Effects of Roasting vs Redox Potential during the Dissolution of Chalcopyrite in Chloride Solutions

LK Navela and E Fosso-Kankeu

***Abstract*—** In this work, the comparative effects of roasting and redox potential control on the dissolution of chalcopyrite ($CuFeS_2$) in chloride media using hydrochloric acid and magnetite as a redox mediator was investigated. Chalcopyrite samples were roasted at 400 °C, 600 °C, and 900 °C for 1.5 hours, followed by 8-hour leaching experiments conducted at 30 °C, 40 °C, 50 °C, and 60 °C. XRF analysis revealed that the unroasted sample contained high copper (26.26 %), iron (19.46 %), and sulfur (7.94 %), confirming its sulfide-rich composition. Roasting at 600 °C reduced Sulphur to 3.42 % and produced more reactive CuO and Fe_2O_3 phases, whereas at 900 °C, extensive oxidation formed refractory $CuFe_2O_4$, limiting reactivity. XRD confirmed these phase transformations, showing progressive oxidation with increasing temperature. Leaching tests demonstrated that roasting temperature and redox potential strongly influenced copper recovery. The highest copper recovery was obtained for the 600 °C roasted sample with magnetite assistance, reaching approximately 80–85 % Cu recovery at 60 °C, compared to 50–60 % for the 400 °C sample and 35–45 % for the 900 °C sample. Without magnetite, recoveries decreased significantly, with the 600 °C roast yielding only 60–70 % Cu and the 900 °C roast achieving 25–35 % Cu. SEM-EDS confirmed increased oxidation and porosity at 600 °C, while 900 °C produced dense oxide layers that hindered dissolution. The results indicate that roasting at 600 °C combined with magnetite redox control provides the optimal balance between structural oxidation and redox stability, maximizing copper extraction efficiency in chloride-based leaching systems.

***Keywords*—** Chalcopyrite, Roasting, Galvanic Reactions, Chloride Solutions.

I. INTRODUCTION

The extraction of copper from chalcopyrite ($CuFeS_2$) has historically been dominated by pyrometallurgical methods due to their high efficiency and widespread industrial application. However, these methods pose significant environmental concerns, particularly due to high energy consumption and sulfur dioxide (SO_2) emissions, which contribute to acid rain and air pollution [1]. Additionally, the depletion of high-grade copper ores has necessitated the exploration of alternative hydrometallurgical techniques, particularly for lowgrade and complex ores that contain high impurities, such as lead and iron [2]. Hydrometallurgical methods, such as chloride leaching, have gained interest due to their potential for lower environmental impact and better selectivity in dissolving copper. However, chalcopyrite presents a major challenge in these processes due to its slow dissolution kinetics, which are attributed to the formation of passivation layers on its surface, inhibiting further reaction [3] . While redox potential control has proven effective in sulfate-based leaching systems, its role in chloride leaching under controlled conditions remains insufficiently explored [4]. This study aims to investigate the impact of roasting and redox potential on chalcopyrite dissolution, with the goal of optimizing copper extraction while minimizing passivation effects.

The study places significant emphasis on understanding the role of redox potential, as it directly influences chalcopyrite dissolution through electrochemical mechanisms. Prior research has indicated that in sulfate-based leaching systems, maintaining an optimal Fe^{3+}/Fe^{2+} ratio is crucial for maximizing dissolution rates [5]. However, the behavior of chalcopyrite in chloride media under similar conditions is not well understood. Roasting, a thermal pre-treatment process, is being explored as a potential solution to enhance chalcopyrite dissolution by modifying the mineral's structure. By subjecting the ore to elevated temperatures, roasting can alter the phase composition, reduce the formation of passivating layers, and improve the accessibility of reactive surfaces for leaching [6]. This study compares the effects of controlled redox potential and roasting, analyzing their respective efficiencies in improving copper recovery. Additionally, it evaluates the impact of different oxidants and catalysts in promoting chalcopyrite leaching, aiming to develop a more sustainable and economically viable approach to copper extraction [7]. By identifying optimal conditions for redox potential and pre-treatment, this research contributes to the advancement of hydrometallurgical techniques for treating chalcopyrite and other refractory copper ores.

II. METHODOLOGY

A. Materials

The study involved preparing chloride leaching solutions using chalcopyrite concentrate, hydrochloric acid, and magnetite, using Deionized water and equipment like a muffle furnace and batch reactors. Redox potential, pH, and X-ray diffraction, XRF and SEM be used for sample

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characterization.

B. Sample Preparation

Leaching Solutions: To assess their effect on dissolving kinetics, chloride-based solutions (HCL) will be made at different concentrations.

Reagents and Oxidants: To control the redox potential magnetite will be utilized

Experimental Procedures

A. Roasting process

A muffle furnace with regulated air conditions was used for roasting, three 100g samples of chalcopyrite was roasted at three different temperatures of 400°C, 600°C and 900°C, each sample was roasted for 1 hour and 30 mins, Roasting was carried out in air, and samples was cooled naturally before analysis, to try break down the sulfide matrix, reduce passivation, and improve surface reactivity

B. Leaching experiments

Leaching experiments was conducted using batch reactors, with precise control over parameters such as temperature, redox potential, and oxidant concentration. The key parameters and their expected impact on dissolution were as follows:

Temperature Control: To determine how thermal energy affects the kinetics of chalcopyrite dissolution, experiments was carried out at four distinct temperatures: 30°C,40°C, 50°C, 60°C.

pH Regulation: To preserve an acidic environment that promotes copper dissolution, the pH of the leaching solution was kept within the range of 1.5

Oxidant Concentration: To identify the ideal oxidant levels for optimizing copper extraction, the effects of different magnetite concentrations (5 g/L to 20 g/L) was investigated.

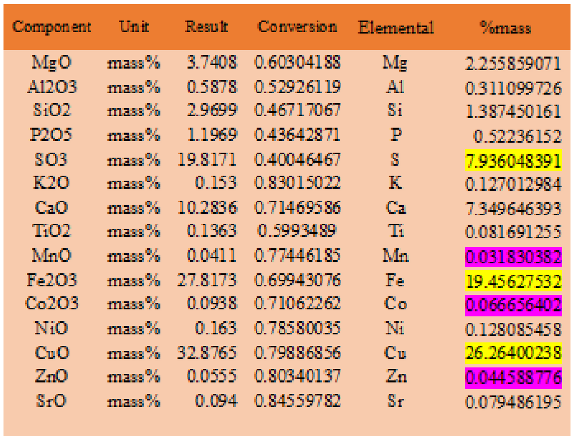
Time control: periodic sample was carried out at regular intervals of 2, 4, 6, 8 hours in order to assess the rates at which copper dissolves.

III. RESULTS AND DISCUSSION

A. Characterization

XRF

TABLE 1: NON-ROASTED SAMPLE



Component	Unit	Result	Conversion	Elemental	%mass
MgO	mass%	3.7408	0.60304188	Mg	2.255859071
Al2O3	mass%	0.5878	0.52926119	Al	0.311099726
SiO2	mass%	2.9699	0.46717067	Si	1.387450161
P2O5	mass%	1.1969	0.43642871	P	0.52236152
SO3	mass%	19.8171	0.40046467	S	7.936048391
K2O	mass%	0.153	0.83015022	K	0.127012984
CaO	mass%	10.2836	0.71469586	Ca	7.349646393
TiO2	mass%	0.1363	0.5993489	Ti	0.081691255
MnO	mass%	0.0411	0.77446185	Mn	0.031830382
Fe2O3	mass%	27.8173	0.69943076	Fe	19.45627532
Co2O3	mass%	0.0938	0.71062262	Co	0.066656402
NiO	mass%	0.163	0.78580035	Ni	0.128085458
CuO	mass%	32.8765	0.79886856	Cu	26.26400238
ZnO	mass%	0.0555	0.80340137	Zn	0.044588776
SrO	mass%	0.094	0.84559782	Sr	0.079486195

The unroasted chalcopyrite sample shows high concentrations of copper (26.26 %), iron (19.46 %), and calcium (7.35 %), which are the three most abundant elements. Copper and iron are the principal constituents of chalcopyrite ($CuFeS_2$), and their high levels confirm the dominance of this sulfide mineral in the unroasted ore. Calcium appears elevated due to the presence of associated gangue minerals such as calcite or silicate impurities that remain in the concentrate. The three lowest elements manganese (0.0318 %), zinc (0.0446 %), and cobalt (0.0667 %) occur only in trace amounts, as they are not integral to the chalcopyrite structure and usually exist as minor inclusions or isomorphic substitutions within the lattice. The high sulfur content (7.94 %) indicates that the mineral is still in its sulfide form, with no oxidation having occurred. This unroasted state is therefore highly reactive in chloride leaching systems under oxidizing redox potentials, as the sulfur rich matrix promotes electrochemical dissolution of Cu and Fe through redox coupling reactions. However, the absence of prior roasting means that passive surface films such as $Fe_2\ O_3$ or CuO have not yet formed, allowing faster initial dissolution but potentially leading to slower kinetics later due to sulfur layer accumulation during leaching.

TABLE II: ROASTED SAMPLE

Component	Unit	Result	Conversion	Elemental	%Mass
MgO	mass%	0.6878	0.60304188	Mg	0.41477221
Al2O3	mass%	0.1932	0.52926119	Al	0.10225326
SiO2	mass%	0.9422	0.46717067	Si	0.4401682
P2O5	mass%	0.3543	0.43642871	P	0.15462669
SO3	mass%	17.7459	0.40046467	S	7.10660597
Cl	mass%	0.0144	35.453	Cl	0.5105232
K2O	mass%	0.0958	0.83015022	K	0.07952839
CaO	mass%	5.9413	0.71469586	Ca	4.24622254
TiO2	mass%	0.106	1.1986978	Ti	0.12706197
Cr2O3	mass%	0.0275	0.68420741	Cr	0.0188157
MnO	mass%	0.0424	0.77446185	Mn	0.03283718
Fe2O3	mass%	31.7729	0.69943076	Fe	22.2229436
Co2O3	mass%	0.1174	0.71062262	Co	0.0834271
NiO	mass%	0.2014	0.78580035	Ni	0.15826019
CuO	mass%	41.5847	0.79886856	Cu	33.2207096
ZnO	mass%	0.0701	0.80340137	Zn	0.05631844
SrO	mass%	0.1025	0.84559782	Sr	0.08667378

At 400 °C, the roasted chalcopyrite still retains a significant amount of sulfur bearing phases, as reflected by the high sulfur content (7.11 %), together with dominant copper (33.22 %) and iron (22.22 %) values that represent the core chalcopyrite composition ($CuFeS_2$). These high elements indicate that roasting at 400 °C is insufficient to fully oxidize and decompose chalcopyrite, much of the mineral remains as sulfide or partially oxidized intermediates. The lowest elements chromium (0.0188 %), manganese (0.0328 %), and zinc (0.0563 %) are trace impurities that remain minor because they do not actively participate in the sulfide oxidation reactions and exist only in small accessory phases. Overall, the 400 °C roast yields a product still rich in reactive sulfide phases, which under controlled redox leaching conditions in chloride media could dissolve efficiently due to higher sulfur availability and less formation of refractory oxides.

XRD

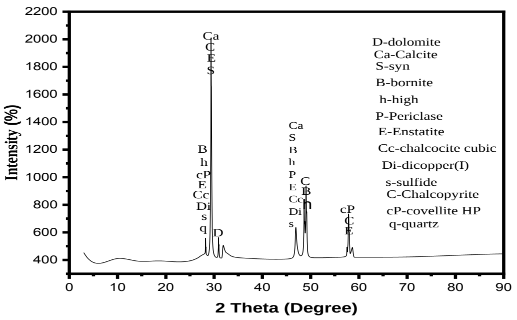


Fig. 1: of XRD Unroasted chalcopyrite

The XRD pattern of the unroasted chalcopyrite sample showed distinct, sharp peaks primarily at 2θ values around 28.16°, 47.12°, and 58.12° The high-intensity peak at approximately 29° indicated a well-crystallized sulfide structure, confirming the dominance of chalcopyrite as the major phase. The lower intensity peaks represent minor impurities or secondary sulfide minerals. Overall, the diffraction pattern confirmed that the sample remained unoxidized, with a highly crystalline sulfide matrix characteristic of natural chalcopyrite ore.

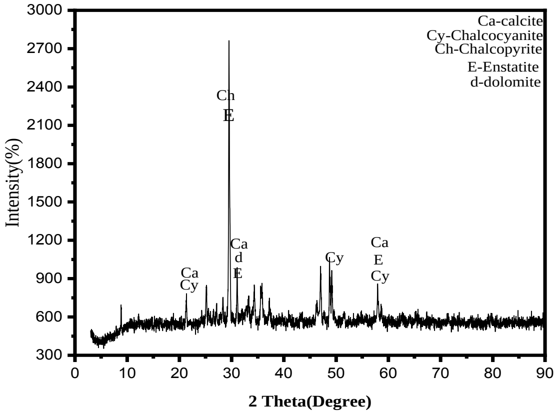


Fig. 2 of XRD 400C

The XRD pattern for the sample roasted at 400°C showed a noticeable reduction in the intensity of the primary chalcopyrite peaks and the emergence of new reflections at approximately 29–33° and 50–58° (2θ). These new peaks correspond to chalcopyrite, Enstatite , calcite , Chalcocyanite phases, indicating the onset of sulfide oxidation. The peak at around 29.5° exhibits the highest intensity, marking the formation of copper oxide as the dominant product, while weaker peaks at lower 2θ values suggest incomplete conversion of chalcopyrite. This partial oxidation reflected a transitional phase between sulfide and oxide states, producing a mixture of reactive intermediates suitable for enhanced leaching.

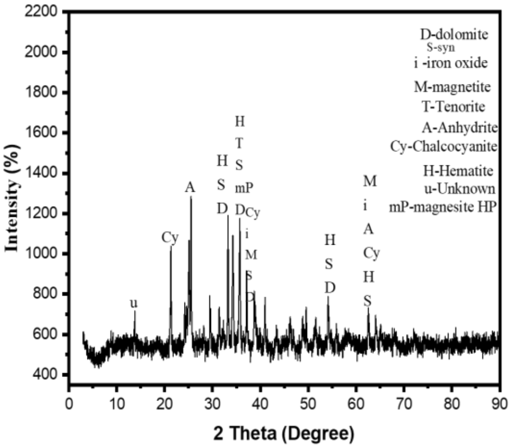


Fig. 3 of XRD 600C

The XRD pattern at 600°C demonstrated further transformation of the mineral structure, with the disappearance of most chalcopyrite peaks and strong, well-defined peaks appearing at approximately 25.6°, 32.3°, and 62.5° (2θ). These correspond to CuO (tenorite) and Fe_2O_3 (hematite), indicating extensive oxidation of both copper and iron sulfides. The peak with the highest intensity occurred near 25.6°, confirming Anhydrite as the dominant crystalline phase, while smaller peaks at higher angles reflect minor iron oxide and sulfate species. The increased peak sharpness and intensity suggest greater crystallinity and phase purity compared to the 400°C sample, representing an optimal oxidation state that enhances surface reactivity. Peaks above 70° become weaker or vanish, which indicated the completion of oxidation and potential overlapping of minor phases with low diffraction intensity.

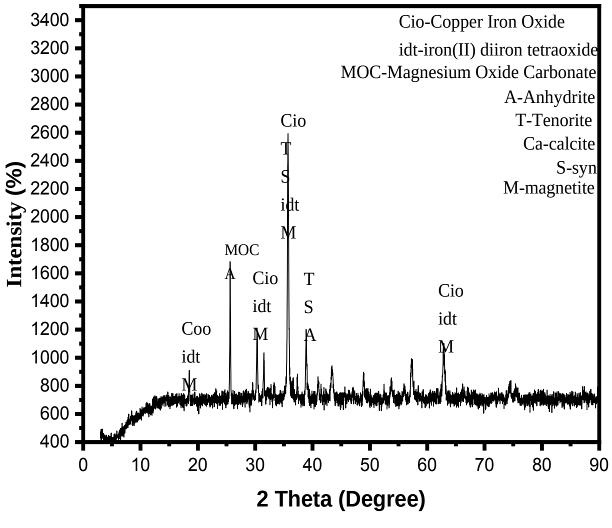


Fig. 4 of XRD 900C

At 900°C, the XRD pattern showed complete transformation of the original chalcopyrite structure into stable oxide and spinel phases. The highest-intensity peak appeared near 35.4° (2θ), corresponding to $CuFe_2O_4$ (copper iron oxide spinel), while secondary peaks around 25.7° and 39.8° were attributed to Magnesium Oxide Carbonate and Tenorite. The low-intensity peaks indicated minor residual or amorphous phases due to thermal sintering. The overall pattern reflected a highly crystalline but dense oxide matrix, signifying over-oxidation and structural consolidation. Consequently, the 900°C product was less reactive in leaching due to reduced porosity and increased phase stability.

B. Cu recoveries results

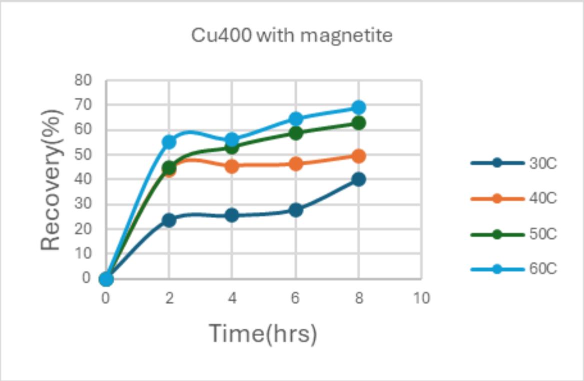


Fig. 5 Cu400 with magnetite

For the 400°C roasted chalcopyrite, the leaching results showed that copper recovery increased gradually with temperature, indicating that both roasting and redox control with magnetite enhanced the dissolution kinetics. The moderate roasting temperature caused partial oxidation of chalcopyrite into Cu_2O, Fe_2O_3, and $CuSO_4$ phases, which improved mineral reactivity without fully destroying the sulfide structure. During the 8-hour leaching period, the presence of magnetite helped to stabilize the redox potential by promoting the Fe^{3+}/Fe^{2+} cycle, which sustained oxidative conditions favorable for copper dissolution. However, because the roasting temperature was relatively low, some unoxidized sulfide cores remained, limiting total copper extraction. Overall, the 400°C roasted sample showed steady but moderate dissolution efficiency, with reaction rates improving significantly between 50°C and 60°C as higher temperatures increased molecular activity and electron transfer between chalcopyrite and the oxidant system.

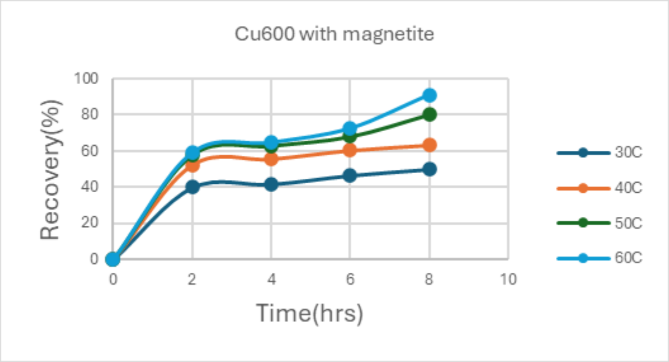


Fig. 6: Cu600C with Magnetie

For the 600°C roasted chalcopyrite, the leaching results revealed the highest copper recovery among the three roasting conditions. At this temperature, the mineral structure was more thoroughly oxidized into CuO and Fe_2O_3, with a porous surface that enhanced accessibility to the hydrochloric acid solution. The magnetite redox couple effectively maintained a favorable oxidative potential, regenerating Fe^{3+} ions that continuously oxidized Cu^{+} and Fe^{2+} species, thus sustaining leaching activity. The dissolution rate increased consistently with temperature, with maximum efficiency observed at 60°C, where both chemical and electrochemical processes were optimized. The synergy between 600°C roasting and magnetite driven redox control minimized passivation effects, allowing prolonged dissolution without surface deactivation. This suggests that roasting at 600°C produced an ideal balance between structural oxidation, surface porosity, and redox stability, leading to superior copper extraction performance.

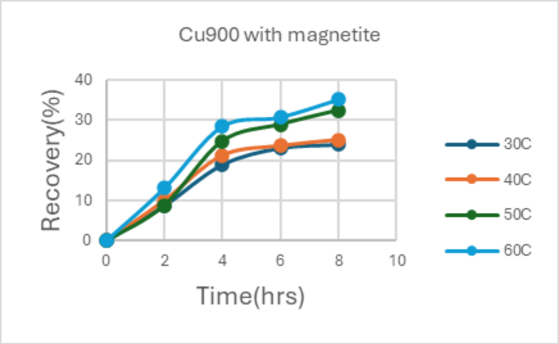


Fig.7: Cu 900C with Magnetite

The leaching graph of roasted chalcopyrite at 900°C in the presence of magnetite showed a steady but limited increase in copper recovery with increasing temperature and time. At lower temperatures (30°C–40°C), the dissolution rate was slow due to the refractory nature of the high-temperature oxide phases such as $CuFe_2O_4$ and Fe_2O_3, which formed during roasting. However, as temperature increased to 50°C and 60°C, copper recovery improved noticeably, reaching approximately 35–45% after 8 hours. This improvement was attributed to magnetite’s role as a redox mediator, maintaining a stable Fe^{3+}/Fe^{2+} balance that sustained oxidative conditions and minimized passivation. The redox cycling facilitated limited breakdown of the dense oxide layer, enhancing ion diffusion and promoting continued copper dissolution at higher leaching temperatures.

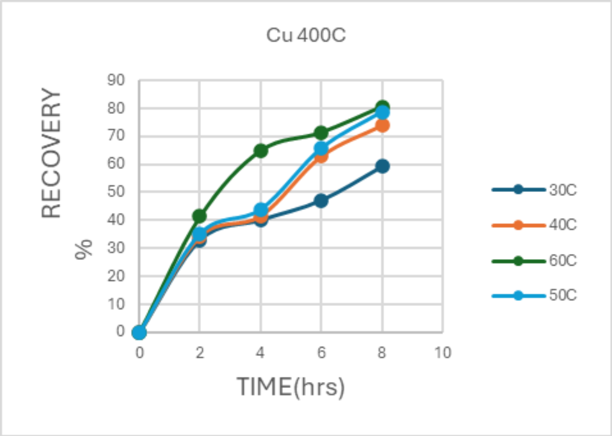


Fig. 8: Cu400

At 400 °C the copper recovery increased gradually with leaching temperature (30 °C to 60 °C), indicating that higher thermal energy promoted faster dissolution and ion diffusion in the HCl medium. However, due to incomplete oxidation and the absence of a redox-controlling agent such as magnetite, the solution’s oxidizing strength diminished over time, resulting in a slower dissolution rate at later stages of the 8-hour leach. Some passivation occurred from sulfur-rich surface films, slightly restricting reaction sites. Overall, the 400 °C sample displayed moderate copper recovery, with leaching temperature being the main driver of improved extraction.

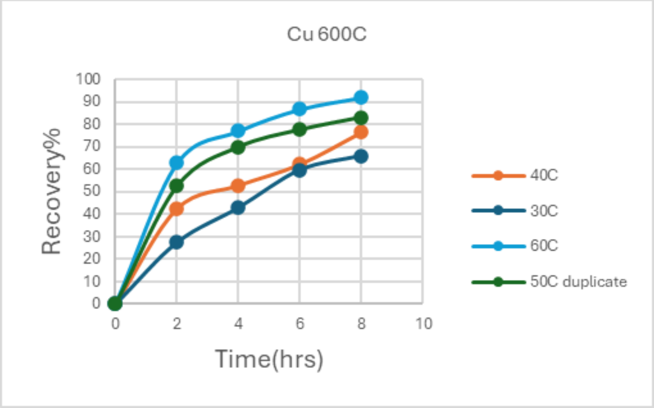


Fig. 9: Cu 600C

The 600 °C roasted sample showed the highest copper recovery among all conditions. At this temperature, the chalcopyrite structure was optimally oxidized into porous CuO phases, increasing surface area and improving acid access. Even without redox stabilization, the leaching efficiency rose consistently with temperature, peaking at 60 °C, where molecular activity and proton attack were most effective. The balanced oxidation level achieved at 600 °C minimized passivation while maintaining reactivity throughout the 8-hour leach. This suggests that 600 °C roasting created a structurally open and chemically active surface that favored chloride leaching, compensating for the lack of external redox control. Hence, 600 °C represents the optimum roasting temperature under non-magnetite conditions.

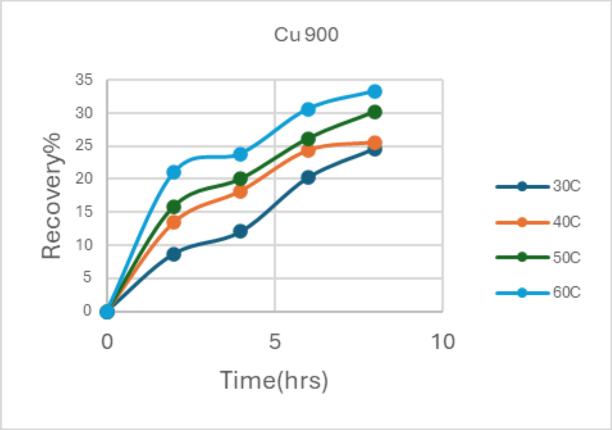


Fig. 10: Cu 900C

The leaching performance of roasted chalcopyrite at 900°C without magnetite exhibited much lower recoveries compared to the magnetite-assisted test. The graph demonstrated minimal copper extraction at 30°C and 40°C, with recoveries typically between 5–25%, and only slight improvement at 50°C and 60°C, reaching around 25–35% after 8 hours. The poor performance was mainly due to the over-oxidation and sintering effects produced during roasting, which created a compact $CuFe_2O_4$ spinel structure resistant to acid attack. In the absence of redox potential control, the oxidizing strength of the leaching solution decreased over time, allowing passivation layers to form and further restricting dissolution. Overall, while temperature marginally enhanced reaction kinetics, the absence of magnetite limited redox regeneration, resulting in slower dissolution and significantly lower copper recovery than the magnetite-assisted system.

SEM-EDS

A. SEM-EDS OF UNROASTED SAMPLE

TABLE V
SEM-EDS UNROASTED SAMPLE

ELEMENT	Copper(Cu)	Iron(Fe)	Sulfur(S)	Oxygen(0)
Spectrum 1	29.81	28.56	41.63	
Spectrum2	0.58	0.51	0.14	36.74
Spectrum3	29.63	5.87	13.68	
Spectrum 4	0.37	2.14		28.97

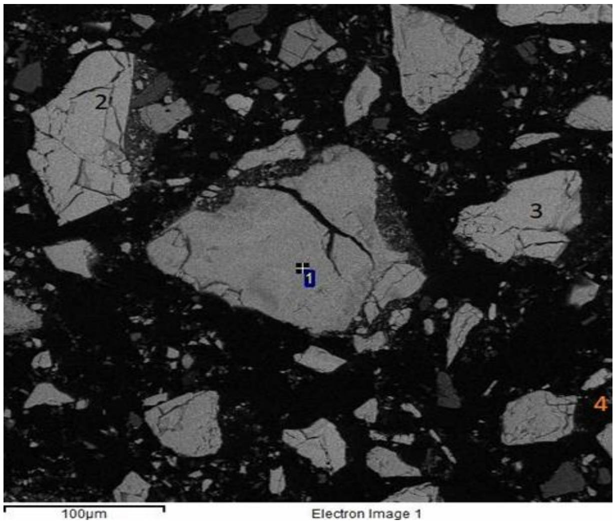


Fig. 11: SEM-EDS unroasted sample

The SEM-EDS analysis of the unroasted chalcopyrite sample involved examining four spectra obtained from the same micrograph to identify the elemental composition in weight percent (wt%). The spectra consistently revealed the presence of copper (Cu), iron (Fe), sulfur (S), and oxygen (O) as the dominant elements. Copper and iron were detected as the major constituents, confirming the presence of chalcopyrite ($CuFeS_2$) as the primary mineral phase. Sulfur appeared in high proportions, reflecting the sulfide nature of the sample, while oxygen signals indicated minor surface oxidation possibly due to atmospheric exposure or sample preparation. Overall, the EDS data confirm that the unroasted mineral is a sulfide-rich chalcopyrite concentrate with minor surface oxides and minimal alteration.

SEM-EDS roasted at 400C

ELEMENT	Copper(Cu)	Iron(Fe)	Sulfur(S)	Oxygen(0)
Spectrum 1	28.05	27.63	44.32	
Spectrum 2	2.97	4.48	4.08	51.33
Spectrum 3	17.06	20.55	11.73	36.53
Spectrum 4	21.57	30.50	12.03	24.78

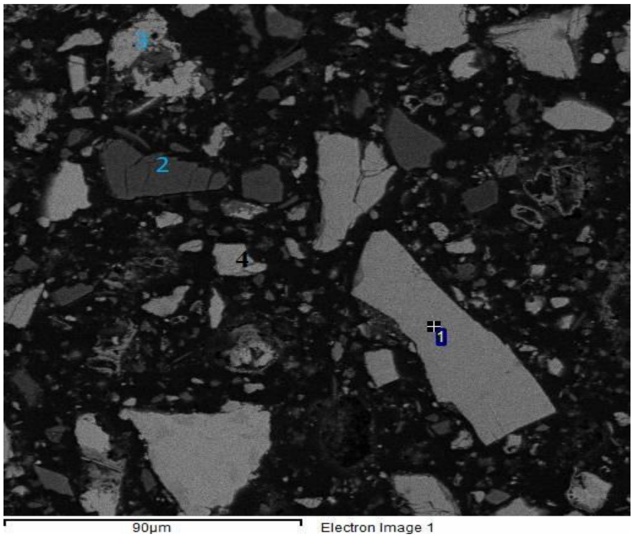


Fig. 12: SEM-EDS 400C

At 400°C, the EDS spectra indicated the presence of copper (Cu), iron (Fe), sulfur (S), and oxygen (O) as the dominant elements. Copper and iron appeared in high proportions, confirming that the chalcopyrite matrix ($CuFeS_2$) remained largely intact but partially oxidized. The significant oxygen signal suggests the onset of sulfide oxidation, forming intermediate oxides such as CuO and Fe_2O_3 , while the persistence of sulfur indicates incomplete decomposition of the sulfide phase. The variation among the four spectra reflects heterogeneous oxidation across the particle surface, characteristic of partial roasting at moderate temperatures where both sulfide and oxide phases coexist.

SEM-EDS roasted at 600C

TABLE VII: SEM-EDS ROASTED AT 600C

ELEMENT	Copper(Cu)	Iron(Fe)	Sulfur(S)	Oxygen(0)
Spectrum 1	35.03	9.79	6.93	44.56
Spectrum 2	11.65	8.16	19.64	47.44
Spectrum 4	1.60	0.59	2.24	67.28
Spectrum 6	0.76	0.68	9.22	82.90

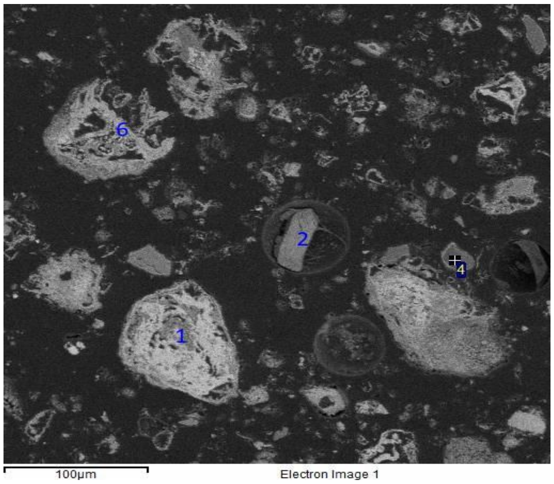


Fig. 1: SEM-EDS 600C

The SEM-EDS characterization of the chalcopyrite sample roasted at 600 °C involved four spectra obtained from a single micrograph to assess the distribution and relative abundance of key elements in weight percent (wt%). The spectra revealed the predominant presence of copper (Cu), iron (Fe), sulfur (S), and oxygen (O), with copper and oxygen exhibiting the highest intensities. The elevated oxygen concentration, particularly in spectra 4 and 6, indicates that partial oxidation of the sulfide matrix occurred during roasting, resulting in the formation of copper and iron oxides such as CuO and Fe_2O_3. The concurrent detection of sulfur in measurable proportions suggests that complete oxidation was not achieved, and residual sulfide phases of chalcopyrite ($CuFeS_2$) or its intermediates remained.

SEM-EDS roasted at 900C

TABLE VIII
SEM-EDS ROASTED 900C

ELEMENT	Copper(Cu)	Iron(Fe)	Sulfur(S)	Oxygen(0)
Spectrum 1	7.78	5.70	0.57	47.70
Spectrum 2	48.09	2.02	1.75	44.53
Spectrum 3		1.63		87.95
Spectrum 4	9.50	11.69	2.50	69.35

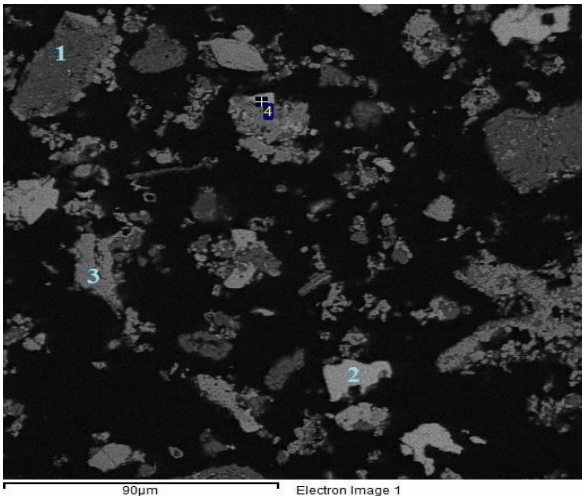


Fig. 14:SEM-EDS 900C

The sample roasted at 900°C showed substantial changes in elemental distribution. The EDS spectra revealed much higher oxygen content and reduced sulfur levels, indicating near-complete oxidation and transformation of chalcopyrite into refractory oxide phases. Copper and iron were still dominant, but the formation of dense CuO, Fe_2O_3, and $CuFe_2O_4$ spinel structures was evident from the lower sulfur intensities and higher oxygen peaks. This temperature promoted extensive phase transformation and structural densification, leading to a more compact and less reactive surface.

B. Comparison of the previous work that have been done

The findings of this Research align with previous research showing that moderate roasting significantly enhances chalcopyrite leaching by improving mineral reactivity. Prasad and Pandey [8] and Faris et al. [9] both reported that controlled oxidation at moderate temperatures leads to the formation of porous CuO and Fe_2O_3 phases that promote acid accessibility and reduce passivation. Similarly in this study roasting at 600 °C produced partially oxidized but reactive surfaces that achieved the highest copper recovery (80–85%), confirming that moderate thermal treatment is optimal for efficient dissolution. In contrast excessive roasting at 900 °C formed compact spinel structures ($CuFe_2O_4$), consistent with Faris et al. [9], who observed that high-temperature roasting decreases solubility due to structural densification.

Furthermore, the redox controlled leaching results correspond closely with findings by Nguyen et al. [10] and Liddicoat and Dreisinger [11], who demonstrated that maintaining an optimal Fe^{3+}/Fe^{2+} ratio in chloride media stabilizes oxidative conditions, thereby sustaining copper dissolution. In agreement the Research found that the addition of magnetite effectively maintained redox balance, minimizing passivation, and improving recoveries compared to non-magnetite systems [12]. These similarities validate that both controlled redox potential and moderate roasting are critical in enhancing chalcopyrite leachability, reinforcing the conclusions drawn by earlier studies while providing new evidence for their combined effect in chloride-based systems.

IV. CONCLUSION

The study examined the effects of roasting and redox potential control on the dissolution of chalcopyrite ($CuFeS_2$) in chloride media to determine which conditions maximize copper recovery. The findings revealed that both factors play a vital role in enhancing leaching performance. Roasting at 600 °C produced porous CuO and Fe_2O_3 phases that improved reactivity, while roasting at 400 °C left unoxidized sulfide cores and 900 °C created refractory $CuFe_2O_4$ spinels that resisted dissolution. Among all tests, the 600 °C roasted sample with magnetite redox control achieved the highest copper recovery of 80–85%, compared to 50–60% at 400 °C and 35–45% at 900 °C, demonstrating that structural oxidation and redox balance must be optimized simultaneously for efficient leaching.

In answering the research questions, the results confirmed that roasting and redox potential act synergistically to improve chalcopyrite dissolution in chloride systems. Moderate roasting at 600 °C enhances surface reactivity, while magnetite ensures stable oxidative conditions through continuous Fe^{3+}/Fe^{2+} regeneration, reducing passivation and sustaining copper dissolution. Excessive roasting above 900 °C, however, leads to dense oxide formation and lower recoveries. Therefore, the optimal condition for effective and sustainable copper extraction is roasting at 600 °C combined with magnetite-controlled redox potential.

Based on the findings, it is recommended that future hydrometallurgical processing of chalcopyrite adopt roasting at 600 °C combined with magnetite assisted redox potential control to maximize copper recovery and minimize passivation. Industrial operations should maintain a stable Fe^{3+}/Fe^{2+} balance during leaching to sustain oxidative conditions and enhance dissolution kinetics. Further research is encouraged to optimize variables such as acid concentration, leaching time, and particle size to improve process efficiency.

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REFERENCES

[1] Ahmadi, A., et al. (2010). Environmental impacts of pyrometallurgical processes. Hydrometallurgy..

[2] Kolela J Nyembwe, Elvis Fosso-Kankeu, Frans Waanders, Kasongo D Nyembwe. 2019. Structural, compositional and mineralogical characterisation of carbonatitic copper sulfide concentrator plant streams: Run of mine, concentrate and tailings. International Journal of Minerals, Metallurgy and Materials. 26(2): 143-151. https://doi.org/10.1007/s12613-019-1718-8

[3] Kolela J Nyembwe, Elvis Fosso-Kankeu, Frans Waanders and Martin Mkandawire. 2021. pH-Dependent leaching mechanism of carbonatitic chalcopyrite in ferric sulfate. Transactions of Non Ferrous Metals Society of China. 31: 2139- 2152. https://doi.org/10.1016/S1003-6326(21)65644-3.

[4] Kolela J Nyembwe, Elvis Fosso-Kankeu, Frans Wanders and Edward Ntumba Malenga. 2018. Mineralogical Observation Made During the Kinetic Dissolution Study of Chalcopyrite Mineral in Sulphate Media under Free pH at Room Temperature. Editors: Elvis Fosso-Kankeu, Frans Waansders, Michel Plaisent. 10th Int'l Conference on Advances in Science, Engineering, Technology & Healthcare (ASETH-18) Nov. 19-20, 2018 Cape Town (South Africa). ISBN: 978-81-938365-2-1. Vol II. Pp 144-148.

[5] Brad Barlow, Elvis Fosso-Kankeu, Kolela J Nyembwe, Frans Waanders and Edward Ntumba Malenga. 2018. Prediction of Dissolution of Copper from a Chalcopyrite Carbonatite Ore of South Africa. Editors: Elvis Fosso-Kankeu, Frans Waansders, Michel Plaisent. 10th Int'l Conference on Advances in Science, Engineering, Technology & Healthcare (ASETH-18) Nov. 19-20, 2018 Cape Town (South Africa). ISBN: 978-81-938365-2-1. Vol I. Pp 96-100.

[6] Kolela J. Nyembwe, Elvis Fosso-Kankeu, Frans Waanders, Bhekie B. Mamba and Martin Mkandawire. 2024. Chalcopyrite Leaching in Ferric Sulphate: The Effect of Fe3O4-CuFeS2 Galvanic Couple on the Cu Dissolution. Minerals. 14: 162. https://doi.org/10.3390/min14020162

[7] Kolela J Nyembwe, Elvis Fosso-Kankeu, Frans Waanders, Martin Mkandawire, Didier K Nyembwe, Bhekie B Mamba. 2024. Influence of Fe3O4 on redox changes during Cu dissolution from CuFeS2 in acidified ferric sulfate. Trans. Nonferrous Met. Soc. China 34(2024) 1965−1975.

[8] Prasad, M.S. and Pandey, B.D. (1998). Effect of roasting on the leaching behaviour of chalcopyrite concentrate. Hydrometallurgy, 47(3), pp.229–239.

[9] Faris, N., et al. (2017). Effect of thermal pre-treatment on dissolution of chalcopyrite. Hydrometallurgy, 169, 68–78. https://doi.org/10.1016/j.hydromet.2016.12.006

[10] Nguyen, T.P., Tsuji, S., Jeon, S., Park, I., Tabelin, C.B., Ito, M. and Hiroyoshi, N., 2020. Redox potential-dependent chalcopyrite leaching in acidic ferric chloride solutions: Leaching experiments. Hydrometallurgy, 194, p.105299.

[11] Liddicoat, J., & Dreisinger, D. (2007). Chloride leaching of chalcopyrite. Hydrometallurgy, 89(1–2), 323–331.

[12] Kolela Nyembwe, Frans Waanders, Martin Mkandawire, Bhekie Mamba. 2024. Complexity of chalcopyrite mineral affecting copper recovery during leaching. Eds. Elvis Fosso-Kankeu, Bhekie Mamba, Antoine F Mulaba-Bafubiandi. 2024. Recovery of Values from Low-Grade and Complex Minerals: Development of Sustainable Processes. Wiley. ISBN: 9781119896418. https://doi.org/10.1002/9781119896890.ch6