Research Article

Application of Response Surface Methodology (RSM) for Simultaneous Optimization of Kinetic Parameters Affecting Gold Leaching in Thiosulfate Based Media: A Statistical Approach

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Over the years, the use of new alternative lixiviants for gold extraction has been investigated to overcome the environmental concerns resulting from the cyanidation process. Moreover, with global economic factors causing a decline in gold prices, it is crucial that novel hydrometallurgical methods of extracting gold minimise operational costs by using low-priced reagents such as thiosulfate. In the current study, the response surface methodology (RSM) approach is used to optimize the kinetic factors (temperature and copper, ammonia, and thiosulphate concentration) affecting gold leaching. Gold ore assayed at 16 g/t was characterized through X-ray fluorescence and X-ray diffraction spectrometric analysis as well as scanning electron microscope-energy dispersive spectrometric technique. Gold ore was predominantly siliceous with minor pyritic content. The results indicate a strong relationship between the actual gold leaching recovery data and the RSM model. Correlation coefficients R^2 and adjusted R^2 are equivalent to 0.9869 and 0.9817. Gold leaching in copper-ammonia-thiosulfate media is best described as a surface chemical reaction-controlled process, suggesting that gold dissolution in thiosulfate is considerably affected by the increase in temperature. The effect of temperature is mostly significant, contributing up to 64.65% of the gold recovery response model. The contribution percentages of the effects of time, thiosulfate $[S_2O_3]$, ammonia $[NH_3]$, and copper $[Cu]$ concentrations were calculated as 12.81%, 5.88%, 5.19%, and 4.65%, respectively. All investigated kinetic parameters were found statistically significant with $p$value <0.05. The optimal concentrations of gold leaching media to achieve potentially complete dissolution of gold from its ore in copper-ammoniacal thiosulphate media based on the effect of the investigated parameters were 0.5 M S_2O_3, 3 M NH_3, and 0.003 M Cu^{2+} with a desirability value equivalent to unity ($d = 1.000$).

1. Introduction

In human history, the extractive metallurgy of gold has always had a preponderant socioeconomic impact because of its distinctive physical and chemical properties, the aesthetic appeal, and the sparseness of gold [1, 2]. For more than a century, cyanide solution has been predominantly used as the lixiviant agent to extract gold from its ores [3]. However, the use of cyanide is associated with an environmental impact ascribed to its virulent and lethal effects on humans, terrestrial animals, and aquatic organisms [4, 5]. Moreover, gold complexation with cyanide is characterized by slow reaction kinetics and consumes large quantities of

reagents in the presence of refractory sulfidic and carbonaceous ores as well as copper-rich gold ores; leading to an increase in the leaching process cost thereof [6]. This has given dawn to the development of several other gold extraction methods with different substitute reagents for cyanide such as thiosulfate, thiocyanate, thiourea, halides, and bisulfide [7]. Amongst the aforementioned methods, gold leaching in thiosulfate media has been mostly developed and carried out due to the fact that it is regarded as an environmentally friendly and cost-effective process with high gold extraction efficiency [8, 9]. The overall redox reaction for gold leaching in the dissolved oxygen—thiosulfate system is given as follows[10]:
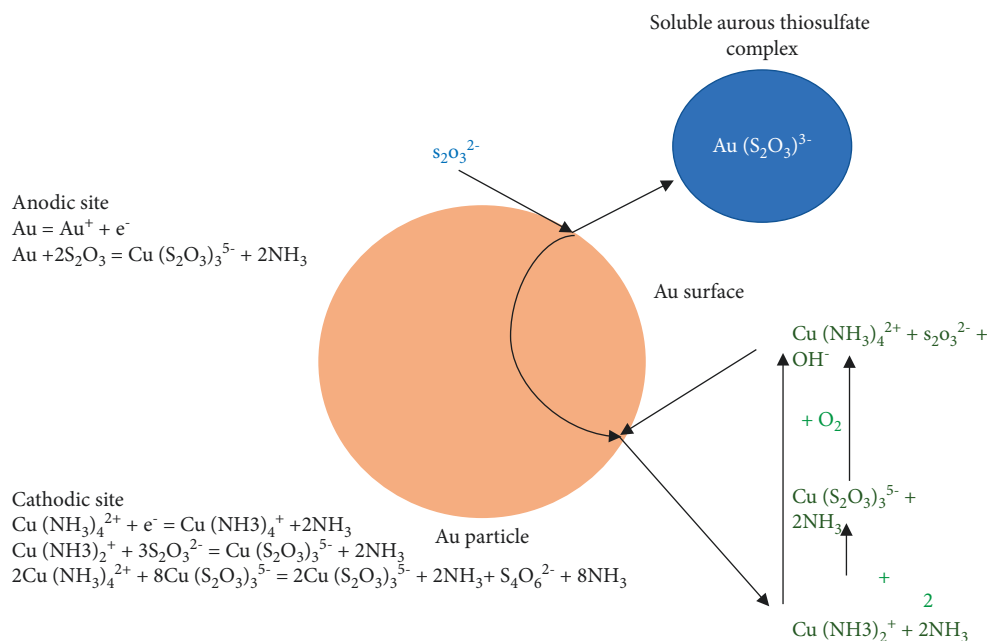
Soluble aurous thiosulfate
complex

$Au (S_2O_3)_2^{3-}$

$s_2o_3{}^{2-}$

Anodic site
$Au = Au^+ + e^-$
$Au + 2S_2O_3 = Cu (S_2O_3)_3^{5-} + 2NH_3$

Au surface

$Cu (NH_3)_4^{2+} + s_2o_3{}^{2-} +$
OH^-

$+ O_2$

$Cu (S_2O_3)_3^{5-} +$
$2NH_3$

Cathodic site
$Cu (NH_3)_4^{2+} + e^- = Cu (NH3)_4^+ + 2NH_3$
$Cu (NH3)_2^+ + 3S_2O_3^{2-} = Cu (S_2O_3)_3^{5-} + 2NH_3$
$2Cu (NH_3)_4^{2+} + 8Cu (S_2O_3)_3^{5-} = 2Cu (S_2O_3)_3^{5-} + 2NH_3 + S_4O_6^{2-} + 8NH_3$

Au particle

$+$

2

$Cu (NH3)_2^+ + 2NH_3$

FIGURE 1: Electrochemical gold leaching process in cupric ammonia complex thiosulfate media [2].

$$4Au + 8S_2O_3^{2-} + O_2 + 2H_2O \longrightarrow Au (S_2O_3)_2^{3-} + 4OH^-. \tag{1}$$
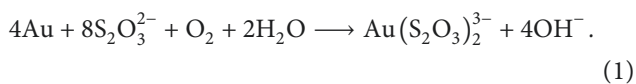
Au+ ions and $S_2O_3^{2-}$ form stable $Au (S_2O_3)_2^{3-}$ complex attributable to the presence of peripheral sulphide like S atoms playing the role of ligands [11] . However, gold leaching is hindered due to the limited amount of dissolved oxygen. Thus, alternative oxidants such as Cu^{2+} and Co^{3+} and Fe^{3+} are used to catalyse gold leaching process [10, 12, 13]. The current study focuses on the addition of Cu^{2+} cupric ions as an oxidant. The following equation describes the mechanism of gold oxidative leaching by thiosulphate in presence of cupric ions [14]. Schematical diagram illustrating the overall mechanism of the gold leaching process is shown in Figure 1.

$$Au + 5S_2O_3^{2-} + Cu (NH_3)_4^{2-} \longrightarrow Au (S_2O_3)_2^{3-} \\ + Cu (S_2O_3)_2^{5-} + 4NH_3. \tag{2}$$
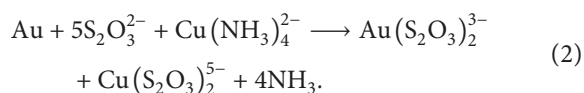
Several studies on gold leaching in thiosulfate-based solutions have been carried out over the years [13–16]. Gold leaching in thiosulphate media is associated with electrochemical processes [12]. The anodic oxidation kinetics of gold with $S_2O_3^{2-}$ complexing agent stipulate is characterised by fast leaching rates [17, 18]. Several research papers suggest that ammonia plays the role of a Cu^{2+} ion stabilizer at high pH, forming $Cu (NH_3)_4^{2-}$ [19, 20]. $Cu (NH_3)_4^{2-}$ complex in Figure 1 adsorbs onto the gold surface and oxidizes it, thus compensating for the dissolved oxygen deficiency. Despite the extensive amount of work on the underlying mechanism of gold leaching, to the best of the authors' knowledge up to the present day, there is a scant literature on the statistical modelling and computational analyses which are merely useful for simultaneous optimisation of multiple kinetic

parameters to enhance gold leaching recovery in copper-ammonia complex and thiosulphate based media. Moreover, most previous studies focused on the optimisation of a single kinetic parameter while maintaining the other parameters constant. Interactions amongst variable factors and variable responses were certainly not taken into consideration. [21]. In the current study, the response surface methology (RSM) approach is used to optimize the kinetic factors (temperature and copper, ammonia, and thiosulphate concentration) affecting gold leaching. RSM is an advanced, rapid, highly accurate, and approved tool to evaluate the interactions amongst leaching kinetic factors and enhance gold recovery [22–24]. Furthermore, the evaluation of the controlling step model has been carried out to provide an insight on the kinetics of gold leaching in ammoniacal thiosulphate based solution in the presence of catalytic cupric ions.

2. Materials and Methods

2.1. Materials. Gold ore was supplied from the Anglo Ashanti mine. The chemical composition of the gold ore is given in Table 1. The X-ray diffractogram and SEM micrograph of the ore are shown in Figures 2 and 3. The X-ray diffraction and SEM-EDS analysis revealed that the ore was predominantly siliceous with a minor pyritic content. Au grade was determined by the lead collection fire assay method. The obtained Au prill after cupellation at 1000°C was subsequently dissolved in aqua regia solution from which aliquots were collected and analyzed through inductively coupled plasma (ICP) spectrometric to determine the gold concentration [Au]. The mean gold ore grade was 16 g/t. pure sodium thiosulfate (99% pure $Na_2S_2O_3$), copper sulfate (99%pure $CuSO_4·5H_2O$), aqueous ammonia (25%v/v NH_3), and sodium hydroxide (99% pure NaOH) were supplied from Ace chemicals.

TABLE 1: Chemical composition and mineralogy of gold ore.

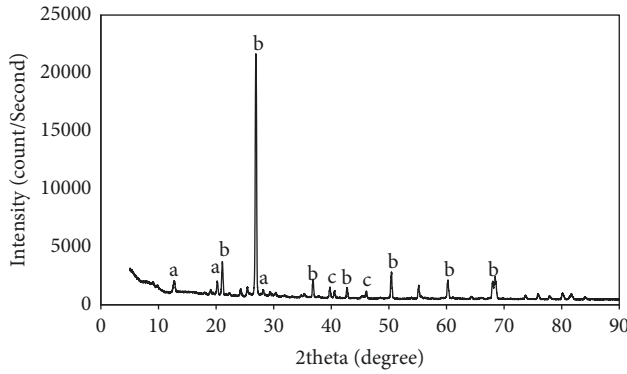| MgO	Al$_2$O$_3$	SiO$_2$	SO$_3$	TiO$_2$	Fe$_2$O$_3$	CuO	ZnO	Rb$_2$O	SrO	ZrO$_2$	PbO
1.95	8.86	71.83	1.53	0.70	9.80	0.02	0.02	0.01	0.02	0.07	0.01

FIGURE 2: X-ray diffraction pattern of gold ore. (a) albite, (b) quartz, and (c) pyrite.

2.2. Leaching Experiment.

Prior to leaching, the gold ore particle size was reduced to 80%passing 100 μm to ensure that the gold particles are physically liberated and increase the surface area of particles. The pH, agitation speed, and solid percent, respectively, equivalent to 10.5, 300 rpm, and 20% were maintained constant for all experiments. Investigated leaching parameters are given in Table 2. Gold ore samples were leached in a 1-liter jacketed Pyrex glass reactor equipped with a turbine blade impeller and a circulating water heating system to control the leaching temperature. The experimental setup is illustrated in Figure 4. Aliquots from the pregnant leach solutions (PLS) were subsequently analyzed through ICP. The calculation of Au recovery% was carried out using the following equation[25]:

$$\text{Recovery\%} = 100 \times \frac{[Au^{n+}] \times V}{m_s \times G},\tag{3}$$

where $[M^{n+}]$, V, m_s, and G represent leached metal ion concentration in g.L^{-1} in the PLS, the pregnant leach solution (PLS) volume in liters, the mass of sample ore in ton, and the gold metal content in g/t respectively.

2.3. Design of Experiment (DoE).

The RSM design of the experiment consisted of 2-level factorial half-full central composite having 32 cube points and 20 axial points. A total of 54 experimental runs were obtained from 27 base runs and 2 replicates were carried out. The 27 base runs with varied kinetic conditions are presented in Table 3. The gold recovery response was analyzed using Minitab 17 statistical software. Validity of the RSM model was based on the analysis of variance (ANOVA). Strong relationship with the model is observed when the correlation coefficients R^2 and adjusted R^2 approach unity. Factor terms are considered statistically significant when p-value <0.05. Mathematical expressions for R^2 and adjusted R^2 are given in equations (4) and (5). RSM response curve is a second-order model with square and 2-way interactions. General form of the multiple linear regression is given in the following equation[26]:

$$R^2 = 1 - \frac{\text{RSS}}{\text{TSS}},\tag{4}$$

$$\text{Adj.}R^2 = 1 - \frac{\left(1 - R^2\right)(N - 1)}{N - p - 1},\tag{5}$$

where RSS and TSS represent the total sum of squares of residuals and the total sum of squares. N and p denote the number of sample sizes and the number of independent variables, respectively.

$$\begin{aligned}
y = {} & \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + \beta_{12} X_1 X_2 + \cdots \\
& + \beta_{13} X_1 X_3 + \cdots + \beta_{1k} X_1 X_k + \beta_{23} X_2 X_3 + \beta_{24} X_2 X_4 \\
& + \cdots + \beta_{2k} X_2 X_k + \cdots + \beta_{k-1k} X_{k-1} X_k \\
& + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \cdots \beta_{kk} X_k^2 X^k + \varepsilon,
\end{aligned}\tag{6}$$

where y, k, and ε denote the response function, the number of term factors, and the error constant, respectively. $X_1, X_2, \ldots, X_k$ are term factors. $\beta_0, \beta_1, \beta_k, \ldots, \beta_{kk}$ represent multivariate regression coefficients.

2.4. Characterization.

Information on the elemental composition of the gold ore was provided using the Rigaku ZSX primus II X-ray fluorescence spectrometer (XRF) operating at 40 mV and 50 kV with a Rhodium X-ray source. The qualitative mineralogical data were provided from the analysis of the diffraction patterns using PDXL software. The diffraction pattern was obtained from the Rigaku Ultima IV diffraction spectrometer operating at 30 mV and 40 kV and equipped with a copper X-ray source and scanning from 5 to 90 at a speed of 0.5°/min. Information on the morphology of the gold samples was provided using the Vega 3 scanning electron microscope fitted with an energy dispersive spectrometer operating at a high voltage (20 V) and a beam intensity range of 10 to 16 W/m^2. The GBC scientific inductively coupled plasma spectrometer (ICP) was used to determine the concentration of gold in the PLS. A particle size analyzer was utilized to analyze the particle size distribution of gold ore.

3. Results and Discussion

3.1. RSM Model Analysis.

Gold leaching recovery response as a function of the studied kinetic parameters has been investigated using the experimental data at different conditions varying according to the RSM central composite design. The analysis of variance of experimental data indicates that the effects of all investigated kinetic parameters are statistically significant. The respective significance values (p-values) of all kinetic parameters in the current study were considerably lower than the threshold significance level or
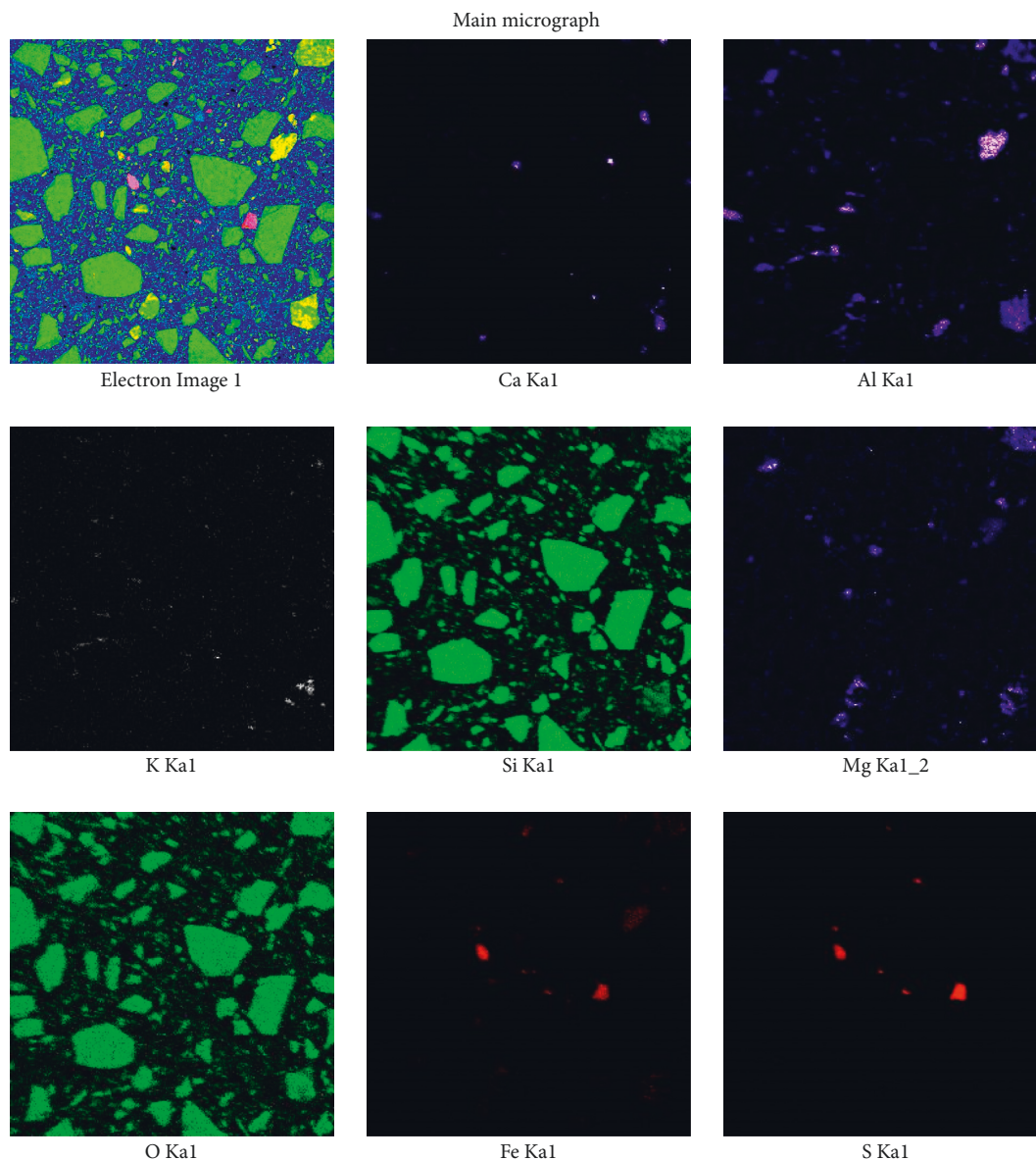
Main micrograph

FIGURE 3: SEM-EDS mapping analysis of gold ore samples.

TABLE 2: Kinetic leaching parameters.

Kinetic parameters	Range
Temperature (°C)	25–45
Time (hour)	1–5
Thiosulphate concentration (mol.L^{-1})	0.5–2.5
Ammonia concentration (mol.L^{-1})	1–3
Copper concentration (mol.L^{-1})	0.001–0.003

alpha level ($p < 0.05$) [23, 24, 26]. Statistical data are presented in Table 4. The normal probability plot is relatively straight, and the distribution of residuals is unimodal. The evaluation of these two plots in Figure 5 provides satisfactory evidence of a strong relationship between the experimental data and the gold leaching recovery response model [27]. Results stipulate that the effect of temperature is mostly significant, contributing up to 64.65% to the gold recovery response model. The contribution percentages of the effects of time, thiosulfate [S$_2$O$_3$], ammonia [NH$_3$], and copper [Cu] concentrations were calculated as 12.81%, 5.88%, 5.19%, and 4.65%, respectively. The squared and 2-way interactions only account for 5.52% increase to the model. From RSM analysis, a multivariate regression response curve in the following equation has been generated with an appreciable correlation coefficients R^2 and an adjusted R^2 equivalent to 0.9869 and 0.9817, respectively. The results of this study corroborate the findings of previous research work based on gold leaching in thiosulfate-copper-ammonia media [20].

$$
\begin{aligned}
R\% = & -130.4 + 5.955A + 16.59B + 24.37C + 20.99\,D \\
& + 16612E - 0.03845A^2 - 0.2005AB - 0.2313A \\
& C - 0.3108A\,D - 196.2AE - 1.469BC - 0.946B\,D \\
& - 1293BE - 2.389C\,D - 1585CE,
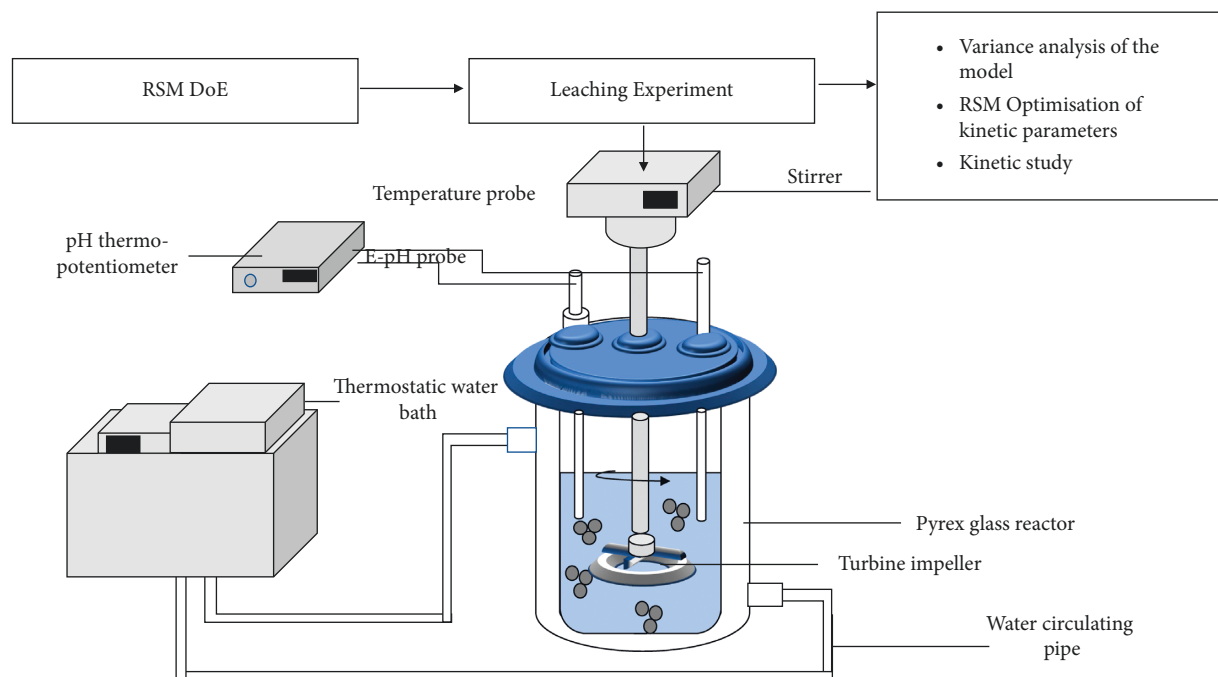\end{aligned}
\tag{7}
$$

FIGURE 4: Leaching experimental setup diagram.

TABLE 3: Response surface design of experiments.

Temp (°C)	Time (h)	$[S_2O_3]$ (mol.L^{-1})	$[NH_3]$ (mol.L^{-1})	$[Cu]$ (mol.L^{-1})	Actual gold recovery	Predicted gold recovery
30	2	1	1.5	0.0025	77.72	76.75
40	2	1	1.5	0.0015	89.62	88.90
30	3	1	1.5	0.0015	80.65	81.70
40	3	1	1.5	0.0025	99.32	98.40
30	2	2	1.5	0.0015	78.33	78.73
40	2	2	1.5	0.0025	98.80	98.13
30	3	2	1.5	0.0025	89.83	89.68
40	3	2	1.5	0.0015	100	99.68
30	2	1	2.5	0.0015	77.67	77.58
40	2	1	2.5	0.0025	98.14	97.77
30	3	1	2.5	0.0025	91.00	91.16
40	3	1	2.5	0.0015	98.99	98.78
30	2	2	2.5	0.0025	86.85	88.69
40	2	2	2.5	0.0015	96.56	97.01
30	3	2	2.5	0.0015	89.78	90.40
40	3	2	2.5	0.0025	99.56	100.00
25	2.5	1.5	2	0.002	75.66	74.95
45	2.5	1.5	2	0.002	99.56	100.00
35	1.5	1.5	2	0.002	84.63	86.01
35	3.5	1.5	2	0.002	99.06	97.59
35	2.5	0.5	2	0.002	86.95	87.88
35	2.5	2.5	2	0.002	96.73	95.73
35	2.5	1.5	1	0.002	87.61	88.12
35	2.5	1.5	3	0.002	96.08	95.49
35	2.5	1.5	2	0.001	87.56	88.31
35	2.5	1.5	2	0.003	95.86	95.29
35	2.5	1.5	2	0.002	90.11	91.80

where $R\%$ represents the Au leaching recovery % and the term factors A, B, C, D, and E denote the temperature (°C), time (hour), and concentration in mol. L^{-1} of thiosulphate $[S_2O_3]$, ammonia [NH3], and copper [Cu], respectively.

3.2. Surface Response

3.2.1. Effects of Temperature and Time on the Gold Leaching Recovery.
Results in Figure 6 show that gold recovery

TABLE 4: Statistical data of analysis of variance (ANOVA).

| Source	DF	Adj SS	Adj MS	F value	p value	Contribution%
Model	15	3101.34	3101.34	190.65	$p \leq 0.01$	98.69
Linear		2927.95	2927.95	539.97	$p \leq 0.01$	93.17
A: Temperature (°C)	1	2031.53	2031.53	1873.28	$p \leq 0.01$	64.65
B: Time (hour)	1	402.58	402.58	371.22	$p \leq 0.01$	12.81
C: [S_2O_3] (mol. L^{-1})	1	184.81	184.81	170.41	$p \leq 0.01$	5.88
D: [NH_3] (mol. L^{-1})	1	163.01	163.01	150.32	$p \leq 0.01$	5.19
E: [Cu] (mol. L^{-1})	1	146.02	146.02	134.64	$p \leq 0.01$	4.65
Square	1	49.28	49.28	45.44	$p \leq 0.01$	1.57
A^2	1	49.28	49.28	45.44	$p \leq 0.01$	1.57
2-way interaction	9	124.11	124.11	12.72	$p \leq 0.01$	3.95
AB	1	32.16	32.16	29.65	$p \leq 0.01$	1.02
AC	1	10.70	10.70	9.87	0.003	0.34
AD	1	19.38	19.38	17.82	$p \leq 0.01$	0.62
AE	1	7.70	7.70	7.10	$p \leq 0.01$	0.25
BC	1	17.26	17.26	15.91	0.011	0.55
BD	1	7.16	7.16	6.61	$p \leq 0.01$	0.23
BE	1	13.38	13.38	12.33	0.014	0.43
CD	1	11.41	11.41	10.52	0.001	0.36
CE	1	5.02	5.02	4.63	0.002	0.16
Error	38	41.21	41.21		0.038	1.31
Total	53	3142.55	3142.55			

(a)

(b)
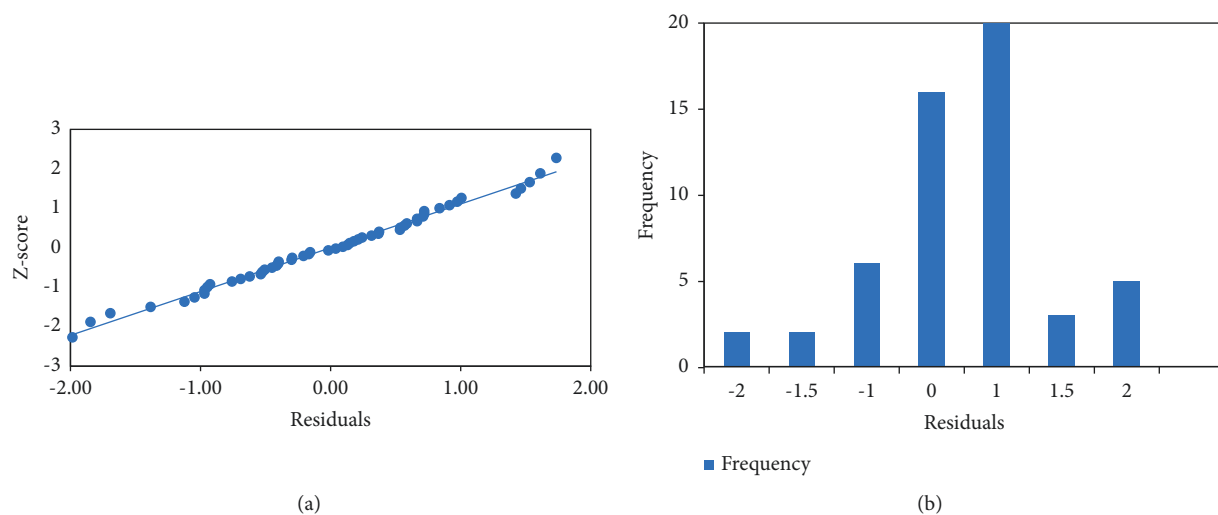
FIGURE 5: Analysis of the model based on normal probability plot (a) and residual histogram (b).

increases with the rise in temperature. The rationale behind the observed response possibly lies in the fact that the rise in temperature up to some extent provides sufficient kinetic energy to the present reactant particles, leading to the increase in the collision frequency [28, 29]. Temperature positively affects both the kinetics and the thermodynamic feasibility of gold leaching [30]. The gold leaching rate determining step is chemically controlled with an activation energy equivalent to 60 KJ ± 10 K [31]. This implies that the gold leaching rate is expected to increase exponentially with the rise in the temperature [32]. However, previous studies stipulated that the rise in temperature above 60°C is the causative factor of evaporation of ammonia, leading to a decrease in pH and affecting the stability of the copper-ammonia Cu $(NH_3)_4^{2-}$ complex which is regarded as the

oxidant or gold leaching catalyst and the degradation of $S_2O_3^{2-}$ complexing ions [33]. Consequently, Au leaching rate is ascertained to be negatively influenced at an elevated temperature [34]. On the other hand, it is observed that gold leaching is time-dependent. Gold leaching for 3 hours to 5 hours yielded the highest gold recovery. In Figure 7, the kinetics of gold leaching in thiosulphate solution based on the shrinking core model (SCM) is investigated.

3.2.2. Effect of Concentration on Gold Recovery. Results confirmed that the gold leaching process is thermodynamically feasible in the presence of $S_2O_3^{2-}$ ions at pH 10.5. At high pH, these ions form a stable and soluble Au(S_2O_3)$_2^{3-}$ [11]. The high pH condition prevents the destruction of
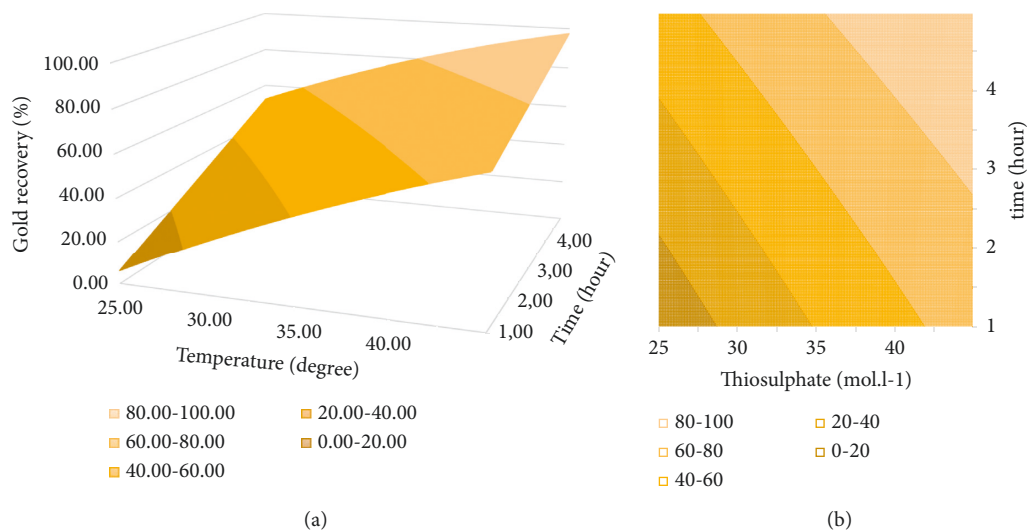
(a)

(b)

FIGURE 6: Surface response and contour plots of gold recovery versus temperature and time.

(a)

(b)
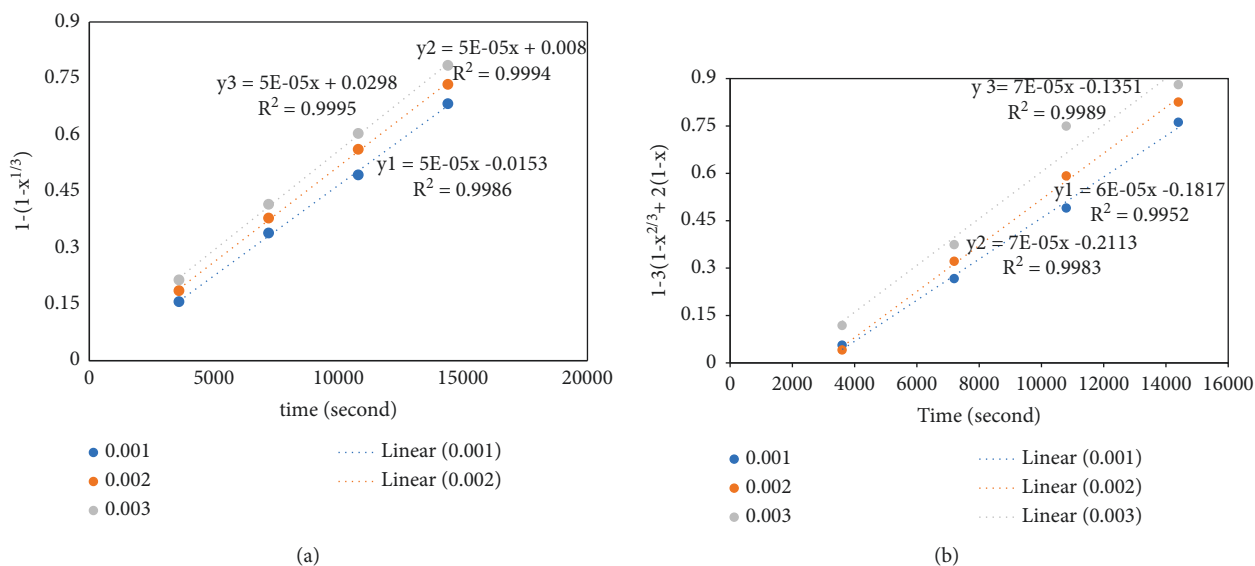
FIGURE 7: Shrinking core model and kinetic plots: (a) surface reaction, (b) diffusion at varied copper [Cu] concentrations (0.001–0.003 mol. L^{-1}).

thiosulphate ions [35]. An increase in $S_2O_3{}^{2-}$ molarity enhanced the gold recovery $\geq 99\%$ after 3 hours at a temperature range above 30°C. Surface response plot for the variation of $S_2O_3{}^{2-}$ concentration and time is shown in Figure 8(a) and 8(b). On the other hand, it has been seen that the increase in copper and NH_3 concentrations has a positive influence on gold recovery. The highest gold recovery (99.56%) was obtained with 0.0025 M Cu^{2+} and 2.5 M NH_3 after 3 hours at 40°C. Previous studies have stipulated that gold solubilisation rate can be 20 times faster with the addition of Cu^{2+} due to its capability to oxidize gold [35]. However, an excessive increase in the Cu^{2+} amount increases the oxidation rate of $S_2O_3{}^{2-}$ [2]. It has been observed that the Cu^{2+} concentration contribution % is approximately equivalent to NH_3 contribution %, probably for the reason of their interlinked interactions related to the Cu $(NH_3)_4{}^{2+}$

complex formation and adsorption on gold surface [36]. Ammonia prevents chemical precipitation of copper and forms Cu $(NH_3)_4{}^{2+}$ complex. Moreover, the dissolution of gangue minerals such as iron oxides and silicates is inhibited in the presence of ammonia [35]. Results from SEM-EDS results in Table 5 stipulate that the chemical composition of gangue materials is unaltered. This suggests that thiosulfate lixiviant has high leaching selectivity. The combined overall contribution % of both Cu^{2+} and NH_3 concentrations to the RSM model is relatively twice greater than that of the thiosulfate concentration in Table 5.

3.3. Response Surface Optimisation. The result of response surface optimization are presented in Figure 9. The optimal concentrations of gold leaching media to achieve potentially
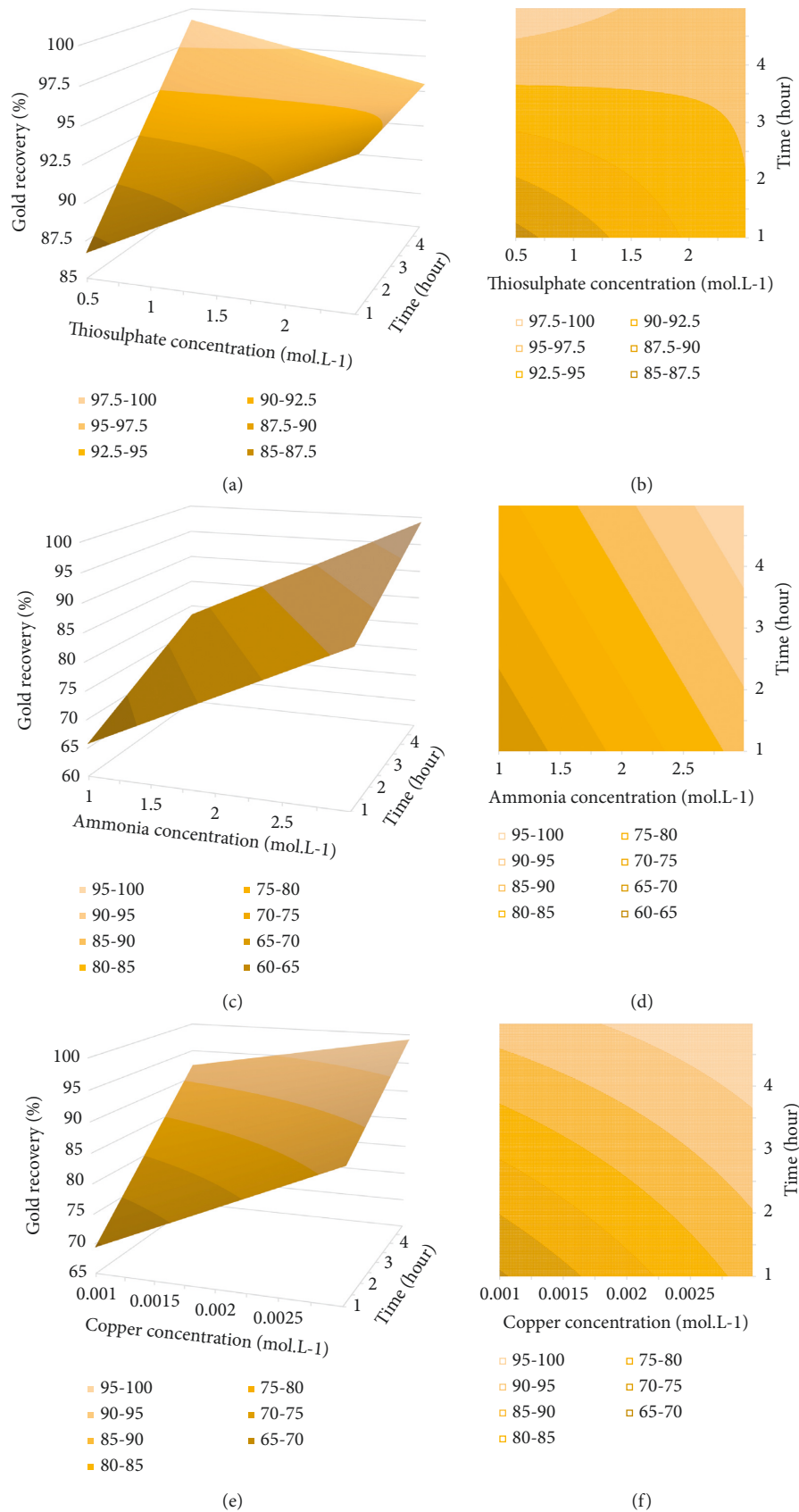
(a)

(b)

(c)

(d)

(e)

(f)

FIGURE 8: Surface response plot of recovery versus concentrations of thiosulfate (a) and (b); ammonia (c) and (d), and Cu^{2+} (e) and (f) at constant after 3 h leaching time at 30°C.

TABLE 5: Energy dispersive spectrometric analysis of gold ore before and after leaching.

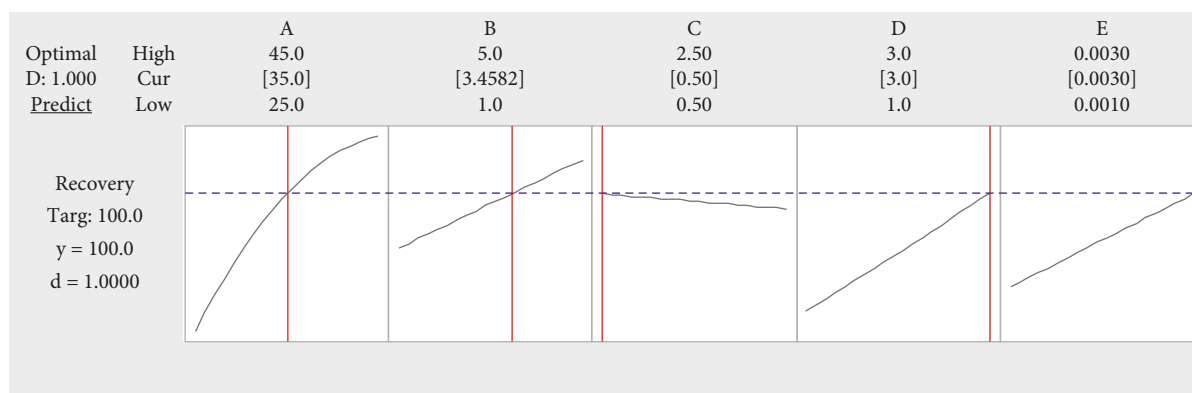| Elemental composition	Before leaching	After leaching
Mg	1.1760	1.0434
Al	4.6892	4.2340
Si	33.5762	33.4687
S	0.6127	1.1534
Ti	0.4197	0.4257
Fe	6.8544	6.6166
Cu	0.0160	0.0240
Zn	0.0161	0.0161
Rb	0.0091	0.0091
Sr	0.0169	0.0169
Zr	0.0518	0.0444
Pb	0.0097	0.0389

FIGURE 9: Predicted optimum conditions: the term factor A, B, C, D, E represent the temperature (°C), time (hours), concentration in mol. L^{-1} of thiosulphate $[S_2O_3]$, ammonia $[NH3]$, and copper $[Cu]$, respectively. y denotes the gold recovery target and d the desirability.

TABLE 6: Alternative optimal conditions for the complete.

Optimal condition	Temp (°C)	Time (h)	$[S_2O_3]$ (M)	$[NH_3]$ (M)	$[Cu]$ (M)	Predicted recovery (%)	Actual recovery (%)	Relative error (%)
1	34.885	1.558	2.5	3	0.003	100	98.45	1.55
2	30.825	5	0.5	3	0.003	100	99.01	0.99
3	34.440	1	2.5	3	0.003	100	98.92	1.08
4	44.419	1	2.45	1	0.001	100	99.34	0.66

complete dissolution of gold from its ore in copper-ammonical thiosulphate media based on the effect of the investigated parameters were 0.5 M S_2O_3, 3 M NH_3, and 0.003 M Cu^{2+} with a desirability value equivalent to unity ($d = 1.000$). The highest gold recovery is yielded after 3.46 hours at 35°C. It was reported that 90% Au could be recovered after 1 hour in ammoniacal thiosulphate [35]. The optimum temperature ranges between 30°C and 40°C. Actual gold leaching recovery obtained at the optimal conditions was 99.52 [37]. The calculated relative error ($\sigma = 0.42\%$) between the actual and the predicted gold recoveries is very low. Therefore, it is inferred that RSM is an accurate and practical approach for the optimisation of gold leaching kinetic parameters. Other alternative optimal conditions are presented in Table 6.

3.4. Shrinking Core Model and Kinetics.

The results indicate that gold leaching in copper-ammonia-thiosulfate media

correlates with surface chemical reaction control. This suggests that the dissolution of gold in thiosulfate media is sensitive to the increase in temperature [18,31,38]. The validity of the shrinking core model has been confirmed through the evaluation of the calculated correlation coefficients ($R^2 > 0.9995$). Kinetic parameters are presented in Table 7 at the optimum condition for gold leaching. The rate constant of the surface and diffusion-controlled reactions, k_c and k_d were determined from the slopes of the linear plots in Figure 10. The rate constants of surface-controlled gold leaching increases from $5.08 \times 10^{-5}\,s^{-1}$ to $5.38 \times 10^{-5}\,s^{-1}$ with the increase in copper concentration from 0.001 mol. L^{-1} to 0.003 mol. L^{-1}. In a previous study, the apparent surface constant had been reported as $5.6 \times 10^{-6}\,s^{-1}$ [39, 40]. Mathematical expressions for chemically and diffusion-controlled reactions are given in the following equations, respectively, where x represents the reacted gold fraction at time t [41, 42].

Table 7: Kinetic parameters for gold leaching in 0.5 mol. L^{-1} $S_2O_3^{2-}$ and 3 mol. L^{-1} NH_3 solution at 35°C and varied copper [Cu] concentrations.

[Cu] (mol. L^{-1})	Surface chemical reaction control		Diffusion control	
	k_c (s^{-1})	R^2	k_d (s^{-1})	R^2
0.001	5.08×10^{-5}	1	6.41×10^{-5}	0.998
0.002	5.08×10^{-5}	0.999	6.87×10^{-5}	0.97
0.003	5.38×10^{-5}	0.997	7.29×10^{-5}	0.993

$$1 - (1 - x)^{1/3} = k_c t, \qquad (8)$$

$$1 - 3(1 - x)^{2/3} + 2(1 - x) = k_d t. \qquad (9)$$

4. Conclusions

In this study, a fundamental statistical and kinetic analysis of gold leaching has been carried out. Gold leaching recovery response as a function of the studied kinetic parameters has been investigated using the experimental data at different conditions varying according to the RSM central composite design. It could be inferred that RSM is an accurate and practical approach for the optimisation of gold leaching kinetic parameters. The following findings are observed:

(i) The findings show a strong relationship between the actual gold leaching recovery data and the RSM model. The correlation coefficients R^2 and adjusted R^2 equivalent to 0.998 and 0.9993, respectively. All investigated parameters were found statistically significant with $p$value <0.05.

(ii) The effect of temperature is mostly significant, contributing up to 64.65% to the gold recovery response model. the contribution percentages of the effects of time, thiosulfate [S_2O_3], ammonia [NH_3], and copper [Cu] concentrations were calculated as 12.81%, 5.88%, 5.19%, and 4.65%, respectively.

(iii) The optimal concentrations of gold leaching media to achieve potentially complete dissolution of gold from its ore in copper-ammonical thiosulphate media based on the effect of the investigated parameters were 0.5 M S_2O_3, 3 M NH_3, 0.003 M Cu^{2+} with a desirability value equivalent to unity ($d = 1.000$).

(iv) Results indicate that gold leaching in copper-ammonia-thiosulfate media is best described as a surface chemical reaction-controlled process, suggesting that gold dissolution is sensitive to temperature increases. The rate constants of surface-controlled gold leaching increases from 5.08×10^{-5} s^{-1} to 5.38×10^{-5} s^{-1}.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

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