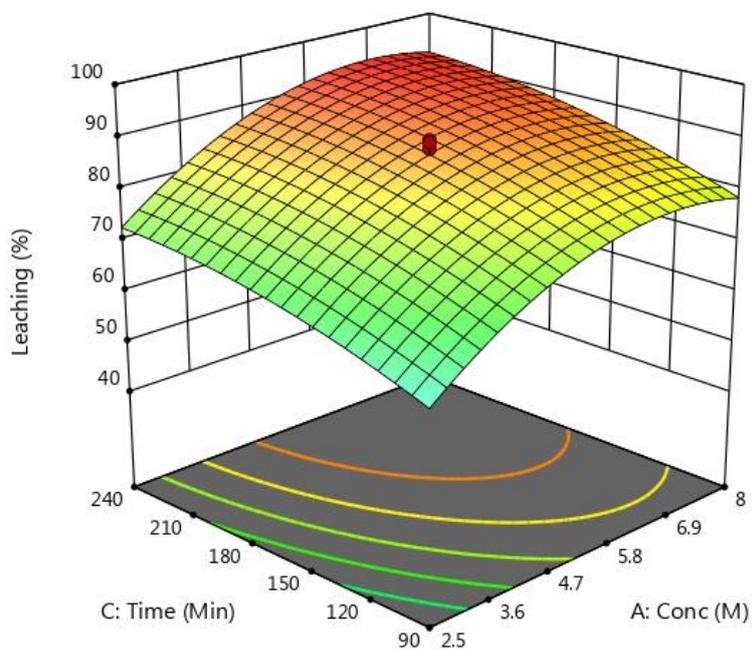


Fig. 2 Response surface plot showing the interaction between acid concentration and leaching time on Th recovery

Fig 2 shows that the surface is curved and rises towards the centre and right-hand side, suggesting a synergistic effect between acid concentration and time. As both acid concentration and leaching time increase, the leaching percentage increases as well, approaching a peak around the centre of the plot. In effect, to maximize thorium recovery, one should operate within the region of higher acid concentration and longer leaching time, though economic consideration may define the limit.

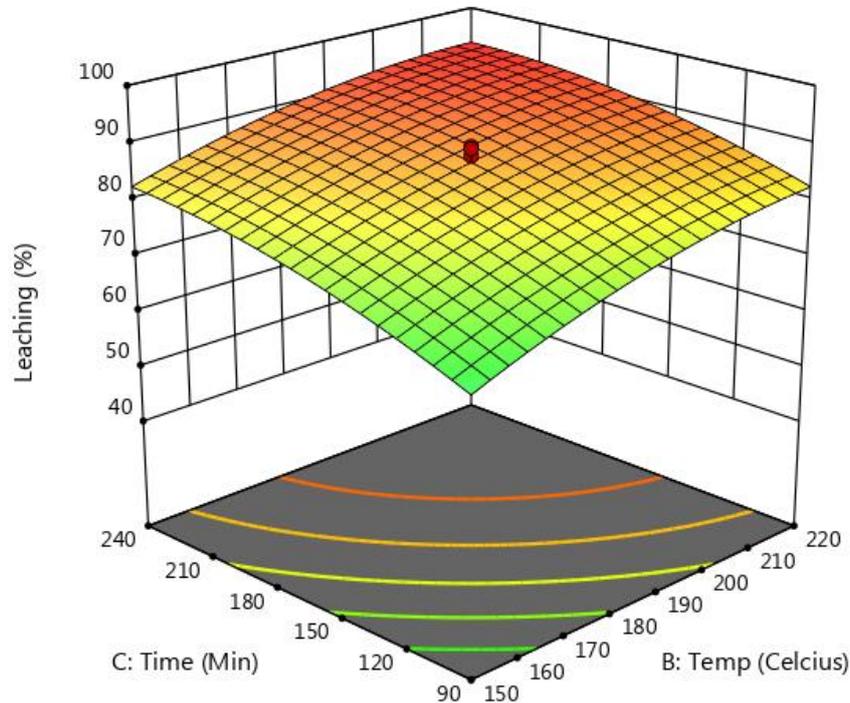


Fig. 3 Response surface plot showing the interaction between temperature and time on Th recovery

Fig. 3 shows that the surface rises with increasing temperature and time, suggesting that higher temperature and longer leaching time increase the percentage of thorium leached from the ore.

3.4 Optimization of Leaching Conditions

The RSM-derived quadratic model predicted optimal conditions for maximum thorium recovery achieved at 3.1M, 196°C, and 237.5 min acid concentration, reaction temperature and leaching time respectively to give 79.56% leaching efficiency. The optimization of leaching conditions involves determining the most effective combination of process variables – acid concentration, temperature and leaching time for maximizing thorium recovery. RSM has previously been applied for thorium leaching studies [13]. Farzaneh *et al* reported optimal results at temperature 225 °C, a leaching time of 210 min with sulphuric acid to concentrate ratio (L/S) of 2.5 to get 88.94% thorium recovery [13]. The thorium recovery was higher in their work and this may be due to a higher temperature (225 °C) compared to a lower temperature (196 °C) in the present work. While the acid concentration determines proton availability for the digestion, L/S ratio tells the quantity of acid adequate for the reaction, A compromise between the parameters is usually necessary to arrive at optimum conditions, considering cost (acid, energy and time).

3.5 Kinetic Study of Thorium Dissolution

In order to understand the mechanism of leaching, kinetic data were obtained at the predicted optimum conditions and evaluated using shrinking core models. The dissolution followed 1st order kinetics with R² value at 0.9291 and a rate constant (k) of 0.0128 min⁻¹. The best fit was observed for the diffusion controlled model $1 - \frac{2}{3}\alpha - (1 - \alpha)^{2/3}$ with R² value of 0.9145 where α is the fraction of thorium that reacted. The activation energy was determined using the Arrhenius equation and a linear plot of ln k against T⁻¹ (R² value = 0.9236) yielded activation energy of 8.74kJ mol⁻¹ indicative of a diffusion controlled process because of the fact that activation energy of less than 40 kJ mol⁻¹ are generally considered as a diffusion controlled process [15,16].

4. Conclusion

In conclusion, the results demonstrate that sulphuric acid as a leaching agent is effective for thorium recovery from monazite ore. Process optimization with response surface methodology (RSM) helped in the identification of key parameters for maximum thorium recovery. The kinetic data showed that the leaching is governed by a mechanism that is diffusion controlled as supported by low activation energy of $8.75 \text{ KJ mol}^{-1} \cdot \text{K}^{-1}$. These findings are important for the hydrometallurgical processing of rare earth ores, especially in the recovery of thorium as a valuable product for the nuclear industry. In addition, the statistical and kinetic models developed provide a foundation for scaling up for the metallurgical industry.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

Designing and executing the experiments: Okoh S; **overall supervision and guidance throughout the project:** K. I Omoniyi; **analysis of the result findings:** E. D Paul and V. O Ajibola.

References

- [1] Khanramaki, F., & Keshtkar, A. R. (2024). Optimization of thorium solvent extraction process from feed solution with Cyanex 272 by response surface methodology (RSM). *Scientific Reports*, 14(1), 15131. <https://doi.org/10.1038/s41598-024-66091-0>
- [2] Jyothi, R. K., De Melo, L. G. T. C., Santos, R. M., & Yoon, H. S. (2023). An overview of thorium as a prospective natural resource for future energy. *Frontiers in Energy Research*, 11, 1132611. <https://doi.org/10.3389/fenrg.2023.1132611>
- [3] Kang, Z and He, X (2016). Thorium-based nuclear fuel cycle - A review. *Progress in Nuclear Energy*, 85, 36-52
- [4] Indryati, S., Hidayat, A. E., Pratama, A. A., Laksamana, R. I., Widana, K. S., Ramlan, M. A., ... & Rommy, R. (2023). Analytical method validation of thorium in ore sample using UV-Vis spectrophotometer. *Eksplorium*, 44(2), 75-80. <https://doi.org/10.55981/eksplorium.2023.6965>
- [5] Gupta, C.K, 1990 Hydrometallurgy in Extraction Processes, Wiley-VCH
- [6] Habashi, F. (1997). Handbook of Extractive Metallurgy. Wiley-VCH
- [7] Gupta, C. K., & Krishnamurthy, N. (1992). Extractive metallurgy of rare earths. *International materials reviews*, 37(1), 197-248.
- [8] Shrivastava, A., and Prasad, R. (2019). Kinetic and thermodynamic modeling of rare earth leaching from monazite using hydrochloric acid.
- [9] Al-Areqi, W. M., Bahri, C. N. A. C. Z., Majid, A. A., & Sarmani, S. (2017). Solvent extraction of thorium from rare earth elements in monazite thorium concentrate. *Malaysian Journal of Analytical Sciences*, 21(6), 1250-1256. <https://doi.org/10.17576/mjas-2017-2106-06>
- [10] Karacahan, M. K. (2024). Optimization and kinetic study of manganese leaching from pyrolusite Ore in hydrochloric acid solutions with oxalic acid. *Journal of Sustainable Metallurgy*, 10(3), 1717-1732. <https://doi.org/10.1007/s40831-024-00869-4>
- [11] Sadri, F., Rashchi, F., & Amini, A. (2017). Hydrometallurgical digestion and leaching of Iranian monazite concentrate containing rare earth elements Th, Ce, La and Nd. *International Journal of Mineral Processing*, 159, 7-15. <https://doi.org/10.1016/j.apradiso.2006.01.012>
- [12] Jonah, S. A., Umar, I. M., Oladipo, M. O. A., Balogun, G. I., & Adeyemo, D. J. (2006). Standardization of NIRR-1 irradiation and counting facilities for instrumental neutron activation analysis. *Applied Radiation and Isotopes*, 64(7), 818-822.
- [13] Uba, S., Elebo, A., Ekwumemgbo, P. A., & Ajibola, V. O. (2024). Application of CCD-RSM Strategy to Forecast Corrosion Inhibition of Expired Erythromycin on Mild Steel in Diverse Optimized HCl Concentration. *Records of Chemical Sciences*, 3(1), 16-22. <https://doi.org/10.33003/frscs-2024-0301/03>

- [14] Baba, A. A., & Adekola, F. A. (2011). Dissolution kinetics and Zinc (II) recovery from spent automobile tyres by solvent extraction with cyanex? 272. *World Review of Science, Technology and Sustainable Development*, 8(2-4), 182-195. <https://doi.org/10.1504/WRSTSD.2011.044215>
- [15] Chindo, S. Y., Omoniyi, K. I., & Raji, M. A. (2022). Chalcopyrite leaching in ammonia-ammonium chloride solutions: insight into the dissolution kinetic studies. *Journal of Sustainable Materials Processing and Management*, 2(2), 90-97. <https://doi.org/10.30880/jsmpm.2022.02.02.011>
- [16] Mukhtar, M., Omoniyi, K. I., & Abdullah, F. (2025). Leaching Parameters Optimization and Kinetic Studies for Leaching of Copper from Zarara Hill Sulphide Ore in HCl, H₂SO₄ and HNO₃ Solutions. *Journal of Science Innovation and Technology Research*. <https://doi.org/10.70382/ajsitr.v7i9.017>
- [17] Galvin, J., & Safarzadeh, M. S. (2018). Decomposition of monazite concentrate in potassium hydroxide solution. *Journal of environmental chemical engineering*, 6(1), 1353-1363. <https://doi.org/10.1016/j.jece.2018.01.042>
- [18] Demchenko, A. P. (2023). Proton transfer reactions: from photochemistry to biochemistry and bioenergetics. *BBA advances*, 3, 100085. <https://doi.org/10.1016/j.bbadv.2023.100085>
- [19] Alfakeer, M., Abdallah, M., & Fawzy, A. (2020). Corrosion inhibition effect of expired ampicillin and flucloxacillin drugs for mild steel in aqueous acidic medium. *International Journal of Electrochemical Science*, 15(4), 3283-3297. <https://doi.org/10.20964/2020.04.09>
- [20] René, M., & Akitsu, T. (2017). Nature, sources, resources, and production of thorium (pp. 201-212). London: IntechOpen.