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Optimization Of Sulfuric Acid Leaching Of Copper From A Cu–Fe Oxidized Ore From Kongo Central Province, Democratic Republic Of Congo

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Abstract: The Democratic Republic of Congo (DRC) is among the world's major copper-producing countries and possesses significant reserves of oxidized copper ores. In order to sustain the growth of the mining sector and improve the economic valorization of low-grade polymetallic deposits, the optimization of hydrometallurgical extraction processes remains a major industrial challenge. This study aimed to optimize the sulfuric acid leaching of copper from a Cu–Fe oxidized ore originating from Kongo Central Province, while minimizing iron dissolution.

The investigated ore was mainly composed of cuprite (Cu_2O), malachite ($Cu_2CO_3(OH)_2$), and limonite ($5Fe_2O_3 \cdot 2SiO_2 \cdot 9H_2O$). Mineralogical and chemical characterizations were performed using X-ray diffraction, atomic absorption spectrometry, inductively coupled plasma analysis, and conventional chemical methods. Leaching experiments were carried out using a fractional factorial experimental design in order to evaluate the effects of acid formality, particle size, temperature, slurry density, and stirring speed on copper and iron dissolution.

The results showed that acid formality (AF) and slurry density (SD) were the most influential parameters controlling copper extraction. The developed optimization model for copper leaching was expressed as:

$$Y = 0.284 + 0{,}183FA - 0.070\ DS + \varepsilon$$

Optimal operating conditions were obtained at an acid formality of 0.40 $mol \cdot dm^{-3}$, a particle size between 90 and 125 µm, a temperature of 50–60°C, an agitation speed of approximately 550 rpm, and a solid/liquid ratio of 1/10. Under these conditions, copper extraction reached 65.9%, whereas iron dissolution remained limited to 1.02%.

Kinetic investigations revealed that an optimal residence time of two minutes allowed selective copper extraction with minimal iron co-dissolution. One extraction stage theoretically yielded 54.7% copper extraction while dissolving only 0.5% iron. Repetition of the leaching process over several stages could therefore selectively exhaust copper from the ore.

This study demonstrates the potential of sulfuric acid hydrometallurgy combined with factorial experimental design for the selective recovery of copper from oxidized Cu–Fe ores in the Democratic Republic of Congo.

Keywords: Copper leaching; Hydrometallurgy; Sulfuric acid; Experimental design; Cuprite; Oxidized ore; Democratic Republic of Congo; Kongo Central.

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1. INTRODUCTION

Copper is one of the most strategic non-ferrous metals worldwide because of its extensive use in electrical engineering, renewable energy technologies, construction, metallurgy, telecommunications, and industrial manufacturing (Davenport et al., 2002). Owing to its high electrical conductivity, corrosion resistance, and recyclability, global demand for copper has continuously increased during the last decades, particularly with the expansion of green technologies and electric mobility (Northey et al., 2014).

The Democratic Republic of Congo (DRC) possesses some of the world's largest copper reserves and has historically occupied a major position among global copper-producing countries. During the mid-1980s, the country ranked among the leading world producers, with an annual production exceeding 500,000 tons of copper. Following a prolonged decline caused by political instability, economic difficulties, and the deterioration of mining infrastructures, the Congolese mining sector has progressively recovered, with copper production surpassing one million tons in 2014 (USGS, 2015).

In order to sustain this production dynamic and strengthen the competitiveness of the Congolese mining industry, there is an increasing need to explore and valorize new mineralized formations capable of supporting economically viable industrial exploitation. Several copper-bearing deposits located in the Kongo Central Province contain oxidized copper ores associated with iron minerals, particularly cuprite (Cu_2O), malachite ($Cu_2CO_3(OH)_2$), and limonite ($5Fe_2O_3 \cdot 2SiO_2 \cdot 9H_2O$). These polymetallic oxidized ores represent promising resources for hydrometallurgical extraction processes.

Hydrometallurgy has become one of the most important technologies for the treatment of low-grade and complex ores because of its lower energy consumption, operational flexibility, and reduced environmental impact compared with pyrometallurgical methods (Habashi, 1999). Among hydrometallurgical operations, leaching constitutes the key stage of the extraction process because it determines the efficiency of downstream purification and metal recovery operations (Vignes, 2009a).

Sulfuric acid is widely used as a leaching reagent for oxidized copper ores due to its low cost, availability, and high dissolution capacity (Dreisinger, 2006). However, one of the major difficulties associated with sulfuric acid leaching lies in its poor selectivity, especially in ores containing significant quantities of iron-bearing minerals. Excessive iron dissolution complicates subsequent purification stages, increases reagent consumption, and negatively affects the overall economic profitability of the process (Gupta & Mukherjee, 1990).

Several studies have demonstrated that leaching efficiency is strongly influenced by operational parameters such as acid concentration, particle size distribution, temperature, agitation speed, and pulp density (Habashi, 1993; Crundwell et al., 2011). The optimization of these parameters is therefore essential for maximizing copper recovery while minimizing iron co-dissolution.

Experimental design methodologies, particularly factorial experimental designs, are increasingly applied in extractive metallurgy because they allow simultaneous evaluation of several process variables while reducing the number of experiments required (Montgomery, 2017). These statistical approaches provide robust mathematical models capable of predicting process behavior and identifying optimal operational conditions.

The present study therefore aims to optimize the sulfuric acid leaching of copper contained in a Cu–Fe oxidized ore from Kongo Central Province, Democratic Republic of Congo, while minimizing iron dissolution. More specifically, the study seeks to:

1. characterize the mineralogical and chemical composition of the ore;
2. evaluate the influence of the main operational parameters on copper and iron leaching;
3. establish a mathematical optimization model for the process; and
4. determine the optimal residence time for selective copper extraction under industrially applicable conditions.

This work contributes to the development of efficient and economically sustainable hydrometallurgical processes for the valorization of oxidized copper resources in the Democratic Republic of Congo.

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2. MATERIALS AND METHODS

2.1. Sampling Site and Geological Context

Our study sample was collected in the Kongo Central Province, Cataracts District, Mbanza-Ngungu Territory, Ngombe Matadi Sector, in the locality of Ngandu, located approximately 50–60 km from Mbanza-Ngungu, along the road leading to Nkamba.

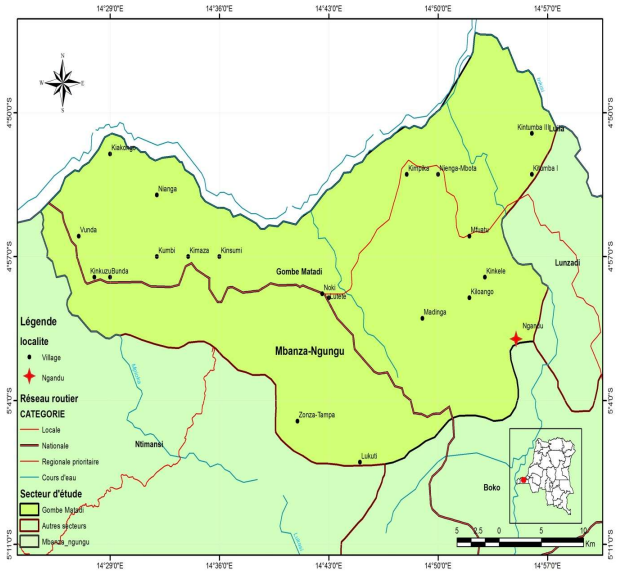


Figure 1. Location Map of the Sampling Site

The geographic coordinates of the sampling site are as follows:

- Altitude: 571 m
- Latitude: 5° 0’ 59.79’’ South
- Longitude: 14°55’ 01’’ East

The different geological formations identified at the site are:

- **P:** Undifferentiated MPIOKA formation, composed of fine-grained red feldspathic quartzites with some red schist intercalations;
- **QPS:** More or less clayey sand of light gray, yellow, ochre, or red color, generally containing gravel at the base. This formation overlies erosion surfaces;
- **X:** Unconsolidated debris, weathering products, etc.;
- **gp:** Polymorphous sandstones;
- **Sa:** Sands with indications of mineralization by Cu (copper), Fe (iron), Mn (manganese), and Pb (lead).

2.2. Methodological Approaches

2.2.1. Sample Processing

The pre-treatment of our sample was carried out at the Chemistry and Geochemistry Laboratory of the Geological and Mining Research Center (CRGM), located in Kinshasa Gombe.

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It consisted of:

- manual crushing, followed by grinding using a vibro-mill, in order to reduce the ore to a particle-size range compatible with the different leaching experiments;
- moisture determination using a VWR oven at 105°C for three hours.

2.2.2. Ore Characterization

Due to the lack of appropriate mineral analysis equipment in Kinshasa for the characterization of our sample, the latter was sent to the EMT laboratory of Gécamines, in Likasi, for mineralogical analyses using an X-ray diffractometer, as well as qualitative and quantitative analyses by flame spectrometry, atomic absorption spectrometry, inductively coupled plasma (ICP), electro-deposition, and classical chemical analysis.

Mineralogical analysis showed that the sample consisted of a mixture of two copper ores: Malachite ($Cu_2CO_3(OH)_2$) and Cuprite (Cu_2O), also containing iron in the form of Limonite ($5Fe_2O_3 \cdot 2SiO_2 \cdot 9H_2O$).

Table 2.2.2.1. Elements Revealed by the Qualitative Analysis of the Ore

Cu	Co	Fe	Ni	Mn	Cr	Zn	Pb	As	W	Ti	Pd	Rh	Ru	In	Hf	Sb	Cd

The quantitative analysis yielded the following chemical composition of the ore.

Table 2.2.2.2. Results of the Ore Composition Analysis

MET No.	LAB No.	Cu (%)	Co (ppm)	Fe (%)	Ni (ppm)	Mn (ppm)	Zn (%)	CaO (%)	MgO (%)	Pb (%)
GB	743894	44.43	60	30.08	22	80	0.04	1.12	0.99	0.06

MET No.	LAB No.	Cd (ppm)	S (%)	SiO_2 (%)	Al_2O_3 (%)	As (ppm)	Ti (ppm)	Cr (ppm)	Sb (ppm)	Bi (ppm)
GB	743894	< 10	2.44	8.23	0.17	2844	04	< 0.01	80	< 0.01

2.2.3. Leaching Experiments

The solid-liquid extraction was carried out in a 1 dm^3 double-jacket reactor in order to maintain a stable working temperature through the circulation of a thermal fluid. The operating volume of the reactor reagents was optimized at 0.4 dm^3.

The materials and methods used in our experiments are presented in Appendices I and II.

2.2.3.1. Study Parameters of Leaching and Their Experimental Levels

The parameters selected for the leaching screening are presented in Table 2.2.3.1.1, together with the two experimental levels retained for each parameter, including the center level.

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Table 2.2.3.1.1. Study Parameters for Leaching

No.	Factors or Parameters under Study in the Process	Levels		
		-1	0	+1
1	Acid Formality, AF (mol dm^{-3})	0.1	0.25	0.4
2	Particle Size Type, PST (Coarse, Intermediate, Fine)	C	I	F
3	Temperature, T (°C)	40	50	60
4	Slurry Density, SD (g of powder for 400 cc of acid)	40.0	50.0	66.4
5	Stirring Speed, S (Slow, Medium, or Fast according to the rpm range)	S	M	F

Note: Particle size type:

- CG ≥ 125 µm;
- 125 µm > IG ≥ 90 µm;
- 90 µm > FG

Note: Stirring speed:

- 450 rpm ≤ SS ≤ 500 rpm;
- 500 rpm ≤ MS ≤ 600 rpm;
- 600 rpm ≤ FS ≤ 700 rpm

Table 2.2.3.1.2. Experimental Design for the Screening of Copper and Iron Leaching

No.	AF	PST	T	SD	S
1	0.10	C	40°C	40.0	F
2	0.10	C	40°C	66.4	F
3	0.10	C	60°C	40.0	F
4	0.10	C	60°C	66.4	F
5	0.10	F	40°C	40.0	S
6	0.10	F	40°C	66.4	S
7	0.10	F	60°C	40.0	S
8	0.10	F	60°C	66.4	S
9	0.40	C	40°C	40.0	S
10	0.40	C	40°C	66.4	S
11	0.40	C	60°C	40.0	S
12	0.40	C	60°C	66.4	S
13	0.40	F	40°C	40.0	F

14	0.40	F	40°C	66.4	F
15	0.40	F	60°C	40.0	F
16	0.40	F	60°C	66.4	F
17	0.25	I	50°C	50.0	M
18	0.25	I	50°C	50.0	M
19	0.25	I	50°C	50.0	M
20	0.25	I	50°C	50.0	M

It should be emphasized that two qualitative variables are present: the stirring speed S (Slow, Fast, or Medium), and the particle size type PST, depending on whether the ore grain diameter is greater than or equal to 125 µm or less than 90 µm, with the interval between the two values (125–90 µm) corresponding to the center point.

The solid-liquid slurry density of the experimental tests was 40.0 g for the lower level, 50.0 g at the center, and 66.4 g for the upper level.

The stirring speed was obtained through the aliasing of acid formality and particle size type.

For economic and time-saving reasons, the choice was made to use a half-reduced factorial design (2^{k-1} experiments), that is, a fractional factorial design where p = 1, with four experiments at the center point.

2.2.3.2. Analysis of the Leaching Signal

The monitoring analyses of copper and iron concentrations in the leachate during the different experiments were carried out at the Chemistry Laboratory of the Université Pédagogique Nationale using UV-visible spectrophotometry.

3. PRESENTATION AND INTERPRETATION OF RESULTS

3.1. Results of the Statistical Experimentation

Tables 3.1.1 and 3.1.2 present the screening results for copper and iron, respectively, in terms of the percentage of dissolved metal.

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Table 3.1.1. Experimental Design and Screening Results for Copper Leaching

Label	X_1	X_2	X_3	X_4	Abs	f_d	[Cu]/mmol L^{-1}	Y (%Cu $_{lixivié}$)
Blk					0,000	50	-3,19	-0,4%
Exp1	-1	-1	-1	-1	0,171	50	89,24	13,1%
Exp2	-1	-1	-1	1	0,192	50	100,59	9,0%
Exp3	-1	-1	1	-1	0,194	50	101,68	14,9%
Exp4	-1	-1	1	1	0,156	50	81,14	7,3%
Exp5	-1	1	-1	-1	0,165	50	86,00	12,6%
Exp6	-1	1	-1	1	0,161	50	83,84	7,5%
Exp7	-1	1	1	-1	0,140	50	72,49	10,6%
Exp8	-1	1	1	1	0,117	50	60,05	5,4%
Exp9	1	-1	-1	-1	0,726	50	389,24	57,1%
Exp10	1	-1	-1	1	0,740	50	396,81	35,5%
Exp11	1	-1	1	-1	0,664	50	355,73	52,2%
Exp12	1	-1	1	1	0,711	50	381,14	34,1%
Exp13	1	1	-1	-1	0,716	50	383,84	56,3%
Exp14	1	1	-1	1	0,720	50	386,00	34,5%
Exp15	1	1	1	-1	0,172	250	448,92	65,9%
Exp16	1	1	1	1	0,162	250	421,89	37,7%

Table 3.1.2. Experimental Design and Screening Results for Iron Leaching

Label	X_1	X_2	X_3	X_4	Abs	f_d	[Fe]/ppm	Y (%Fe $_{lixivié}$)
Blk					0,000	250	1,50	0,00%
Exp1	-1	-1	-1	-1	0,005	250	26,50	0,09%
Exp2	-1	-1	-1	1	0,002	250	11,50	0,02%
Exp3	-1	-1	1	-1	0,027	250	136,50	0,45%
Exp4	-1	-1	1	1	0,017	250	86,50	0,17%
Exp5	-1	1	-1	-1	0,002	250	11,50	0,04%
Exp6	-1	1	-1	1	0,007	250	36,50	0,07%
Exp7	-1	1	1	-1	0,002	250	11,50	0,04%
Exp8	-1	1	1	1	0,006	250	31,50	0,06%
Exp9	1	-1	-1	-1	0,063	250	316,50	1,03%
Exp10	1	-1	-1	1	0,047	250	236,50	0,47%
Exp11	1	-1	1	-1	0,063	250	316,50	1,03%
Exp12	1	-1	1	1	0,067	250	336,50	0,67%
Exp13	1	1	-1	-1	0,041	250	206,50	0,67%
Exp14	1	1	-1	1	0,02	250	101,50	0,20%
Exp15	1	1	1	-1	0,062	250	311,50	1,02%
Exp16	1	1	1	1	0,057	250	286,50	0,57%

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It should be noted that X1, X2, X3, and X4 represent respectively the acid formality AF, the particle size type PST, the operating temperature T, and the slurry density SD.

The last four experiments, namely 17, 18, 19, and 20, carried out at the center of the experimental domain, provide an estimate of the reproducibility of the experimental results for copper leaching. The standard deviation σcentrum of 0.8% between the center-point results is an estimator of the experimental error on the leaching percentage.

Table 3.1.3. Copper Leaching Experiments at the Center of the Experimental Domain and Screening Results

Label	X_1	X_2	X_3	X_4	Abs	f_d	[Cu]/mmol L^{-1}	Y (%$Cu_{lixivié}$)
Exp17	0	0	0	0	0,467	50	249,24	29,3%
Exp18	0	0	0	0	0,450	50	240,05	28,2%
Exp19	0	0	0	0	0,450	50	240,05	28,2%
Exp20	0	0	0	0	0,477	50	254,65	29,9%

Under the assumption of equal variance for all responses of the experimental design, σ(y), the standard error σ(E) of the effect of each process parameter or variable is:

$$\delta(E) = \delta(y)/\sqrt{N}$$

The application of this formula gives the standard error of the variable effects and, in the case of copper:

$\delta(E) = \frac{0,209}{\sqrt{16}} = 5,2\%$.

In the case of iron, where the concentrations of dissolved metal are very low, with an overall experimental standard deviation σ(y) = 0.0038, the application of the previous formula gives the standard error of the variable effects as:

$\delta(E) = \frac{0,0038}{\sqrt{16}} = 0,09\%$.

The effects of the leaching variables, namely acid formality AF, particle size type PST, operating temperature T, and slurry density SD, recoded respectively as X1 to X4, as well as their second- and third-order interactions, are presented for copper in the following table.

It should be noted that the table presenting the calculation of these effects, according to the Yates algorithm, is provided in Appendix VI.

Table 3.1.4. Main and Interaction Effects of Copper Leaching Parameters

Eff_X1	Eff_X2	Eff_X3	Eff_X4	Eff_X12	Eff_X13	Eff_X14	Eff_X23	Eff_X24	Eff_X34	Eff_X123	Eff_X124	Eff_X134	Eff_X234
18,31%	**0,46%**	**0,15%**	**-6,98%**	**1,48%**	**0,65%**	**-4,22%**	**0,93%**	**-0,55%**	**-0,41%**	**1,45%**	**-0,72%**	**0,06%**	**-0,40%**

Compared with the level of experimental noise, estimated at 5.2%, that is, the standard error of the variable effects previously calculated for copper, only X1 (AF) and X4 (SD) showed significant main effects, the first being positive and the second negative.

The effect of the stirring speed S is partially confounded with those of PST and AF.

The figure below presents, for copper, the histogram of the first-order effects of the four variables (acid formality AF, particle size type PST, operating temperature T, and slurry density SD).

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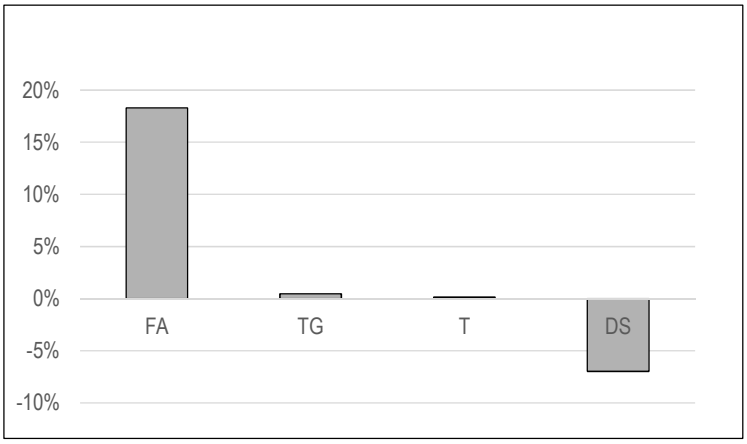


Figure 3.1.2. Mean Effects of the Different Factors on Iron Leaching

In accordance with the significant effects identified during the sulfuric acid leaching experimentation of copper, and considering the negligible extraction of iron, the modeling of the process is simple and takes the following form:

$$\hat{Y} = 0{,}284 + 0{,}183\ FA - 0{,}070\ DS + \varepsilon$$

Thus, apart from the loss of information resulting from the aliasing between AF and PST, it can be suggested that increasing the acid formality while decreasing the slurry density reasonably improves the copper leaching yield, without significant dissolution of iron.

Experiment 15 in Table 3.1.1 on page 18 reflects the best copper leaching conditions in our experimental design, with an acid formality of 0.40 mol dm^{-3}, a fine particle size, a temperature of 60°C, a slurry density equal to 100 g/1000 cc, and a high stirring speed. Under these conditions, the copper extraction yield reached 65.9%.

Under the same leaching conditions, iron extraction was only 1.02%.

3.2. Results of the Kinetic Experimentation

The following table presents the kinetic data of copper leaching under the indicated conditions.

Table 3.2.1. Kinetic Data of Cu Leaching at T = 60°C (AF = 0.40 mol·dm^{-3}, SD = 0.125, S = 500 rpm)

Time (min)	[Cu] in Leachate (mol·dm^{-3})	% Cu Leached
0	0	0.0
2	320.61	36.7 ± 0.87
5	359.08	41.1 ± 0.87
10	386.87	44.2 ± 0.87
15	387.40	44.2 ± 0.87
30	386.56	44.2 ± 0.87
60	400.77	45.8 ± 0.87

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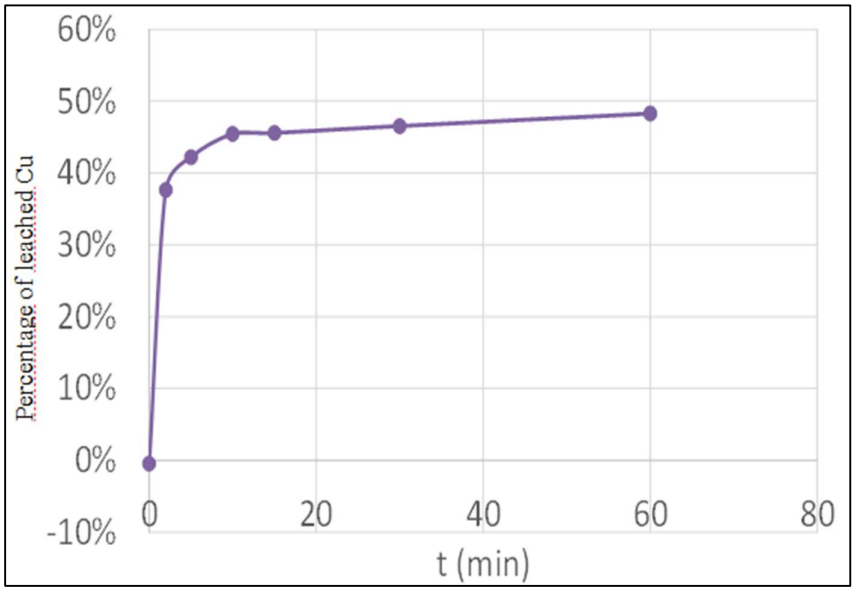


Figure 3.2.1. Kinetic Data of Cu Leaching at T = 60°C (AF = 0.40 mol·dm⁻³, SD = 0.125, S = 500 rpm)

The above data reveal that after two minutes, the extraction kinetics reached a yield of 36.7%, corresponding to 83% of the extraction potential, considering that after 30 minutes the yield reached 44.2%.

The following table presents the kinetic data of iron leaching under the indicated conditions.

Table 3.2.2. Kinetic Data of Fe Leaching at T = 60°C (AF = 0.40 mol·dm⁻³, SD = 0.125, S = 500 rpm)

Time (min)	Fe (mg/L)	% Fe Leached
0	0	0
2	187.5	0.5
5	203.12	0.54
10	229.16	0.61
15	270.56	0.72
30	322.78	0.86
60	370.25	0.98

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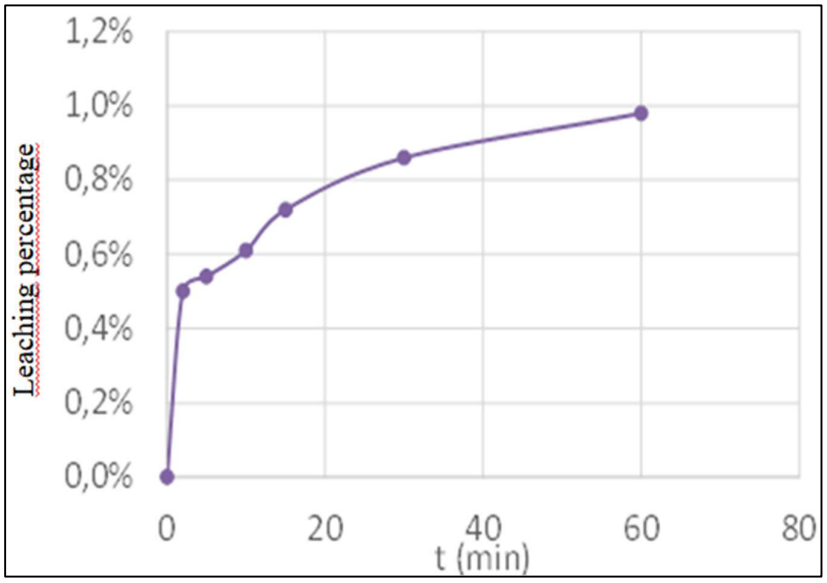


Figure III.3.2.2. Kinetic data for Fe leaching at T = 60°C (FA = 0.40 mol.dm⁻³, DS = 0.125, V = 500 rpm)

Figure III.3.1.5 shows that after two minutes, the Fe leaching rate is only 0.50%, corresponding to less than 50% of the extractive potential, considering that after 60 minutes the amount of leached iron reaches only 0.98%, that is, barely more than double.

Taking these two kinetic experiments into account makes it possible to estimate an optimal residence time of 2 minutes for copper leaching without significant iron extraction, which can be applied to an industrial extraction stage.

Under these conditions (T = 60°C, FA = 0.40 mol.dm⁻³, DS = 0.125, V = 500 rpm, and residence time = 2 min), one copper extraction stage would theoretically leach 65.9% × 83%, corresponding to 54.7% copper, while carrying only 1.02% × 50%, corresponding to 0.5% iron.

By repeating the leaching operation over four stages, the copper can be selectively exhausted from the ore.

4. DISCUSSION

The present study demonstrated that sulfuric acid leaching can effectively recover copper from oxidized Cu–Fe ores while maintaining relatively low iron dissolution under controlled operating conditions. The obtained results confirm the importance of process optimization in hydrometallurgical operations involving complex polymetallic ores.

The mineralogical characterization revealed that the investigated ore was mainly composed of cuprite, malachite, and limonite. The high copper content (44.43%) associated with substantial iron concentrations (30.08%) indicates the polymetallic nature of the ore and explains the difficulty of achieving selective copper dissolution using sulfuric acid. Similar observations were reported by Davenport et al. (2002), who emphasized that oxidized copper ores containing iron oxides frequently exhibit low selectivity during acid leaching due to the simultaneous dissolution of iron-bearing phases.

The statistical experimental design showed that acid formality (AF) and slurry density (SD) were the most significant factors influencing copper extraction. The positive effect of acid concentration observed in this study is consistent with the findings of Habashi (1993) and Gupta and Mukherjee (1990), who demonstrated that increasing sulfuric acid concentration enhances proton availability, thereby promoting the dissolution kinetics of copper oxides and carbonates. In the present work, the increase in acid formality up to 0.40 mol·dm⁻³ significantly improved copper recovery without causing excessive iron dissolution.

Conversely, slurry density exhibited a negative effect on copper extraction. This behavior may be explained by reduced mass transfer efficiency and insufficient reagent availability at higher solid concentrations. Crundwell et al. (2011) similarly reported that increasing pulp density may reduce leaching efficiency due to limitations in particle dispersion, diffusion phenomena, and acid accessibility to reactive mineral surfaces.

The limited influence of temperature observed during the screening experiments suggests that copper dissolution from oxidized minerals such as malachite and cuprite proceeds relatively rapidly even under moderate thermal conditions. However, temperature showed a more noticeable effect on iron dissolution, probably because iron-bearing minerals such as limonite require higher activation energy for dissolution. Dreisinger (2006) noted that elevated temperatures often accelerate iron solubilization more strongly than copper dissolution in sulfuric acid systems, thereby reducing process selectivity.

The experimental design also highlighted the partial confounding between stirring speed, particle size, and acid formality due to the aliasing structure of the fractional factorial design. Nevertheless, the best leaching performance was obtained under conditions combining fine particle size, high acid concentration, and high stirring speed. The beneficial effect of fine particle size is well documented in hydrometallurgical literature because particle size reduction increases the reactive surface area available for dissolution reactions (Habashi, 1999).

The developed mathematical model:

$\widehat{Y} = 0{,}284 + 0{,}183\ FA - 0{,}070\ DS + \varepsilon$ adequately describes the relationship between the main operational variables and copper recovery. The positive coefficient associated with AF confirms the promoting role of acid concentration, whereas the negative coefficient of SD reflects the inhibitory effect of excessive slurry density. According to Montgomery (2017), such simplified predictive models derived from factorial designs constitute valuable tools for industrial optimization because they facilitate process control while minimizing experimental costs.

One of the most important findings of this study concerns the kinetic behavior of copper and iron dissolution. Copper extraction increased very rapidly during the first minutes of leaching, reaching 36.7% after only two minutes, corresponding to approximately 83% of the maximum extraction potential observed after longer residence times. In contrast, iron dissolution remained very limited during the same period, reaching only 0.5%. These results demonstrate the possibility of achieving selective copper recovery through short residence-time leaching.

This selective behavior may be attributed to the higher reactivity of copper oxide minerals compared with limonitic iron phases in sulfuric acid media. Similar kinetic selectivity has been reported by Gupta and Mukherjee (1990), who observed that copper oxides generally dissolve faster than iron oxyhydroxides due to differences in crystal structure, surface reactivity, and acid consumption mechanisms.

The identification of an optimal residence time of two minutes represents an important industrial advantage because shorter leaching durations reduce reactor volume requirements, operational costs, and energy consumption. Furthermore, the theoretical extrapolation of multi-stage leaching indicates that copper can be progressively exhausted from the ore while maintaining limited iron contamination. According to Vignes (2009a), multistage counter-current leaching systems are particularly effective for maximizing metal recovery while preserving process selectivity in hydrometallurgical operations.

Although the present study produced promising results, some limitations should be acknowledged. The fractional factorial design introduced partial aliasing between certain variables, particularly stirring speed and particle size effects. In addition, the work focused mainly on laboratory-scale batch experiments. Further investigations should therefore evaluate continuous pilot-scale leaching systems, solvent extraction–electrowinning integration, acid consumption optimization, and the environmental management of iron-bearing residues.

Overall, the findings demonstrate that sulfuric acid leaching combined with statistical experimental design constitutes an efficient and economically promising approach for the selective recovery of copper from oxidized Cu–Fe ores in the Democratic Republic of Congo.

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5. CONCLUSION

The present study focused on the optimization of sulfuric acid leaching of copper from an oxidized Cu–Fe ore originating from Kongo Central Province in the Democratic Republic of Congo. The investigated ore was mainly composed of cuprite (Cu_2O), limonite ($5Fe_2O_3 \cdot 2SiO_2 \cdot 9H_2O$), and minor proportions of malachite ($Cu_2CO_3(OH)_2$). The objective of the study was to maximize copper recovery while minimizing iron co-dissolution under conditions applicable to industrial hydrometallurgical processing.

The mineralogical and chemical characterization of the ore confirmed the presence of economically valuable copper concentrations associated with significant iron content. This characterization provided essential information for selecting and controlling the operational parameters involved in the leaching process, including acid formality, particle size distribution, operating temperature, agitation speed, and slurry density.

The application of fractional factorial experimental design proved to be an efficient methodological approach for evaluating the effects and interactions of the different process variables while reducing the number of experimental trials. The statistical analysis demonstrated that acid formality (AF) and slurry density (SD) were the most significant factors influencing copper extraction. The optimization model established for copper leaching was expressed as:

$$\hat{Y} = 0{,}284 + 0{,}183\ FA - 0{,}070\ DS + \varepsilon$$

The obtained results showed that the optimal operating conditions corresponded to an acid formality of 0.40 $mol \cdot dm^{-3}$, a particle size ranging from 90 to 125 µm, a temperature close to 50–60°C, an agitation speed of approximately 550 rpm, and a solid/liquid ratio of 1/10. Under these conditions, copper extraction reached 65.9%, whereas iron dissolution remained limited to only 1.02%, demonstrating the relative selectivity of the process.

The kinetic study further revealed that the leaching reaction was very rapid during the first minutes of operation. An optimal residence time of two minutes was identified for the extraction stage, corresponding theoretically to 54.7% copper recovery with only 0.5% iron dissolution. These findings indicate that selective copper recovery can be achieved efficiently within short operational times, thereby reducing reagent consumption and improving the economic viability of the process.

Overall, this work highlights the potential of sulfuric acid hydrometallurgy combined with statistical experimental design for the valorization of oxidized copper ores from the Democratic Republic of Congo. The proposed approach constitutes a promising basis for the development of industrial-scale extraction processes adapted to complex Cu–Fe mineralizations. Future studies should investigate multi-stage continuous leaching systems, solvent extraction and electrowinning integration, as well as the economic and environmental performance of the process under industrial operating conditions.

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