# Factorial Analysis of Phosphorus Removal during Bioprocessing of Iron Oxide Ore Using Acidithiobacillus Ferrooxidans (ATF)

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## ABSTRACT

This paper presents a factorial analysis of phosphorus removed during bioprocessing of iron oxide ore using Acidithiobacillus Ferrooxidans. The analysis was based on ore as-beneficiated concentration and ore particle size. The model is expressed as;

$$P_R = -0.1954\,\alpha^2 + 0.5888\alpha - 0.001\,\gamma + 0.0316$$

The validity of the two-factorial model was found to be rooted on the expression $P_R - 0.0316 = -0.1954\,\alpha^2 + 0.5888\alpha - 0.001\,\gamma$ where both sides of the expression are correspondingly approximately equal. Statistical analysis of removed phosphorus concentration for each value of the ore particle size as obtained from experiment and derived model-predicted results show standard errors of 0.0725 and 0.0549% respectively. Furthermore, removed phosphorus concentration per unit particle size as obtained from experiment and derived model-predicted results were 0.25 and 0.24 % $mm^{-1}$ respectively. Deviational analysis indicates that the derived model gives best-fit process analysis within a deviation range of just 0.55 – 9%.

**Keywords:** Analysis, Phosphorus Removal, Acidithiobacillus Ferrooxidans, Agbaja Iron Ore.

## INTRODUCTION

Abrupt structural failure of steel in service due to embrittlement caused by presence of phosphorus above the admissible quantity has raised the unavoidable need for a full scale researches geared on reducing the phosphorus content of pig iron which eventually transforms into steel.

Hydrometallurgy based dephosphorization of iron ore as observed from experiment and model prediction [1-3] has shown that phosphorus removal during leaching using oxalic acid solution, is highly dependent on the final pH of the leaching solution (which varies time), and other factor such as initial solution pH, initial leaching temperature, mass-input of the iron oxide ore and ore mineralogy etc.

A model has been derived for predictive analysis of the concentration of phosphorus removed during leaching of iron oxide ore in sulphuric acid solution [4]. The work indicated that phosphorus removal from the iron oxide ore as obtained from experiment and derived model is dependent on the initial and final pH of the leaching solution. This is because the final pH of the leaching solution is greatly determined by the initial pH which is function of hydrogen ion concentration.

Phosphorus removal has been observed [5] to also be dependent on leaching temperature. The model derived using experimental results generated previously [5] indicated that at a leaching temperature range 45-70$^0$C, the maximum deviation of the model-predicted removed phosphorus concentration (from the corresponding experimental values) was less than 29%.

Past research [6] has shown the possibility of dephosphorizing iron ore by breaking the phosphor-containing iron ore into granules of less than 0.074mm and then mixing it with iron pyrite pre-broken to the granules of less than 0.074mm based on mass percent of 5%-20%. In this process, the mass concentration of ore slurry was adjusted to 10%-20% by the aphosphorosis 9K culture and pH of original ore slurry kept at a range of 1.5 to 3.5. The research was found suitable for direct-extracting and dephosphorizing phosphor-containing iron ore using bacteria, giving a yield of above 80% within 30-45 days. In countries having high phosphorus-iron ore, the highlighted dephosphorization process is capable of providing a reliable technical support; giving good dephosphorization at low cost.

Some biological processes for phosphorus removal have been evaluated based on the use of several types of fungi and bacteria, some being

acid producing. Recently, Aspergillus niger and their cultural filtrates were used for removing phosphorus from Agbaja (Nigeria) iron oxide ore. The results of this work [7] show that phosphorus removal efficiencies at the end of the 49 days of the leaching process are 81, 63 and 68% for 5, 100 and 250 mesh grain sizes respectively.

The aim of this work is to carry out a factorial analysis of phosphorus removed during bioprocessing of iron oxide ore using acidithiobacillus ferrooxidans. The essence of this work is to ascertain the level of dephosphorization achievable at different iron ore particle sizes where all other input process parameters are kept constant.

## MATERIALS AND METHODS

Agbaja (Nigeria) iron ore concentrate used for this work was obtained from Nigeria Metallurgical Development Centre (NMDC) Jos. The concentrate was dried in air (under atmospheric condition) and used in the as-received condition. Five samples of constant weight quantity of the dried iron ore concentrate of particle size 0.16mm were each added to a culture of ATF in a conical flask and the mixtures allowed to react for 2 weeks at a temperature of $25^0$C after which the mixtures were filtered and the concentration of removed phosphorus determined using atomic absorption spectrometer (AAS). The average of the removed phosphorus concentration determined in each experiment set was taken as the precise result. The experiment was repeated with different ore particle sizes; 0.32, 0.63, 0.83 and 1.6 mm and the corresponding phosphorus removal also determined using AAS. Details of the experimental procedures and process conditions prevailing during the bio oxidation process are as reported in the previous work [8].

### Model Formulation
Experimental data obtained from the highlighted research work were used for the model derivation. Computational analysis of these data shown in Table 1, gave rise to Table 3 which indicate that;

$P_R$- $S_e$ ≈- N$\alpha^2$ + K$\alpha$ - S $\gamma$       (1)
Introducing the values of K, N, S and $S_e$ into equation (1)
$P_R$ - 0.0316 = - 0.1954 $\alpha^2$ + 0.5888$\alpha$ - 0.001 $\gamma$  (2)
$P_R$ =- 0.1954 $\alpha^2$ + 0.5888$\alpha$ - 0.001 $\gamma$ + 0.0316  (3)

Where
$P_R$ = Conc. of removed phosphorus (%)
($\gamma$) =As beneficiated phosphorus content of the ore (%)
($\alpha$) = Iron oxide ore particle size (mm)

K = 0.5888, $S_e$= 0.0316, N = 0.1954 and S = 0.001 are equalizing constant (determined using C-NIKBRAN [9])

Table 1: Variation of removed phosphorus concentration with iron ore particle size [8]

| ($\gamma$) | Ore particle size (mm) | $P_R$ (%) |
|---|---|---|
| 0.9 | 0.16 | 0.11 |
| 0.9 | 0.32 | 0.16 |
| 0.9 | 0.63 | 0.35 |
| 0.9 | 0.83 | 0.39 |
| 0.9 | 1.60 | 0.47 |

## Boundary and Initial Condition

Consider iron ore (in a furnace) mixed with a culture of ATF. The atmosphere was not contaminated i.e (free of unwanted gases and dusts). Initially, atmospheric levels of oxygen are assumed just before the reaction between the ore and the microbes. Mass of iron oxide ore: (50g), treatment time: 2 weeks, constant treatment temperature: $25^o$C, range of ore particle size used; 0.16 – 1.61mm.

The boundary conditions are: oxygen atmosphere at the top and bottom of the ore particles interacting with the microbes. At the bottom of the particles, a zero gradient for the gas scalar are assumed and also for the gas phase at the top of the particles. The reduced iron is stationary. The sides of the particles are taken to be symmetries.

## RESULTS AND DISCUSSIONS
The result of the chemical analysis carried out on the beneficiated iron ore concentrate is presented in Table 2. The table shows that the percentage of phosphorus present in the as-beneficiated ore is 0.9%.[

Table 2: Result of chemical analysis of iron ore used [8]

| Element/Compound | Fe | P | $SiO_2$ | $Al_2O_3$ |
|---|---|---|---|---|
| Unit (%) | 78.6 | 0.90 | 5.30 | 11.0 |

### Model Validation
The validity of the model is strongly rooted in equation (2) (core model equation) where both sides of the equation are correspondingly approximately equal. Table 3 also agrees with equation (2) following the values of $P_R$ - 0.0316 and - 0.1954 $\alpha^2$ + 0.5888$\alpha$ - 0.001$\gamma$ evaluated from the experimental results in Table 1.

Table 3: Variation of $P_R$ - 0.0316 with - 0.1954 $\alpha^2$ + 0.5888$\alpha$ - 0.001 $\gamma$

| $P_R$ - 0.0316 | - 0.1954 $\alpha^2$ + 0.5888α - 0.001 γ |
|---|---|
| 0.0784 | 0.0883 |
| 0.1284 | 0.1675 |
| 0.3184 | 0.2924 |
| 0.3584 | 0.3532 |
| 0.4384 | 0.4410 |

Furthermore, the derived model was validated by comparing the removed phosphorus concentration predicted by the model and that obtained from the experiment. This was done using various evaluative techniques such as computational, statistical, graphical and deviational analysis.

### Computational Analysis

Computational analysis of the experimental and model-predicted removed phosphorus concentration was carried out to ascertain the degree of validity of the derived model. This was done by comparing phosphorus removal per unit ore particle size evaluated from model-predicted results with those from actual experimental results

*Removed phosphorus concentration per unit ore particle size $P_R{}^P$* (%/ mm) was calculated from the equation;

$$P_R{}^P = P_R / \alpha \qquad (4)$$

Therefore, a plot of the concentration of phosphorus removed against iron ore particle size as in Fig. 1 using experimental results in Table 1, gives a slope, S at points (0.16, 0.11) and (1.6, 0.47) following their substitution into the mathematical expression;

$$P_R{}^P = \Delta P_R / \Delta \alpha \qquad (5)$$

Equation (5) is detailed as

$$P_R{}^P = P_{R2} - P_{R1} / \alpha_2 - \alpha_1 \qquad (6)$$

Where

$\Delta P_R$ = Change in removed phosphorus concentrations of $P_{R2}$, $P_{R1}$ at two values of the iron ore particle sizes$\alpha_2$, $\alpha_1$. Considering the points (0.16, 0.11) and (1.6, 0.47) for ($\alpha_1$, $P_{R1}$) and ($\alpha_2$, $P_{R2}$) respectively, and substituting them into equation (6), gives the slope as 0.25 % mm$^{-1}$ which is the removed phosphorus concentration per unit ore particle size during the actual bioleaching process.
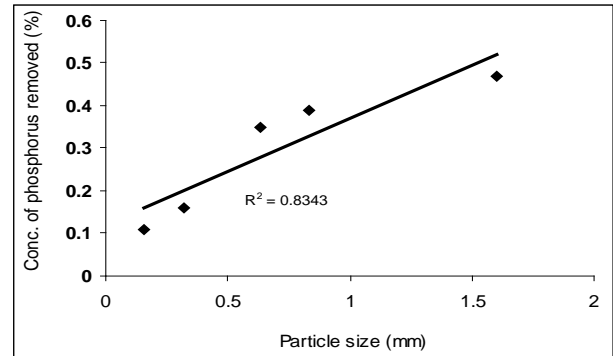


Fig. 1: Coefficient of determination between concentration of removed phosphorus and ore particle size as obtained from the experiment [8]

Similarly a plot of the concentration of removed phosphorus against ore particle size (as in Fig. 2) using derived model-predicted results gives a slope: 0.24 % mm$^{-1}$ on substituting the points (0.16, 0.1199) and (1.6, 0.4726) for ($\alpha_1$, $P_{R1}$) and ($\alpha_2$, $P_{R2}$) respectively into equation (6). This is the model-predicted removed phosphorus concentration per unit particle size.

Fig. 2: Coefficient of determination between concentration of removed phosphorus and ore particle size as obtained from derived model
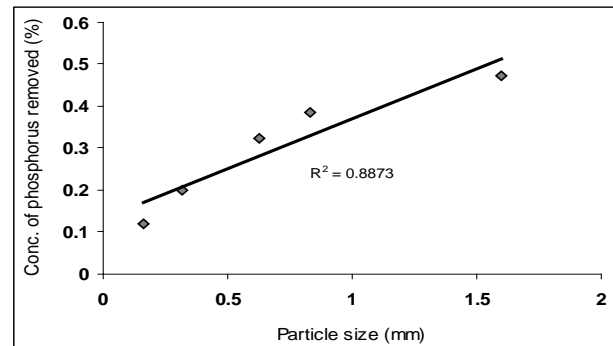


A comparison of this set of values for removed phosphorus concentration (per unit ore particle size) also shows proximate agreement and a high degree of validity of the derived model.**Statistical Analysis**
The standard errors (STEYX) in predicting the removed phosphorus concentration (using results from experiment and derived model) for each value of the ore particle size are 0.0725 and 0.0549% respectively. The standard error was evaluated using Microsoft Excel version 2003. Considering the coefficient of determination $R^2$ from Figs. 1 and 2, the correlations between removed phosphorus concentration and ore particle size as obtained from experiment and derived model predicted results, was calculated using the equation;

$$R = \sqrt{R^2} \qquad (7)$$

The evaluations show correlations 0.9134 and 0.9420 respectively. These evaluated results

indicate that the derived model predictions are significantly reliable and hence valid considering its proximate agreement with results from actual experiment.

## Graphical Analysis

Comparative graphical analysis of Fig. 3 shows very close alignment of the curves from model-predicted removed phosphorus concentration (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 phosphorus removed concentration.
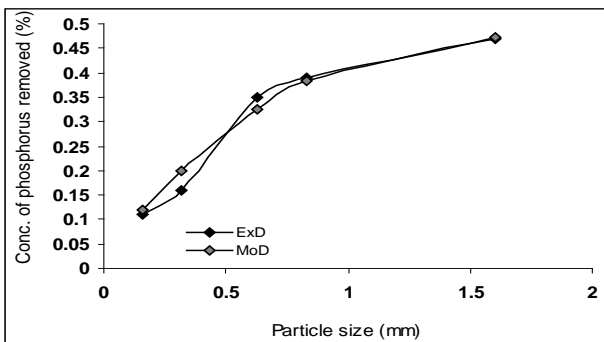


Fig. 3: Comparison of the concentrations of removed phosphorus (relative to ore particle size) as obtained from experiment [8] and derived model

## Deviational Analysis

Analysis of removed phosphorus concentrations from the experiment 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 iron ore and the physiochemical interactions between the ore and the microbes (ATF) which were found to have played vital roles during the process were not considered during the model formulation. This necessitated the introduction of correction factor, to bring the model-predicted removed phosphorus concentration to those of the corresponding experimental values.

Deviation (Dn) of model-predicted removed phosphorus concentration from that of the experiment is given by

$$D_n = \left(\frac{P_v - E_v}{E_v}\right) * 100 \tag{8}$$

Where
Pv = Removed phosphorus concentration as predicted by derived model
Ev = Removed phosphorus concentration as obtained from experiment

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

$$Cr = -Dn \tag{9}$$

Therefore

$$C_r = -\left(\frac{P_v - E_v}{E_v}\right) * 100 \tag{10}$$

Introduction of the corresponding values of Cr from equation (10) into the derived model gives exactly the removed phosphorus concentration as obtained from experiment.
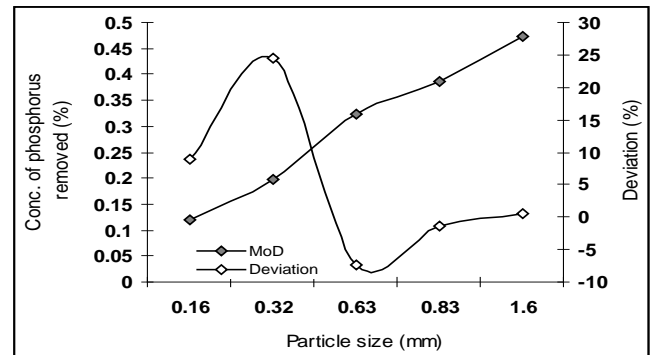


Fig. 4: Variation of model-predicted removed phosphorus concentration with associated deviation from experimental results (relative to ore particle size)

Fig. 4 shows that the maximum deviation of the model-predicted removed phosphorus concentration from the corresponding experimental values is less than 25%. The figure shows that the least and highest magnitudes of deviation of the model-predicted removed phosphorus concentration (from the corresponding experimental values) are 0.55 and 24.44 % which corresponds to removed phosphorus concentrations: 0.4726 and 0.1991 %, as well as ore particle size: 1.6 and 0.32 mm respectively.
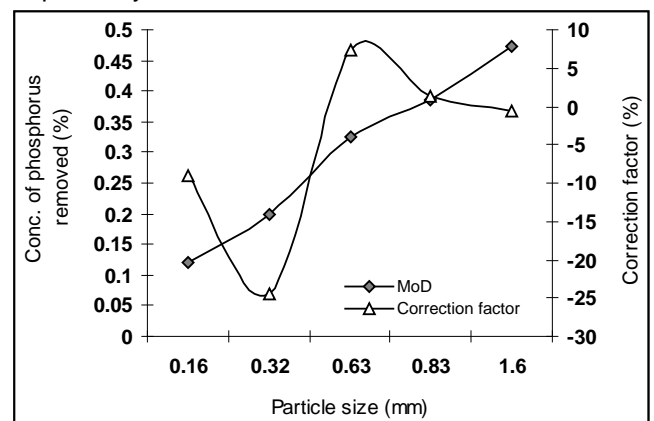


Fig. 5: Variation of model-predicted removed phosphorus concentration with associated correction factor (relative to ore particle size)

Comparative analysis of Figs. 4 and 5 indicates that the orientation of the curve in Fig. 5 is opposite that of the deviation of model-predicted removed phosphorus concentration (Fig. 4). This is because correction factor is the negative of the deviation as shown in equations (9) and (10).

It is believed that the correction factor takes care of the effects of surface properties of the iron ore and the physiochemical interactions between the iron ore and microbes which have played vital roles during the process, but were not considered during the model formulation. Fig. 5 indicates that the least and highest magnitudes of correction factor to the model-predicted removed sulphur concentration are - 0.55 and - 24.44 % which corresponds to removed phosphorus concentrations: 0.4726 and 0.1991 %, as well as ore particle size: 1.6 and 0.32 mm 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 that the deviation is a deficit (negative sign) or surplus (positive sign).

## CONCLUSIONS

Factorial analysis of phosphorus removal during bioprocessing of iron oxide ore using acidithiobacillus ferrooxidans has been carried out. The validity of the two-factorial model was rooted on the expression $P_R - 0.0316 = - 0.1954 \alpha^2 + 0.5888\alpha - 0.001 \gamma$ where both sides of the expression are correspondingly approximately equal. Statistical analysis of removed phosphorus concentration for each value of the ore particle size as obtained from experiment and derived model-predicted results showed standard errors of 0.0725 and 3.45 0.0549% respectively. Removed phosphorus concentration per unit particle size as obtained from experiment and derived model-predicted results were 0.25 and 0.24 % $mm^{-1}$ respectively. Deviational analysis indicates that the derived model gives best-fit process analysis within a deviation range of just 0.55 - 9%.

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