

Research Article

Recovery of Gold from Transition Gold Ores via Response Surface Methodology—Process Variables Optimisation

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Abstract

The depletion of free-milling and oxide gold ores has necessitated the beneficiation of gold from complex transition gold ores which contain pyrite and carbonaceous matter (CM) that poses numerous recovery challenges. This study offers a comprehensive optimisation of cyanidation parameters by Response Surface Methodology (RSM) to enhance gold recovery from these ore types. Eight critical factors (dissolved oxygen (6-30 ppm), pyrite content (0-1%), CM content (0-2.5%), cyanide concentration (250-750 ppm), lead nitrate dosage (0-200 g/t), activated carbon concentration (0-20 g/L), particle size (75-106 μm), and gravity pre-concentration (Yes/No)) were systematically assessed using the Central Composite Design (CCD). With 94 design experimental runs undertaken in the laboratory, a statistically significant reduced cubic model (F-value = 14.14, $p < 0.0001$) was developed which was able to explain 83% of recovery variability ($R^2 = 0.831$). The most significant parameters were the concentration of activated carbon ($p < 0.0001$) and the content of CM ($p < 0.0001$). Per the interactions, significant improvement in gold recovery was observed when activated carbon contents were increased. Validation experiments recorded experimental recoveries of (89-95%) which strongly aligned with the predicted recoveries. This projected the robustness of the model to accurately predict. Consequently, this framework can serve as a basis for process and reagent optimisation for mining companies treating complex transition gold ores.

Keywords

Design of Experiment, Response Surface Methodology, Transition Zone, Complex Gold Ore, Gold Recovery, Prediction

1. Introduction

The timeless allure of gold continues to drive innovation in extraction technologies. Yet as near-surface oxide deposits dwindle, miners increasingly encounter complex transition ores that resist conventional cyanidation methods. Gold recovery via cyanidation is a widely used hydrometallurgical process due to its efficiency in extracting gold from ores [1]. However, the process is influenced by multiple factors, including ore mineralogy, reagent concentrations, and opera-

tional parameters, which can significantly impact recovery efficiency [2-4]. On the basis of ease of extraction, gold ores can be generally classified as non-refractory and refractory gold ores. While non-refractory gold ores yield gold recoveries >90% by simple cyanidation and/or gravity concentration, refractory gold ores are mostly characterised by low recoveries (<90%) mainly due to their gangue mineralogy and the degree of association of gold to some of these gangue miner-

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als [5, 6]. Sulphide minerals and carbonaceous matter are the prime causes of refractoriness in gold ores [7]. The various classes of gold ores are usually found in depth defined zones. The oxidised zone (usually hosting non-refractory gold ores) are found near earth surface while the hypogene/sulphide zone (usually hosting refractory gold ores) is usually deep seated within the earth crust [8]. Sandwiched between these two zones is the supergene (transition) zone which is characterised by a complex mineralogy due to their partially oxidised nature. Research has shown that the ores found in the transition zone are characterised by gold which are sub-microscopic and in solid suspension with mineralogy clay, iron sulphide and carbonates. Again, there are the presence of partially oxidised iron sulphide minerals as well as various types of carbonaceous matter (CM), making gold recovery from these zones very difficult [9, 10]. The presence of sulphide minerals such as pyrite and CM can interfere with gold dissolution by consuming cyanide and/or oxygen or through preg-robbing mechanisms [11-14]. Additionally, factors such as dissolved oxygen (D/O), cyanide concentration, lead nitrate addition, activated carbon concentration, particle size, and gravity pre-concentration play crucial roles in determining gold recovery [15-18]. The increasing interest of recovering gold from transition gold ore zone deposits across the world warrants the importance of optimising these process parameters as against the increasingly variable mineralogical changes of these complex transition gold ores which are understudied.

Given the complexity of these interactions, traditional one-factor-at-a-time (OFAT) experimental approaches, which adjust one variable at a time, has proven to be insufficient for these complex systems and are often inadequate for optimising gold recovery. They fail to capture the intricate interplay between factors [19, 20]. Instead, a Design of Experiments (DoE) approach, particularly Response Surface Methodology (RSM), provides a systematic framework for evaluating multiple variables and their interactions [21-23]. RSM enables the development of predictive models that can identify optimal process conditions while minimizing experimental runs [24-26]. In this regard, RSM has been applied in numerous disciplines including pharmaceutical, environmental remediation, energy systems, healthcare, mining and metal recovery, etc [27-32].

This study employed a Central Composite Design (CCD) within an RSM framework to investigate the effects of eight key parameters on gold recovery from a transition zone ore in Ghana. The selected factors included dissolved oxygen (D/O), pyrite content (%), carbonaceous matter (CM) content (%), cyanide concentration (ppm), lead nitrate dosage (g/t), activated carbon concentration (g/L), particle size (μm), gravity pre-concentration (Yes/No). CCD offers a better alternative when optimising factors of a process as compared to the Full factorial design (FFD) and Box-Behnken Design (BBD) due to a couple of advantages it presents. For CCD, higher-order interactions are well understood as compared to the FFD which is mostly good at screening because it involves only

one and two-way interactions. Again, the CCD comparatively extends a little advantage over the BBD since the BBD does not allow the study of factors at their extremities making it less efficiently [33]. Ultimately, CCD presents as a better choice at factor optimisation.

This study evaluated the statistical significance of each factor and their interactions through Analysis of Variance (ANOVA), with model suitability assessed using correlation co-efficient (R^2), adjusted R^2 , and predicted R^2 values. Furthermore, 3D response surface plots and interaction effects were generated to visualize optimal conditions for maximizing gold recovery. The findings provide innovative insights into the complex interplay between ore mineralogy and leaching parameters, offering a data-driven approach to optimising cyanidation processes for transition gold ores with high pyrite and carbonaceous content.

2. Materials and Methods

2.1. Design of Experiment (DoE)

A comprehensive investigation was conducted to evaluate the effects of key parameters on gold recovery via cyanidation using a design of experiments (DoE) approach. The study examined eight factors across their specified ranges (Table 1). The process variables were selected based on the mineralogy of the ores from the transition zone as characterized by X-Ray Diffractometer (XRD) (Table 2) and the current operational parameters of most gold mining companies in Ghana. A response surface methodology (RSM) with 94 experimental runs was employed to assess factor and interaction effects, with gold recovery percentage as the response variable. Table 1 shows the experimental design matrix and the experimental factors in coded format and experimental response.

The Design Expert version 13.0 (STATEASE Inc., Minneapolis, Minnesota, USA) was used to analyse the experimental data acquired following different test runs. The program was selected for the study given that it offers the user a variety of alternatives for test work and statistical interpretation of multi-factor experiment designs [34-36].

2.2. Cyanidation Procedure

2.2.1. Sample Preparation

Free-milling ore was obtained from a mining company in the western region of Ghana. The ore was 3-stage crushed using jaw, cone and roll crusher and ground to target particle sizes (based on the various permutations derived from the experimental design matrix as shown in the Appendix) using a ball mill at the Minerals engineering department of the University of Mines and Technology, Tarkwa-Ghana. Particle size distribution was verified via screen analysis. Pure pyrite and charcoal (used as CM) were dosed in the ore based on the runs from the design matrix (Appendix). The ranges were chosen

based on characterisation data obtained from 6 transition zone samples received from 3 mining companies in Ghana. Table 2 summarizes the results from the various characterisation tests conducted. Comparatively, XRD revealed similar mineral phases of the transition zone ores to the free-milling ore used

for the simulation test runs. This work aimed at varying percentages of CM and pyrite hence a simulated ore (free-milling ore mixed with various percentages of pyrite and CM as per the design matrix) was used to this effect.

Table 1. Experimental design matrix and their coded levels for the central composite design.

Design Summary						
Study Type	Response Surface	Subtype	Randomized			
Design Type	Central Composite	Runs	94			
Design Model	Reduced Cubic	Blocks	No Blocks			
Build Time (ms)	2					
Factor	Name	Units	Type	SubType	Minimum	Maximum
A	D/O	ppm	Numeric	Continuous	6	30
B	Pyrite	%	Numeric	Continuous	0	1
C	CM	%	Numeric	Continuous	0	2.5
D	CN Conc.	ppm	Numeric	Continuous	250	750
E	Lead Nitrate	g/t	Numeric	Continuous	0	200
F	Carbon Conc.	g/l	Numeric	Continuous	0	20
G	Particle Size	microns	Numeric	Continuous	75	106
H	Gravity		Categoric	Nominal	No	Yes

2.2.2. Cyanidation Test

Batch tests conducted using 200 g of ore in 1-L bottle on a roller. Based on the experimental design matrix, various factors were varied and permuted for each run as indicated in Appendix 1. The pulp density, agitation speed of the roller and the pH were maintained at 50%, 65 rpm and between 10.5-11 respectively. Pyrite (B) and carbonaceous matter (C) levels varied to evaluate their interference. For runs with H = "Yes"

(thus requiring gravity separation), a Knelson concentrator was used for pre-concentration before leaching of the tailings. Overall recovery was estimated for samples as such.

Residue solid tailings were washed, dried and subjected to fire assaying to determine the gold left in tailings. Gold recovery for each run was estimated using equation 1.

$$Au \text{ Recovery} = \frac{Au_{head} - Au_{tailings}}{Au_{head}} * 100 \quad (1)$$

Table 2. Mineralogical characterisation by LECO and XRD.

Sample ID	Total Sulphur	Sulphide Sulphur	Total Carbon	Organic Carbon	Mineralogical Characterisation by XRD
Mine A	1.22	0.93	3.61	2.11	Quartz, Kaolinite, Muscovite
	1.23	0.91	1.98	1.48	Quartz, Albite, Muscovite
	1.16	0.94	1.42	1.35	Quartz, Kaolinite, Muscovite

Sample ID	Total Sulphur	Sulphide Sulphur	Total Carbon	Organic Carbon	Mineralogical Characterisation by XRD
Mine B	0.19	0.11	0.82	0.15	Quartz, Dolomite, Chlorite
	0.28	0.21	0.73	0.13	Quartz, Dolomite, Muscovite
Mine C	0.78	0.73	1.83	1.67	Quartz, Gypsum, Chlorite
Free milling Ore	0.13	0.07	0.11	<0.01	Quartz, Kaolinite, Muscovite

2.3. Statistical Analysis

The results from the experimental design were statistically evaluated using the Design-Expert software in this investigation. The experimental results were statistically validated using model parameters, including the F-value, correlation coefficient (R^2), and adjusted R-squared (R^2_{Adj}). The suitability of the models was verified using the analysis of variance (ANOVA) feature of the Design-Expert software. A Model's F-value with $p < 0.05$ and the Lack of Fit F-value with $p > 0.05$ for response variables indicate that the model is significant and the Lack of Fit is non-significant relative to the pure error, respectively. Equation. 2-6 provide mathematical equations for approximating the F-value, R^2 , and R^2_{Adj} [25]. Interaction plots and 3D response surfaces were generated to visualize optimal conditions.

$$Mean\ square(MS) = \frac{SS}{Df} \quad (2)$$

$$F = \frac{MS_{regression}}{MS_{residual}} \quad (3)$$

$$R^2 = \frac{SS_{regression}}{SS_{model} + SS_{residual}} \quad (4)$$

$$R^2_{adj} = \frac{SS_{regression}/Df}{(SS_{model} + SS_{residual})/(Df_{model} + Df_{residual})} \quad (5)$$

$$Residual \rightarrow e = (y - y_0) \quad (6)$$

Where SS denotes the sum of squares; Df represents the degrees of freedom; y signifies the predicted value, while y_0 indicates the actual value.

3. Results and Discussion

3.1. Model Development and Analysis of Variance (ANOVA)

Design Expert Software (version 13.0) was used in the regression analysis and drawing of response plots. With gold recovery designated as the response variable, a model equation (in the coded value of the experimental factors) was developed as shown in Equation 7.

$$Au\ Recovery = 92.47 - 1.85A - 3.96B - 8.64C + 0.20D - 4.56E + 9.51F - 0.99G - 1.34H + 1.45AE - 5.17AG - 1.92AH + 3.72BD + 1.93BF - 4.87BG + 2.68BH + 8.77CF + 2.43CH - 8.73EG + 6.78C^2 - 17.69F^2 - 3.80ACH - 3.11AEH + 3.80BFH + 7.51BGH \quad (7)$$

Where A, B, C, D, E, F, G, H are the various coded factors. ANOVA analysis was used to assess the significance of regression models, individual model coefficients, and lack of fit. F-test was employed to compare the regression mean with the residual mean square. Indication from Table 3 informs that the model (reduced cubic model) gave an F-value of 14.14 and a p-value of >0.0001 . These values indicate that the model is significant given that there is only 0.01% chance of an F-value this large being obtained due to noise. Again, the significance of the model was validated by the very low p-value for which <0.05 is desired. A lack-of-fit test was significant ($p = 0.0023$), indicating that the model does not fully explain all systematic variation. This significance may stem from either the inability of the model to predict well and/or the perfect replication of runs such that their variance is very small. In situations where the fit cannot be improved, confirmation runs to validate the experimental results can be relied on. The pure error (10.70), however, is relatively small,

meaning the model remains useful for optimisation despite minor inadequacies.

The appropriateness of the regression model was assessed using the correlation coefficient (R^2) and the adjusted coefficient of determination (adj. R^2) values. Typically, the R^2 value for an effective statistical model should be close to 1 [19, 29]. The R^2 and adjusted R^2 values respectively for this model were 0.83 and 0.77 (Table 4). This indicate that 83% of the variability in recovery is explained by the model. In mineral processing, $R^2 > 0.8$ is often acceptable due to inherent ore variability. The difference between the R^2 and the predicted R^2 was about 6% which is mostly not desirable (thus $>4\%$). This may be due to minor, uncontrollable factors (like slight mineralogical heterogeneity) that do not undermine the core relationships and high model complexities, which stems from too many parameters, which can easily overfit data. Regardless, a good model accuracy and strong correlation between experimental and predicted values has been shown by statis-

tical analysis. The difference between the predicted R^2 and the adjusted R^2 was less than 0.2, indicating a reasonable agreement between the two. Adequate precision is a measure of the extent to which the predicted values accurately reflect the true underlying relationship while accounting for noise or variability in the data. The model developed demonstrated a very high signal-to-noise ratio (17.5798). This suggests that the model is reliable and valuable for making predictions, given its adequate signal.

The significance of each model term can be deduced from their respective p-values. Consequently, a p-value < 0.05 signifies that the model terms are statistically significant at a 95% confidence level [37]. From Table 3, factors including pyrite,

carbonaceous material content, lead nitrate and activated carbon addition significantly influenced gold recovery while dissolved oxygen, cyanide concentration and particle size showed minimal impact on gold recovery per the model ($p > 0.05$).

Figure 1 shows the plot of predicted vs actual values (a) and externally studentized residuals vs predicted (b). The predicted vs actual plot indicates a linear graph signifying that the experimentally observed values and the predicted values were in close agreement. This implies that the constructed model would predict the relevant variables with high degrees of accuracy.

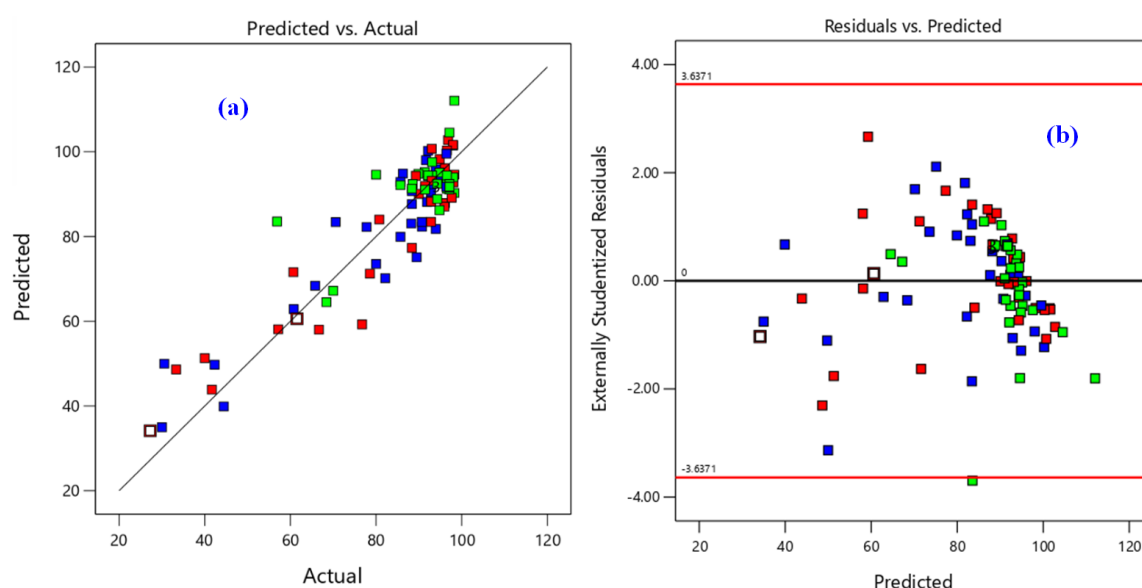


Figure 1. A plot of (a) predicted vs actual values and (b) externally studentised residuals vs predicted values for Au recovery.

Again, the externally studentized residuals vs. predicted plots indicate that the assumptions of the residuals (linearity, independence, homoscedasticity, and uncorrelated) have been satisfied [38]. This was confirmed with the residuals falling within the bounds close to the zero-axis. This indicates the

lack of a constant error, although an outlier was observed. Again, the residuals are broadly spread about zero, thus there is no evident sign of nonlinear, increasing, or decreasing patterns [25].

Table 3. ANOVA for Au recovery after modified model fitting.

Source	Sum of Squares	df	Mean Square	F-value	p-value
Reduced Cubic Model	25069.39	24	1044.56	14.14	< 0.0001
A-D/O	50.00	1	50.00	0.6768	0.4135
B-Pyrite	283.91	1	283.91	3.84	0.0500
C-CM	3985.91	1	3985.91	53.96	< 0.0001
D-CN Conc.	2.32	1	2.32	0.0313	0.8600
E-Lead Nitrate	356.67	1	356.67	4.83	0.0314
F-Carbon Conc.	5034.81	1	5034.81	68.16	< 0.0001

Source	Sum of Squares	df	Mean Square	F-value	p-value
G-Particle Size	9.67	1	9.67	0.1310	0.7186
H-Gravity	166.47	1	166.47	2.25	0.1379
AE	97.34	1	97.34	1.32	0.2550
AG	211.39	1	211.39	2.86	0.0952
AH	213.82	1	213.82	2.89	0.0934
BD	702.23	1	702.23	9.51	0.0029
BF	189.43	1	189.43	2.56	0.1139
BG	217.88	1	217.88	2.95	0.0904
BH	139.22	1	139.22	1.88	0.1742
CF	3900.00	1	3900.00	52.80	< 0.0001
CH	345.40	1	345.40	4.68	0.0341
EG	661.05	1	661.05	8.95	0.0038
C ²	327.87	1	327.87	4.44	0.0388
F ²	2242.90	1	2242.90	30.36	< 0.0001
ACH	842.25	1	842.25	11.40	0.0012
AEH	501.83	1	501.83	6.79	0.0112
BFH	797.23	1	797.23	10.79	0.0016
BGH	552.31	1	552.31	7.48	0.0079
Residual	5096.92	69	73.87		
Lack of Fit	5086.22	65	78.25	29.25	0.0023
Pure Error	10.70	4	2.68		
Cor Total	30166.31	93			

Table 4. Fit Statistics for the developed model.

Std. Dev.	8.59	R ²	0.8310
Mean	84.45	Adjusted R ²	0.7723
C. V. %	10.18	Predicted R ²	0.6394
		Adeq Precision	17.5789

3.2. Response Surface Analysis

3.2.1. Single Effect of Various Factors on Au Recovery

Prediction profiler of each factor for gold recovery is shown in Figure 2. The solid black lines represent the various situations that could occur if one input changed while keeping all other variables constant. Blue lines show 95% confidence and prediction bands, respectively. The prediction profile

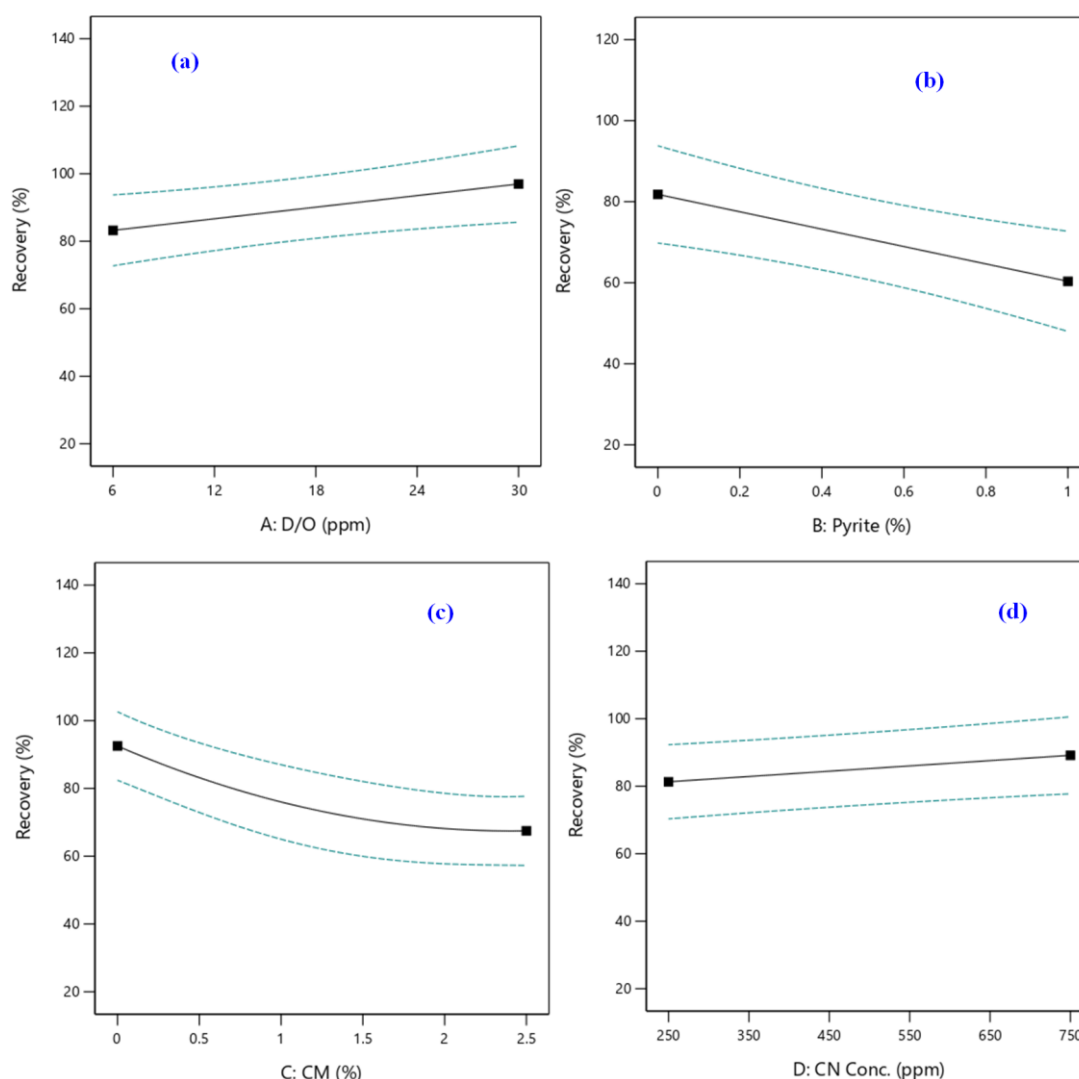
denotes that increasing the dissolved oxygen concentration (D/O) (Figure 2a) caused an increase in gold recovery, although its effect is minimal per the model. This trend may be expected for a typical cyanidation process because D/O is crucial to increasing leaching kinetics for gold. Hence, an increase in gold recovery in the presence of high oxygen environment. [39] reported that oxygen in leaching circuits enhances gold dissolution (even for fine gold). With the presence of lead nitrate in the runs, the effect of D/O may be overlapped since lead nitrate is also an excellent oxidant.

In Figure 2b, the profile of pyrite against recovery indicates

a declining recovery with increasing pyrite content. The presence of reactive pyrite can cause high consumption of cyanide and oxygen which are very crucial to gold leaching kinetics [40]. This is caused by the formation of thiocyanate which consumes free cyanide from solution [41]. Again, the formation of a passive layer of Au_2S from pyrite oxidation on gold particle, inhibits cyanide access thereby reducing leaching efficiency [40, 42, 43]. The decline in recovery may be attributed to these phenomena. The effect of carbonaceous matter (CM) presence on gold recovery is shown on Figure 2. As observed, increasing CM content caused a decline in gold recovery. This is expected since the presence of CM adsorbs aurocyanide complexes from leaching solutions, leading to reduced recoveries (a phenomenon known as preg-robbing). This observations have been recorded by many researchers [11, 12, 44-46]. The content (%) of CM play a significant role in the extent of preg-robbing [47].

Cyanide concentration (CN) projects an increase in gold

recovery with increasing cyanide concentration as seen in Figure 2d. Cyanide concentration is crucial for gold reaction kinetics. [48] reported similar trends of increasing recovery with increasing cyanide concentration. Since the presence of pyrite has a higher probability of increasing cyanide consumption, increasing the cyanide concentration will be important to buttress this effect. Figure 2e shows the single effect of lead nitrate addition on gold recovery. Lead nitrate addition in cyanide leaching processes is mostly aimed at reducing the cyanide consumption by inhibiting the dissolution of metallic sulphide or promoting the oxidation of soluble sulphides to sulphate [49, 50]. Again, NO_3^- is an excellent oxidant hence it helps boost the oxidising conditions of the system, thereby increasing gold recovery [51]. Other benefits of lead nitrate addition include activating the surface of a passivated particle of gold and preventing the formation of a passivation film on the surface of gold [41].



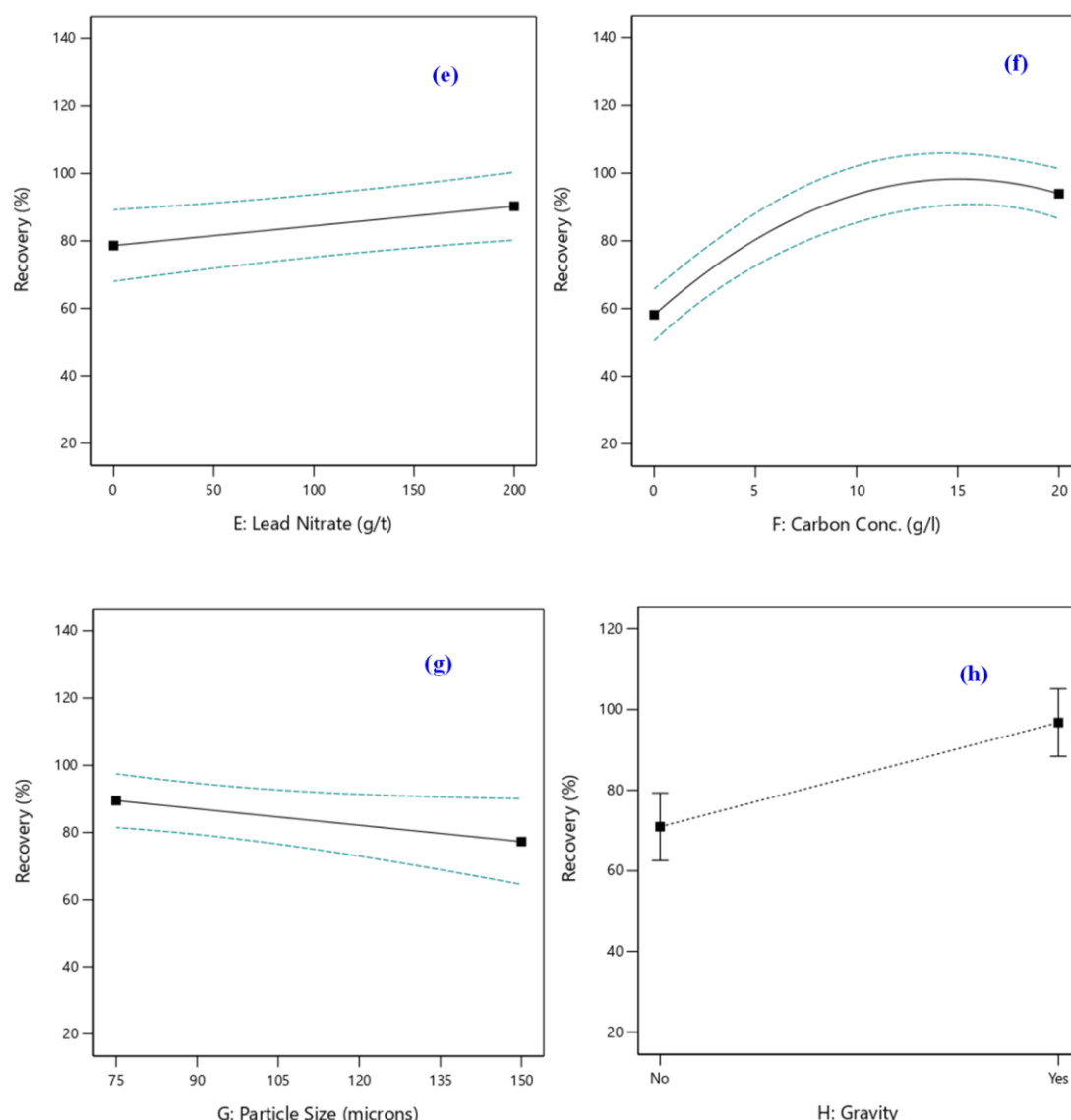


Figure 2. Prediction profiler for gold recovery or the various factors: (a) D/O (b) Pyrite (c) CM (d) CN Conc. (e) lead nitrate (f) Activated Carbon conc. (g) Particle size (h) Gravity concentration.

In terms of activated carbon concentration (Carbon conc.), trend seen in Figure 2f indicates an increase in gold recovery with increasing carbon concentration. This observation is not surprising since the presence of activated carbon competes with CM for aurocyanide complexes. Since activated carbon has undergone carbonisation and activation, its adsorption activity and capacity may be higher as compared to the CM present, hence a replicative increase in recovery as the concentration of activated carbon in the leaching system increased. Particle size is linearly correlative with liberation hence larger particle size was projecting a decreased recovery while smaller particle size gave a higher recovery comparatively (Figure 2g). Smaller particle size increases the surface

area of the particles thereby enhancing reagent-particle interaction [52]. The importance of gravity concentration prior to cyanidation was ascertained with high gold recovery obtained when gravity concentration was conducted (Figure 2h). Gold ores with significant content of gravity recoverable gold (GRG) may affect the cyanidation process negatively if such coarse gold particles are not pre-concentrated prior to cyanidation. Coarse grained gold particle may take a longer time to dissolve in leaching tanks (given the 24 -hr residence time) hence undissolved portions may report to the tailings leading to low gold recoveries. Ultimately, pre-concentration by gravity separation removes GRG and improves the overall gold recovery. This explains the trends seen.

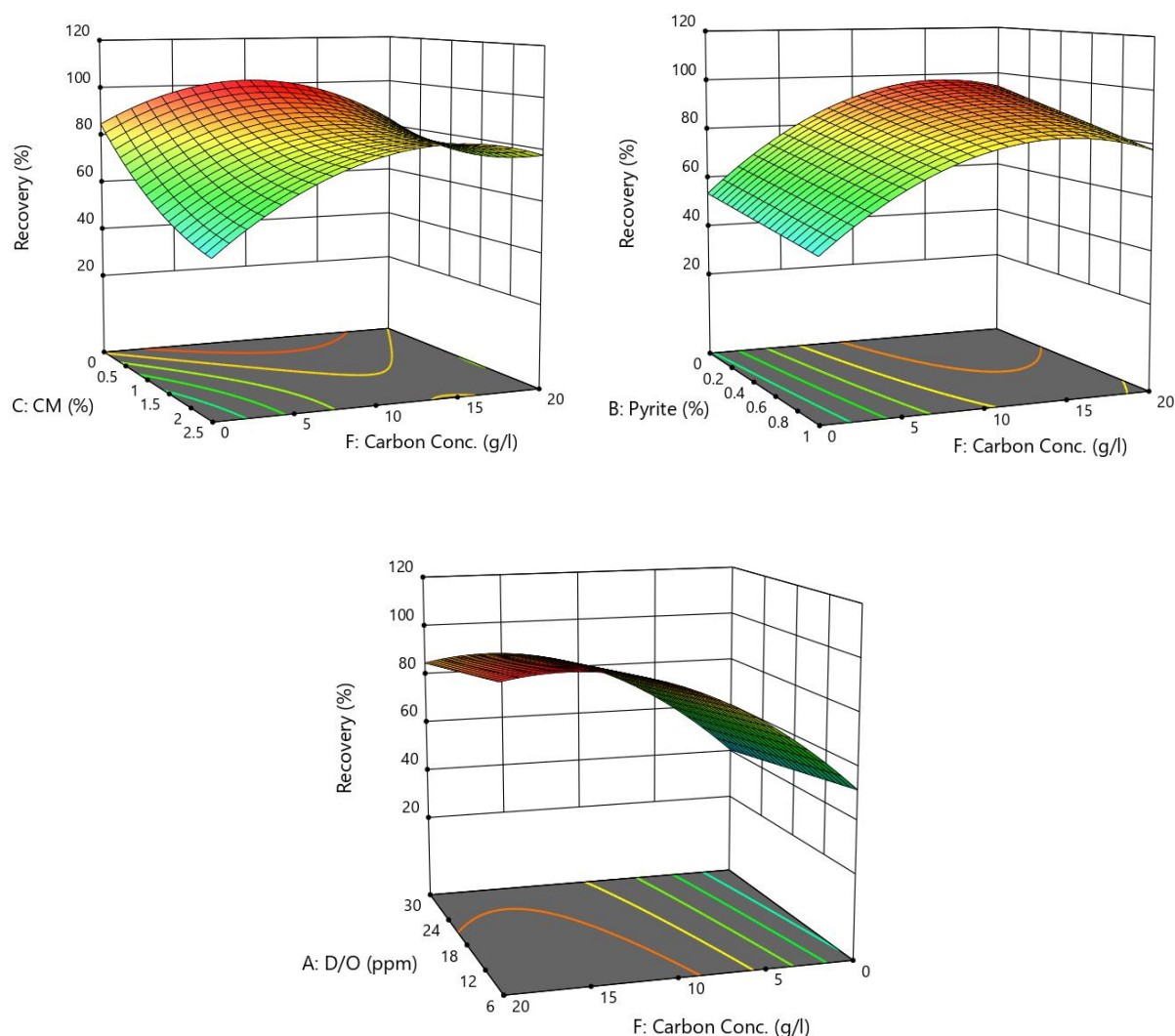


Figure 3. 3D surface plot interactions of activated carbon concentration, CM content, Pyrite content and D/O.

3.2.2. Combined Effect of Activated Carbon Concentration, Pyrite and CM Content on Gold Recovery

The interplay between CM content and activated carbon content as against gold recovery is indicated as a 3D- plot in Figure 3a. The data suggests that increasing the content of CM with no activated carbon content projected very low recoveries due the preg-robbing effect of the CM. However, even at high CM content, elevated activated carbon concentration caused a significant increase in gold recovery. The high activity and capacity of activated carbon when introduced, competes with the CM present, adsorbing a higher percentage of the aurocyanide complexes. This highlights the importance of increasing activated carbon contents for gold ores with high carbonaceous matter content. Regardless, it is crucial for large scale operations to optimize activated carbon addition to maximize gold recovery rates while maintaining cost-effectiveness. This balance is particularly relevant in

sustainable operations, where efficient resource utilisation is paramount.

A critical observation of Figure 3b shows a deteriorating effect of high pyrite content on gold recovery. However, in the presence of increasing activated carbon content, there was an appreciable increase in gold recovery but to an extent where the recoveries plateau. Per the module factor interactions, results suggest that ores with such complex mineralogy can behave differently even with elevated increase in operational parameters. Some studies have shown that the presence of activated carbon can enhance the precipitation of elemental sulphur from solution [53]. With the precipitation of elemental sulphur from solution cyanide consumption may reduce. This may explain the reason behind the increasing gold recovery with increasing activated carbon content. This underscores the importance of tailored process design in gold extraction, offering a framework to address challenges posed by carbon and pyrite interactions. Figure 3c portrays the combined effect of D/O and carbon concentration on gold recovery. Increasing carbon concentration sees an increase in

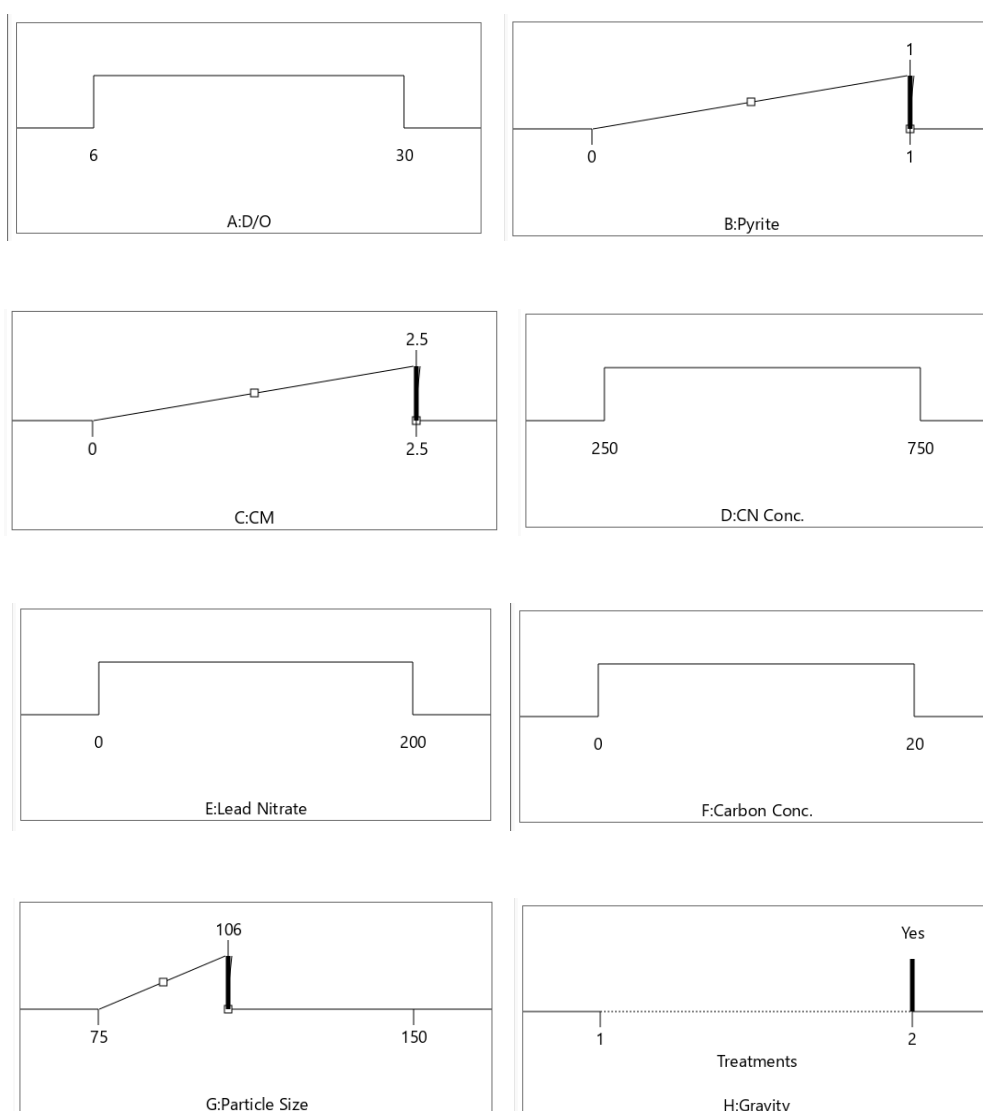
gold recovery however no appreciable increase in was observed while D/O was altered. Increasing D/O can increase the rate of cyanide consumption and high pyrite dissolution which may in turn, reduce gold leaching kinetics and affect recovery in the long run [54]. The may explain why there was no appreciable increase in gold recovery with the high D/O levels.

3.3. Optimisation of Process Parameters

Commercial gold mining operations which use agitation method of leaching is cost intensive due to the comminution processes and subsequent hydrometallurgical downstream processes. It is important to monitor and implement systems that target optimising operation parameter and reducing operational cost while maximizing gold recovery and profitability. Using tradition approach of laboratory optimisation runs may be time consuming and resource intensive. Hence, the use of modelling tools is vital to modern optimisation designs. For gold mining operations, gold recoveries >90%

are desired while cutting down on reagent consumption. It is therefore imperative to optimise process parameters especially with the nature of complex ores that are currently encountered in gold mining operations.

Numerical optimisation was performed using the desirability function in Design Expert Software to determine the optimal conditions for the operational parameters. Figure 4 illustrates the multi-objective optimisation ramps for all the input variables and recovery as the output variable. Preconcentration by gravity separation was chosen since the optimisation targeted higher recoveries (>90 %) and the single effect (Figure 2h) showed improved recoveries with gravity pre-concentration. The optimisation report included 100 solutions encompassing various levels of independent variables. Solutions with a maximum desirability value of 1 were identified as the optimised conditions for the cyanidation of complex gold ores. The response values for five chosen solutions under optimised preparation conditions for recovery ranged from 90.37-96.94% as predicted by the model.



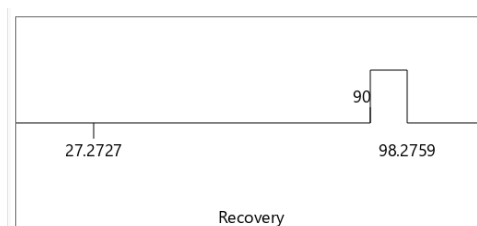


Figure 4. Multi-object optimisation ramps for input variables and output variable.

RSM Model Validation

The model's suitability and accuracy in predicting response variable was assessed with 5 of the 100 optimised preparation conditions validated through experimental execution under these settings. The experimental results under optimised preparation circumstances yielded recovery ranges of ap-

proximately 89-95% as depicted in Table 5. The experimental results for gold recovery align closely with the model-predicted values, demonstrating the model's accuracy in predictions. This indicates that the model is dependable and suitable for future forecasts.

Table 5. Optimum conditions, experimental and predicted value if response at optimised conditions.

Number	D/O ppm	Pyrite %	CM %	CN Conc. ppm	Lead Nitrate g/t	Carbon Conc. g/l	Particle Size µm	Gravity	Recovery (Predicted), %	Desirability	Recovery (Actual), %
1	30	1	2.5	250	0	20	106	Yes	90.719	1	94.59
2	29.2	1	2.5	749.999	193.334	19.333	106	Yes	90.695	1	92.94
3	7.756	1	2.5	275.898	175.11	9.639	106	Yes	90.374	1	90.59
4	21.313	1	2.5	747.313	13.17	10.683	106	Yes	96.94	1	94.12
5	15.206	1	2.5	406.216	175.727	12.094	106	Yes	92.623	1	89.41

4. Conclusions

Necessitated by the increasing prevalence of complex transition gold ores which are characterised by high pyrite and CM, this study employed RSM with a Central composite design to systematically assess and optimise key mineralogical and leaching parameters to overcome challenges such as preg-robbing, cyanide consumption and passivation effect. Statistically, a significant reduced cubic model (F-value = 14.14, $p < 0.0001$) was developed with R^2 of 0.831. The dominant influence of activated carbon concentration and (p < 0.001) and CM content (p < 0.0001) on gold recovery was highlighted with activated carbon presence duly mitigating preg-robbing effect of CM by competitively adsorbing aurocyanide complexes. Increasing pyrite content (p = 0.05) negatively impacted gold recovery due to cyanide and oxygen consumption, while lead nitrate addition (p = 0.0314) enhanced leaching efficiency by suppressing pyrite interference and enhancing oxidation.

Optimisation studies identified conditions achieving

predicted recoveries of 90-97%, which were experimentally validated, yielding 89-95% recovery. This confirmed the model's accuracy and robustness. This data-driven framework could provide the basis for optimising operating parameters while maximising gold recovery for high pyrite and CM complex ores. However, it is worth noting that this framework will be very useful when the ores contain unmineralized/lowly mineralised pyrite. This study projects a framework that can be utilised by mining companies treating ores contain high content of unmineralized/lowly mineralised pyrite as well as high CM to transform the processing of such challenging gold ores by replacing heuristic approaches with quantitative, statistically validated decision-making. The industrial impact may extent to a boost in profitability (increase in recoveries by optimised leaching), high operational precision (optimised parameter), waste reduction (reagent usage) and resource expansion (increasing the economic viability for processing complex transition gold ore deposits).

Abbreviations

RSM	Response Surface Methodology
CM	Carbonaceous Matter
D/O	Dissolved Oxygen
OFAT	One-Factor-at-a-Time
DoE	Design of Experiment
CCD	Central Composite Design
FFD	Full Factorial Design
BBD	Box-Behnken Design
ANOVA	Analysis of Variance
XRD	X-Ray Diffractometry
R ² _{adj}	Adjusted R-squared
R ²	Correlation co-efficient
GRG	Gravity Recoverable Gold
Conc.	Concentration

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Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

Appendix

Table 6. Experimental runs as against Response (Recovery%) per run.

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8	Response
Run	A: D/O	B: Pyrite	C: CM	D: CN Conc.	E: Lead Nitrate	F: Carbon Conc.	G: Particle Size	H: Gravity	Recovery
	ppm	%	%	ppm	g/t	g/l	microns		%
1	30	0	2.5	750	200	0	106	No	76.74
2	30	1	0	250	0	0	106	No	90.74
3	6	0	2.5	750	200	0	75	Yes	78.57
4	6	0	2.5	250	0	20	75	No	77.78
5	18	0.5	1.25	500	100	10	75	No	89.90
6	6	0	2.5	750	200	0	75	No	27.27
7	18	0.5	1.25	500	100	10	90	No	92.16
8	30	0.5	1.25	500	100	10	90	No	93.10
9	6	0	2.5	250	0	0	106	Yes	89.47
10	30	0	2.5	250	200	0	75	Yes	82.14
11	18	0.5	1.25	500	200	10	90	No	94.83

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8	Response
Run	A: D/O	B: Pyrite	C: CM	D: CN Conc.	E: Lead Nitrate	F: Carbon Conc.	G: Particle Size	H: Gravity	Recovery
	ppm	%	%	ppm	g/t	g/l	microns		%
12	6	1	0	250	200	0	75	No	93.94
13	18	0	1.25	500	100	10	90	No	93.10
14	18	0.5	1.25	500	0	10	90	Yes	91.43
15	18	0.5	1.25	500	100	10	90	No	93.10
16	18	0	1.25	500	100	10	90	Yes	80.00
17	30	0	2.5	750	0	0	75	No	41.67
18	18	0.5	1.25	250	100	10	90	No	94.83
19	6	1	0	250	0	20	106	No	86.27
20	18	0.5	1.25	500	100	20	90	No	94.83
21	30	1	0	250	200	20	106	No	88.24
22	30	1	2.5	250	0	20	106	Yes	88.37
23	18	0.5	0	500	100	10	90	No	98.28
24	6	0.5	1.25	500	100	10	90	Yes	88.57
25	18	0.5	1.25	500	100	10	106	Yes	88.37
26	6	0	2.5	250	0	20	75	Yes	96.43
27	6	1	2.5	250	200	0	106	Yes	30.56
28	30	1	2.5	250	0	20	106	No	70.59
29	6	0	0	750	0	0	106	No	96.83
30	18	0.5	1.25	750	100	10	90	Yes	91.43
31	6	1	2.5	250	200	0	106	No	30.00
32	30	0	0	750	200	0	75	Yes	96.55
33	18	1	1.25	500	100	10	90	No	91.38
34	30	1	0	750	0	0	75	No	94.87
35	30	1	0	750	0	0	75	Yes	92.86
36	30	1	0	250	0	20	75	No	91.92
37	30	0	2.5	750	200	20	75	No	97.98
38	6	1	2.5	250	200	20	75	No	93.94
39	18	0.5	1.25	500	100	20	90	Yes	56.90
40	30	1	0	750	0	20	106	Yes	93.02
41	30	1	0	250	0	20	75	Yes	92.86
42	6	1	0	250	0	20	106	Yes	88.37
43	6	1	2.5	250	0	0	75	No	42.31
44	6	1	2.5	250	0	0	75	Yes	44.44
45	18	0.5	1.25	500	100	10	90	Yes	97.14
46	6	0	0	750	0	20	75	No	95.96

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8	Response
Run	A: D/O	B: Pyrite	C: CM	D: CN Conc.	E: Lead Nitrate	F: Carbon Conc.	G: Particle Size	H: Gravity	Recovery
	ppm	%	%	ppm	g/t	g/l	microns		%
47	6	0	0	750	0	20	75	Yes	60.71
48	30	1	0	250	0	0	106	Yes	85.71
49	30	0	2.5	750	200	0	106	Yes	33.33
50	30	0	0	750	200	0	75	No	96.00
51	6	0	0	750	200	20	106	Yes	88.37
52	6	1	2.5	750	0	0	106	No	66.67
53	6	0.5	1.25	500	100	10	90	No	96.55
54	6	0	0	750	200	20	106	No	98.04
55	30	1	2.5	750	200	20	106	No	92.16
56	30	0.5	1.25	500	100	10	90	Yes	97.14
57	30	0	0	250	200	0	106	Yes	85.71
58	18	0.5	1.25	500	100	10	90	No	96.55
59	6	1	0	750	200	20	75	Yes	89.29
60	18	0.5	1.25	500	100	10	106	No	98.04
61	6	0	2.5	250	0	0	106	No	60.78
62	18	1	1.25	500	100	10	90	Yes	94.29
63	6	1	2.5	250	200	20	75	Yes	96.43
64	30	1	2.5	750	200	0	75	Yes	40.00
65	30	1	2.5	750	200	0	75	No	80.77
66	18	0.5	1.25	500	100	10	75	Yes	85.71
67	18	0.5	1.25	500	100	0	90	No	70.00
68	30	1	0	250	200	20	106	Yes	90.70
69	18	0.5	1.25	500	0	10	90	No	96.55
70	6	0	0	250	200	20	75	No	95.96
71	18	0.5	1.25	500	100	10	90	Yes	97.14
72	30	0	2.5	250	200	0	75	No	65.79
73	18	0.5	1.25	750	100	10	90	No	98.28
74	30	0	0	250	200	0	106	No	91.67
75	18	0.5	2.5	500	100	10	90	Yes	94.29
76	18	0.5	1.25	500	100	10	90	Yes	97.14
77	30	0	2.5	750	200	20	75	Yes	92.86
78	30	0	2.5	750	0	0	75	Yes	57.14
79	6	0	0	250	200	20	75	Yes	92.86
80	6	0	2.5	750	0	20	106	Yes	93.02
81	18	0.5	1.25	250	100	10	90	Yes	97.14

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8	Response
Run	A: D/O	B: Pyrite	C: CM	D: CN Conc.	E: Lead Nitrate	F: Carbon Conc.	G: Particle Size	H: Gravity	Recovery
	ppm	%	%	ppm	g/t	g/l	microns		%
82	6	0	2.5	750	0	20	106	No	96.08
83	18	0.5	0	500	100	10	90	Yes	97.14
84	30	1	0	750	0	20	106	No	96.08
85	30	0	0	250	0	20	106	Yes	93.02
86	30	0	0	250	0	20	106	No	92.16
87	6	1	0	250	200	0	75	Yes	80.00
88	18	0.5	1.25	500	200	10	90	Yes	97.14
89	18	0.5	1.25	500	100	0	90	Yes	68.42
90	30	1	2.5	750	200	20	106	Yes	97.67
91	18	0.5	2.5	500	100	10	90	No	98.28
92	6	0	0	750	0	0	106	Yes	90.00
93	6	1	2.5	750	0	0	106	Yes	61.54
94	6	1	0	750	200	20	75	No	97.98

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Biography



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Research Field

Francis Kwaku Darteh: precious metals and extractive metallurgy, geometallurgy, biotechnology and bioremediation techniques, nanotechnology

Kojo Twum Konadu: Hydrometallurgy, Biohydrometallurgy of precious and base metals, Solid characterization

Grace Ofori-Sarpong Akuffo: microbial-mineral interaction, environmental biohydrometallurgy, geometallurgy, acid mine drainage issues, precious minerals beneficiation

Richard Kwasi Amankwah: gold beneficiation, water quality management, microwave processing of minerals, small-scale mining, medical geology, microbial mineral recovery and environmental biotechnology