

Open-System Predictive Assessment of Lead Extraction Rate during Biooxidation of Galena by *Acidithiobacillus Ferrooxidans* (ATF)

C. I. Nwoye^{*1}, J. U. Odo¹, S. O. Nwakpa¹ and O. O. Onyemaobi²

¹ Department of Metallurgical and Materials Engineering, Nnamdi Azikiwe University, Awka, Nigeria.

² Department of Materials and Metallurgical Engineering, Federal University of Technology, Owerri, Nigeria.

Corresponding author: chikeyn@yahoo.com ; 0806 8006 092

Abstract

Open-system predictive assessment of lead extraction rate during biooxidation of galena by *acidithiobacillus ferrooxidans* (ATF) has been carried out based on the leaching time and final pH of leaching solution using a derived model. The model;

$$\gamma = -0.0176 (\ln t + \ln \alpha) + 0.135$$

indicates an logarithmic relationship between lead extraction rate and combined input of time and pH. Results were predicted using regression model (standard model) and then plotted along side with results from the experiment and derived model to compare their respective spread and trend so as to establish the degree of validity of the derived model. The standard errors incurred in predicting lead extraction rate for each value of the leaching time and final leaching solution pH considered, as obtained from derived model and experiments are 5.15×10^{-4} and 4.66×10^{-4} % as well as 1.26×10^{-3} and 1.54×10^{-3} % respectively. The correlations between lead extraction rate and leaching time as obtained from derived model and experimental results were evaluated to be same (0.9959), and between lead extraction rate and final pH of leaching solution 0.9596 and 0.9749 respectively. The concentration of lead extracted within a leaching time interval 210-490 hrs as obtained from derived model and experiment are 3.136 and 3.108 g/dm³ respectively. Deviation analysis indicates that the maximum deviation of the model-predicted lead extraction rate from the corresponding experimental value is less than 10%. It was also found that the validity of the model is rooted on the core expression $7.4074 \gamma = -0.1304 (\ln t + \ln \alpha) + 1$ where both sides of the expression are correspondingly approximately equal.

Keywords: Open-System, Prediction, Lead Extraction Rate, Biooxidation, *Acidithiobacillus Ferrooxidans*.

1. Introduction

About two decades ago, the application of bioleaching to the treatment of refractory gold deposits has been of great interest to mining companies all over the world. The majority of the gold in these deposits is locked up in a sulphide matrix within the ore, and provides for very poor gold recoveries unless the sulphide minerals are removed first.

The pyrite and arsenopyrite minerals are basically the two most common sulphides associated with these refractory gold ore. In the past, the treatment method used involves first making a sulphide concentrate that contains the gold and then roasting this concentrate at a high temperature to drive off the sulphides as gases. This is then followed by recovery of the gold from the residue that is left behind.

Roasting of these sulphides has since become increasingly unacceptable due to the accompanying production of sulphurous gases which are very harmful to the environment.

On the other hand, bioleaching is environmental friendly and an alternative technique to roasting in that gaseous emission is not created.

Results of study [1] on the factors affecting bioleaching kinetics of sulphide ores using acidophilic microorganisms revealed that the major draw back in the process is the slow kinetics of dissolution of metal valuables from the sulphide ores. The research work also highlighted various factors which determine the overall kinetics as including: bacterial activity and concentration, iron and sulphur oxidation, oxygen consumption, reactor design and nature of ore.

Acidithiobacillus ferrooxidans is an aerobic microorganism that uses oxygen as a final electron acceptor during the oxidation process. However, in absence of oxygen, it is still able to grow in the presence of inorganic reduced sulphur compounds by using the ferric ion as an alternative electron acceptor [2]. In this condition however, its growth is slower [3].

Reduction in the bioleaching rate has been deduced [4] to result from presence of high concentrations of solids which initiates an increase in the friction between particles, and probably avoiding the adhesion between the particles and bacteria. This friction has been reported [5] to be capable of causing mechanical damage to the cell.

Successful attempts have been made [6] to model data generated from bioleaching process using regression analysis [6]. The work shows time (days), used as the only independent variable, and so data collected fits in as a third order polynomial regression model. The resulted general equation of the model shows (Minitab 13.0):

$$\text{Arsenic} = 23.888. - 1.0597 \text{ Days} + 0.5161 \text{ Days}^2 - 0.0131 \text{ Days}^3 \quad (1)$$

Equation (1) resembles the general three phase bacterial growth model. The determination coefficient evaluated from results generated by the model was 0.3237, which represents a value relatively low due to absence of other significant factors such as particle size, pulp density, air injection, 9K medium, CO₂, and ferric chloride added.

Orthogonality permits the comparison between low and high levels for each factor affecting bioleaching in their ability to dissolve the metal. In the research work [6], the low level was taking as 0 and the high level as 1. Furthermore, time (days) was also included as the only quantitative factor, hence expanding the model to:

$$\begin{aligned} \text{Arsenic} = & \beta_0 + \beta_1 \text{ Pulp Density} + \beta_2 \text{ Surface Area} + \beta_3 \text{ Ferric Chloride} + \beta_4 \\ \text{Carbon} & \text{ Dioxide} + \beta_5 \text{ Air} + \beta_6 \text{ 9 K Medium} + \beta_7 \text{ Strains} + \beta_8 \text{ Days} \end{aligned} \quad (2)$$

Where

$$\beta_0, \beta_1, \dots, \beta_8 = \text{Regression coefficients}$$

Based on the foregoing, on analyzing the experiment [6] as time series (time as independent variable) by multiple regression, it fits the third order polynomial model.

$$\text{Arsenic} = \beta_0 + \beta_1 t + \beta_2 t^2 + \beta_3 t^3 \quad (3)$$

Where

t = Time in days of bioleaching

$\beta_0, \beta_1, \beta_2, \beta_3$ = Regression coefficient.

The aim of this work is to formulate a model for open-system predictive assessment of lead extraction rate based on the leaching time and final pH of leaching solution during biooxidation of galena by acidithiobacillus ferrooxidans.

2. Materials and methods

Weighed quantities of galena concentrate were placed in conical flasks containing prepared bioleaching solutions of different molarities and pH values. Details of the experimental procedure and associated process conditions are as stated in the past report [7].

3.1 Model formulation

Experimental data obtained from research work [7] were used for this work. Computational analysis of the experimental data [7] shown in Table 1, gave rise to Table 2 which indicate that;

$$K \gamma \approx -N \ln t - N \ln \alpha + 1 \quad (4)$$

Introducing the values of N and K into equation (4) reduces it to;

$$7.4074 \gamma = -0.1304 \ln t - 0.1304 \ln \alpha + 1 \quad (5)$$

$$7.4074 \gamma = -0.1304 (\ln t + \ln \alpha) + 1 \quad (6)$$

$$\gamma = \left(\frac{-0.1304 (\ln t + \ln \alpha) + 1}{7.4074} \right) \quad (7)$$

$$\gamma = -0.0176 (\ln t + \ln \alpha) + 0.135 \quad (8)$$

Where

(γ) = Lead extraction rate ($\text{g/dm}^3 \text{ hr}^{-1}$)

(α) = Final pH of leaching solution

(t) = Leaching time (hrs)

$K = 7.4074$; Overall microbe- substrate interaction factor (determined using C-NIKBRAN [8])

$N = 0.1304$; Lead precipitation constant (determined using C-NIKBRAN [8])

Table 1: Variation of lead extraction rate with leaching time and final pH of leaching solution [7]

(t)	(α)	(γ)
210	3.48	0.0195
280	3.12	0.0157
350	3.02	0.0137
420	2.87	0.0105
490	2.83	0.0084

4. Boundary and Initial Condition

Galena was placed in conical flasks 30 cm high containing bioleaching solution. The leaching solution is non flowing (stationary). Before the start of the leaching process, the flask was assumed to be initially free of attached unwanted bacteria and other micro organism. The effect of oxygen on the process was assumed to be atmospheric since it is an open system process. In all cases, weight of galena used was 60g. The range of the final pH of leaching solutions and leaching times: 2.83-3.48 and 210-490 hrs respectively were used. A constant leaching temperature of 25°C and average ore grain size of 150µm were also used. Details of the experimental technique and other process conditions are as presented in the report [7].

The leaching process boundary conditions include: atmospheric levels of oxygen (considering that the flasks was open at the top) at both the top and bottom of the ore particles in the gas and liquid phases respectively. A zero gradient was assumed for the liquid scalar at the bottom of the particles and for the gas phase at the top of the particles. The sides of the particles were assumed to be symmetries.

5. Results and Discussion

The derived model is equation (8). The computational analysis of Table 1 gave rise to Table 2

Table 2: Variation of 7.4074γ with $-0.1304 (\ln t + \ln \alpha) + 1$

7.4074γ	$(\ln t + \ln \alpha)$	$-0.1304 (\ln t + \ln \alpha)$	$-0.1304 (\ln t + \ln \alpha) + 1$
0.1444	6.5941	-0.8599	0.1401
0.1163	6.7726	-0.8831	0.1169
0.1015	6.9632	-0.9080	0.0920
0.0778	7.0946	-0.9251	0.0749
0.0622	7.2347	-0.9434	0.0566

5.1 Model validation

The validity of the model is strongly rooted on equation (6) where both sides of the equation are correspondingly approximately equal. Table 2 also agrees with equation (6) following the values of 7.4074γ and $-0.1304 (\ln t + \ln \alpha) + 1$ evaluated from the experimental results in Table 1. Furthermore, the derived model was validated by comparing the concentration of extracted lead predicted by the model and that obtained from the experiment [7]. This was done using various analytical techniques.

Computational Analysis

Computational analysis of the experimental and model-predicted concentration of extracted lead was carried out to ascertain the degree of validity of the derived model. This was done by comparing the concentration of extracted lead obtained by calculations involving experimental results with the model-predicted results.

Concentration of extracted lead C_L (g/dm³) was calculated from the equation;

$$C_L = \Delta \gamma \times \Delta t \quad (9)$$

Equation (9) is detailed as

$$C_L = \gamma_2 - \gamma_1 \times t_2 - t_1 \quad (10)$$

Where

$\Delta\gamma$ = Change in the lead extraction rates γ_2, γ_1 within a range of leaching time: $t_1 - t_2$.

Δt = Change in the leaching times t_2, t_1 .

Therefore, a plot of lead extraction rate against leaching time as in Fig. 1 using experimental results in Table 1, and substitution of points (210, 0.0195) and (490, 0.0084) for (t_1, γ_1) and (t_2, γ_2) respectively into the mathematical expression in equation (10) gives - 3.108 g/dm³ as the concentration of extracted lead during the actual experimental bioleaching process.

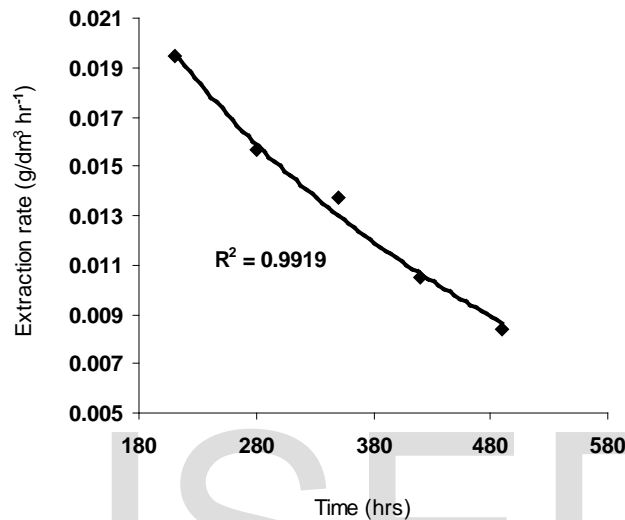


Fig. 1: Coefficient of determination between extraction rate and leaching time as obtained from the experiment [7].

Similarly, a plot of lead extraction rate against leaching time as in Fig. 2 using model-predicted results, and substitution of points (210, 0.0189) and (490, 0.0077) for (t_1, γ_1) and (t_2, γ_2) respectively into the mathematical expression in equation (10) gives - 3.136 g/dm³ as the model-predicted concentration of extracted lead. These concentrations of extracted lead evaluated from experiment and derived model indicate proximate agreement and hence validity of the model. The negative signs preceding the magnitudes of the extraction rate do not indicate that the extraction rate is negative, but that it decreases with increase in leaching time.

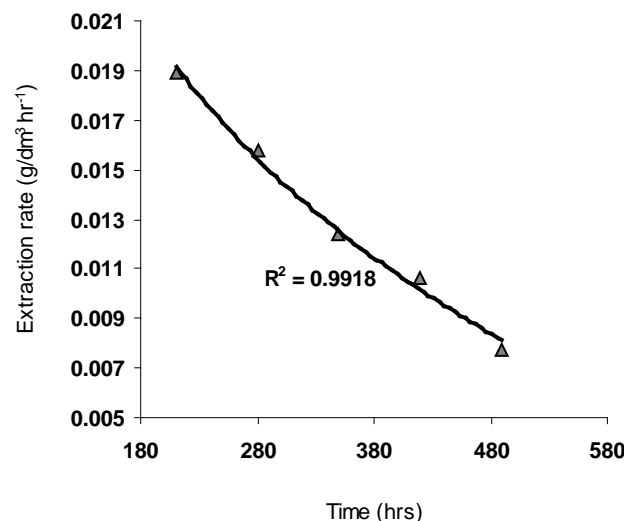


Fig. 2: Coefficient of determination between extraction rate and leaching time as predicted by model

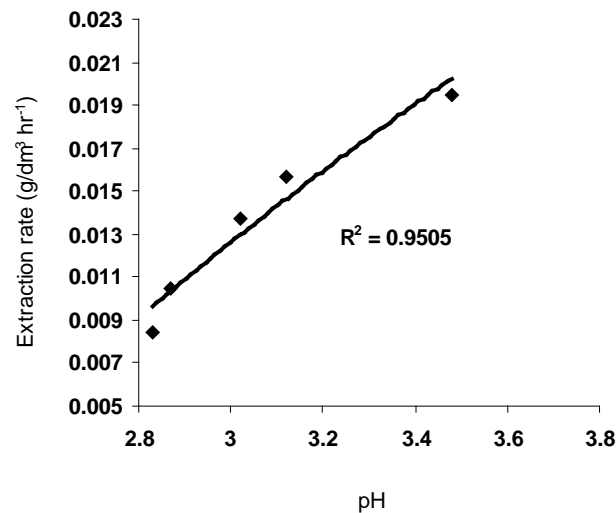


Fig. 3: Coefficient of determination between extraction rate and pH as obtained from the experiment [7].

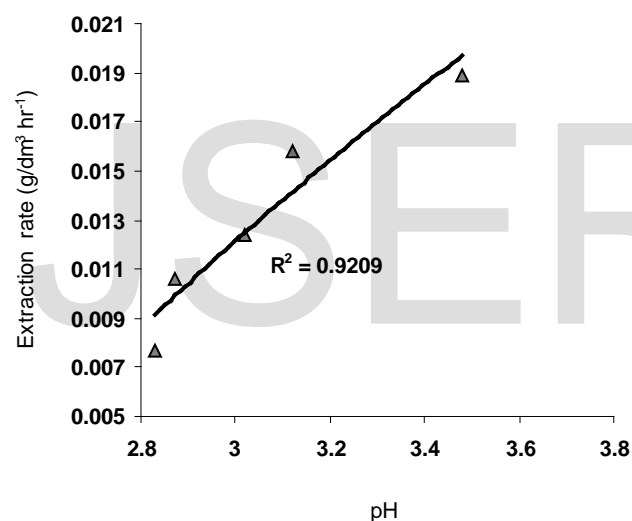


Fig. 4: Coefficient of determination between lead extracted rate and final pH of leaching solution as predicted by model

Statistical Analysis

The standard errors (STEYX) incurred in predicting lead extraction rate for each value of the leaching time and final leaching solution pH considered, as obtained from derived model and experiments are 5.15×10^{-4} and 4.66×10^{-4} % as well as 1.26×10^{-3} and 1.54×10^{-3} % respectively. The standard error was evaluated using [7].

The correlations between lead extraction rate and leaching time as well as lead extraction rate and final pH of leaching solution as obtained from derived model and experimental results [7] were calculated. This was done by considering the coefficients of determination R^2 from Figs. 1-4, using the equation;

$$R = \sqrt{R^2} \quad (11)$$

The evaluated correlations are shown in Tables 3 and 4 for experimental and model-predicted results which are in proximate agreement.

Table 3: Comparison of the correlations between extraction rate and leaching time as evaluated from experimental and derived model

Analysis	Based on leaching time	
	ExD	D-MoD
CORREL	0.9959	0.9959

Table 4: Comparison of the correlations between extraction rate and final pH of leaching solution as evaluated from experimental and derived model

Analysis	Based on final pH of leaching solution	
	ExD	D-MoD
CORREL	0.9596	0.9749

Graphical Analysis

Comparative graphical analysis of Figs. 5 and 6 shows very close alignment of the curves from model-predicted lead extraction rate (MoD) and that of the experiment (ExD). The degree of alignment of these curves is indicative of the proximate agreement between both experimental and model-predicted lead extraction rate.

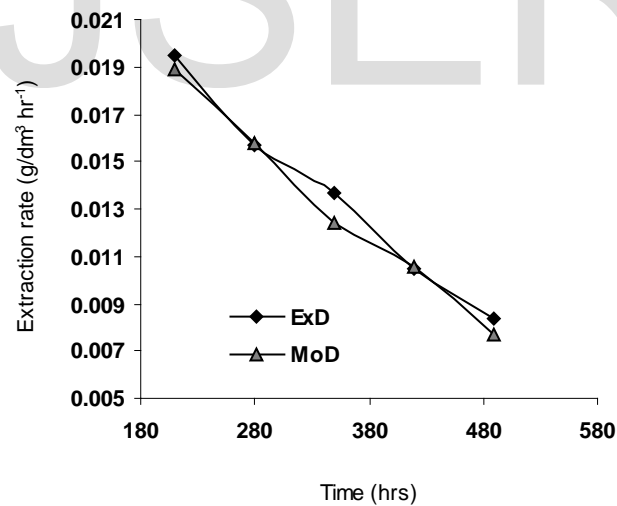


Fig. 5: Comparison of lead extraction rate (relative to leaching time) as obtained from experiment [7] and derived model.

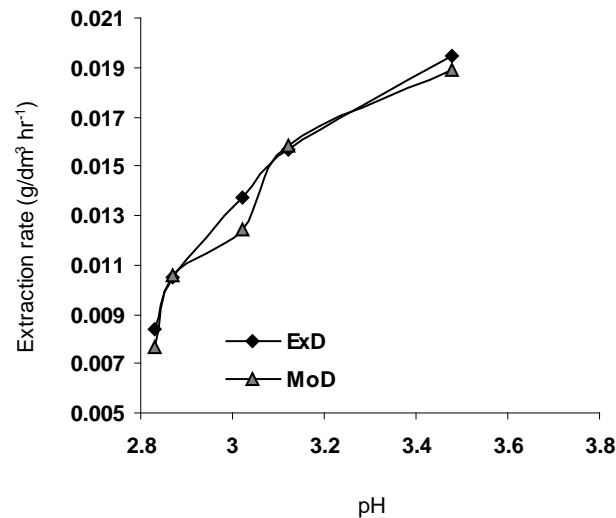


Fig. 6: Comparison of lead extraction rate (relative to final pH of leaching solution) as obtained from experiment [7] and derived model.

Regression model culled from Microsoft Excel [9] was used to predict the extraction rate within the same boundary conditions on which the derived model was based. Results predicted by the regression model was plotted; extraction rate against leaching time and final pH of leaching solution respectively along with results from the experiment and derived model for the purpose of comparatively analyzing its spread and trend relative to results from experiment and derived model. This is also a way of checking the validity of the derived model with reference to a standard model prediction.

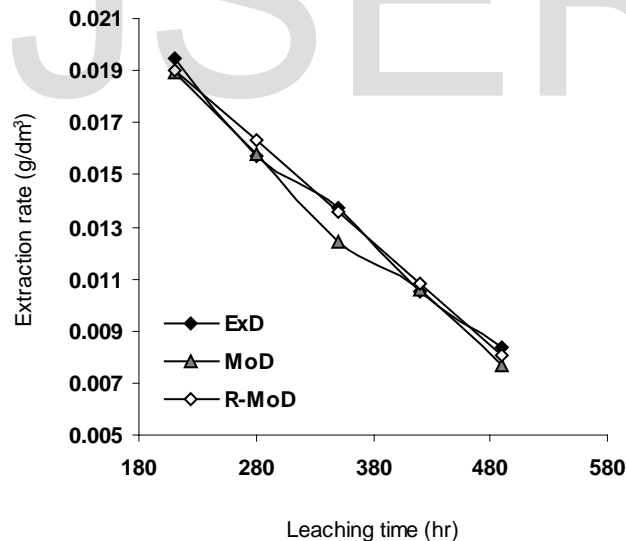


Fig. 7: Comparison of lead extraction rate (relative to leaching time) as obtained from experiment [7] derived and regression model.

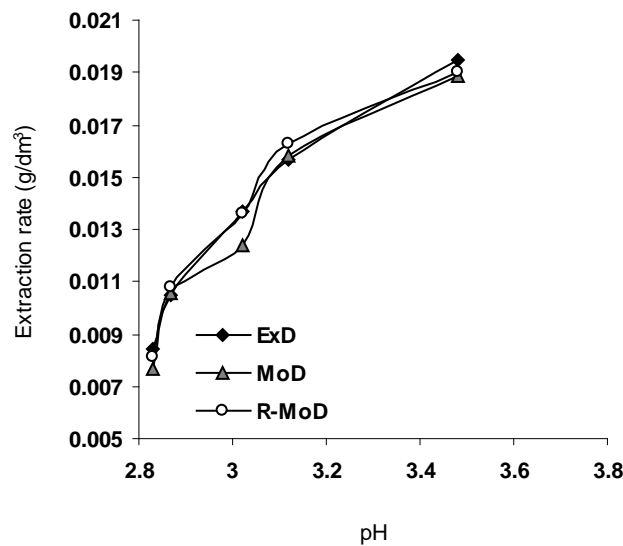


Fig. 8: Comparison of lead extraction rate (relative to final pH of leaching solution) as obtained from experiment [7] derived and regression model.

Graphical analysis of Figs. 7 and 8 shows very close alignment of the curves from derived model (D-MoD) and regression model (R-MoD) predicted results as well as experimental (ExD) results of lead extraction rate. It is strongly believed that the degree of alignment of these curves is indicative of the proximate agreement between ExD, D-MoD and R-MoD predicted results.

Deviation Analysis

Comparative analysis of lead extraction rate from experiment [7] and derived model revealed deviations on the part of the model-predicted values relative to values obtained from the experiment. This is attributed to the fact that the surface properties of the sulphide ore and the physiochemical interactions between the ore and the leaching solution (containing the microbes) which played vital roles during the process [7] were not considered during the model formulation. This necessitated the introduction of correction factor, to bring the model-predicted lead extraction rate to those of the corresponding experimental values.

Deviation (Dn) of model-predicted lead extraction rate from that of the experiment [7] is given by

$$Dn = \left(\frac{P^L - E^L}{E^L} \right) \times 100 \quad (12)$$

Correction factor (Cr) is the negative of the deviation i.e

$$Cr = -Dn \quad (13)$$

Therefore

$$Cr = - \left(\frac{P^L - E^L}{E^L} \right) \times 100 \quad (14)$$

Where

P^L = Model-predicted lead extraction rate ($\text{g}/\text{dm}^3 \text{ hr}^{-1}$)

E^L = Lead extraction rate from experiment ($\text{g}/\text{dm}^3 \text{ hr}^{-1}$)

Cr = Correction factor (%)

Dn = Deviation (%)

Introduction of the corresponding values of Cr from equation (14) into the model gives exactly the corresponding experimental extraction rate.

Figs. 9 and 10 show that the maximum deviation of the mode-predicted lead extraction rate from the corresponding experimental values is less than 10% and quite within the acceptable deviation limit of experimental results.

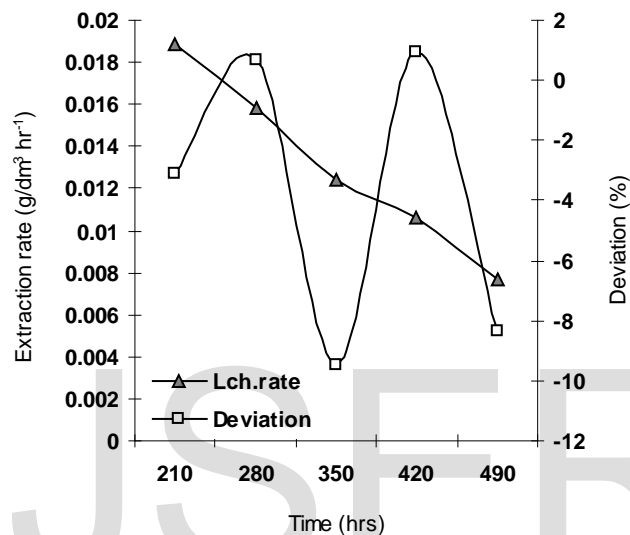


Fig. 9: Variation of model-predicted extraction rate (relative to leaching time) with its associated deviation from experimental values

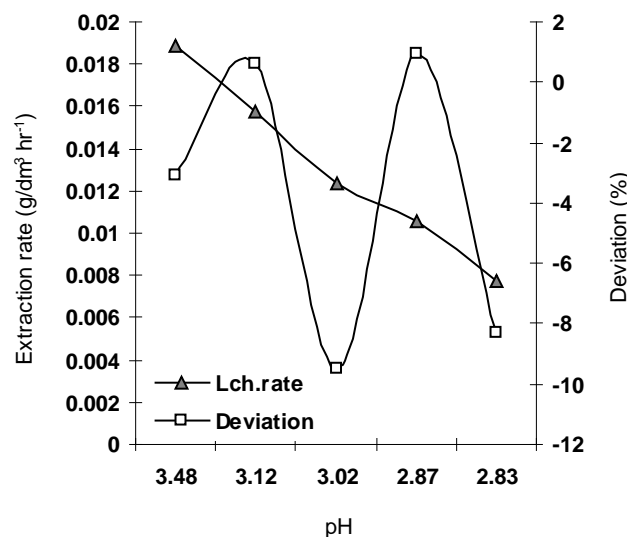


Fig. 10: Variation of model-predicted extraction rate (relative to final pH of leaching solution) with its associated deviation from experimental values

These figures show that least and highest magnitudes of deviation of the model-predicted lead extraction rate (from the corresponding experimental values) are 0.64 and -9.49% which

corresponds to lead extraction rates: 0.0158 and $0.0124 \text{ g/dm}^3 \text{ hr}^{-1}$ and leaching times: 280 and 350 hrs respectively.

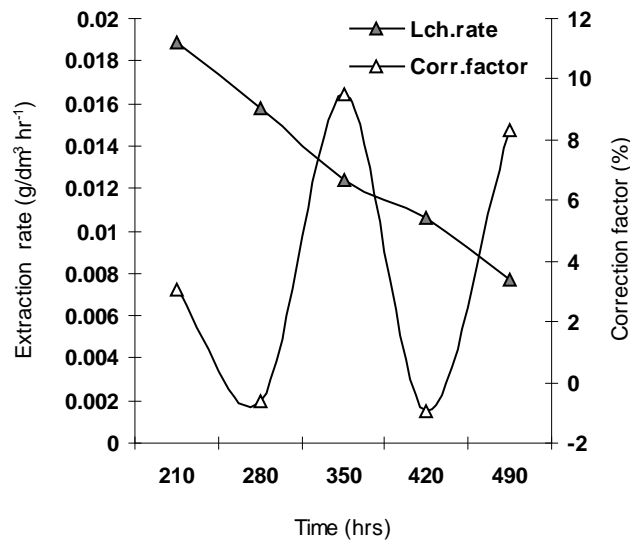


Fig. 11: Variation of model-predicted extraction rate (relative to leaching time) with its associated correction factor

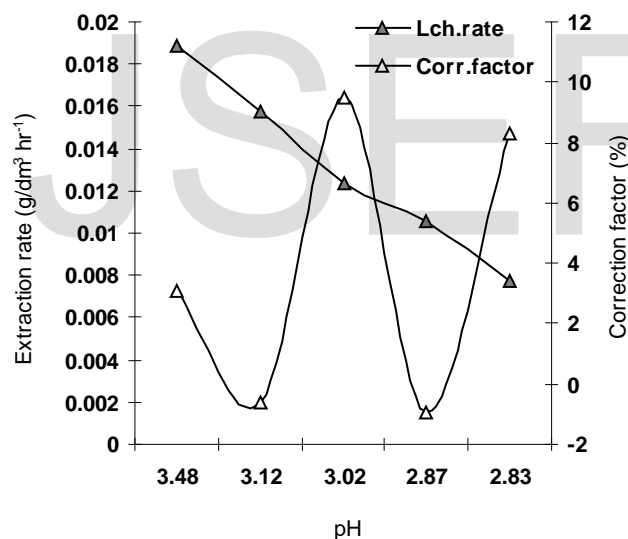


Fig. 12: Variation of model-predicted extraction rate (relative to final pH of leaching solution) with its associated correction factor

Comparative analysis of Figs. 9-12 indicates that the orientation of the curve in Figs. 11 and 12 is opposite that of the deviation of model-predicted lead extraction rate (Figs. 7 and 8). This is because correction factor is the negative of the deviation as shown in equations (13) and (14). It is believed that the correction factor takes care of the effects of the surface properties of the ore and the physiochemical interaction between the ore and the leaching solution (containing the microbes) which (affected experimental results) were not considered during the model formulation. Figs. 11 and 12 indicate that the least and highest magnitudes of correction factor to the model-predicted lead extraction rate are -0.64 and $+9.49\%$, corresponding to lead extraction rates: 0.0158 and $0.0124 \text{ g/dm}^3 \text{ hr}^{-1}$ and leaching times: 280 and 350 hrs respectively.

It is important to state that the deviation of model predicted results from that of the experiment is just the magnitude of the value. The associated sign preceding the value signifies if the deviation is deficit (negative sign) or surplus (positive sign).

6. Conclusion

Open-system predictive assessment of lead extraction rate during biooxidation of galena by *acidithiobacillus ferrooxidans* (ATF) has been carried out based on the leaching time and final pH of leaching solution using a derived model. The model indicates an logarithmic relationship between lead extraction rate and combined input of time and pH. The standard errors incurred in predicting lead extraction rate for each value of the leaching time and final leaching solution pH considered, as obtained from derived model and experiments are 5.15×10^{-4} and 4.66×10^{-4} % as well as 1.26×10^{-3} and 1.54×10^{-3} % respectively. The concentration of lead extracted within a leaching time interval 210-490 hrs as obtained from derived model and experiment are 3.136 and 3.108 g/dm³. Deviation analysis indicates that the maximum deviation of the model-predicted lead extraction rate from the corresponding experimental value is less than 10%. The validity of the model is rooted on the core expression $7.4074 \gamma = -0.1304 (\ln t + \ln \alpha) + 1$ where both sides of the expression are correspondingly approximately equal.

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