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The Impact of Acid Concentration and Temperature on Copper Leaching from Waste SIM Cards

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Abstract: This study investigates copper recovery from waste SIM cards using hydrometallurgical acid leaching with nitric acid. Microchip components were mechanically separated from their plastic substrates prior to leaching experiments with varying nitric acid concentrations (2 M-6 M) and temperatures (40-80°C) for 180 minutes. Copper dissolution was analyzed using atomic absorption spectrophotometry at different time intervals. Results demonstrated that acid concentration significantly enhanced copper dissolution, with 4M and 6M nitric acid achieving similar maximum recovery rates of approximately 74% within 120 minutes. Temperature variations (40-80ºC) showed minimal impact on extraction efficiency, suggesting that the process is not thermally activated under these conditions. Based on the experimental conditions tested, 4M nitric acid at 40ºC was identified as the most economically favorable condition, achieving 72.9% Cu recover. This study provides valuable insights for sustainable precious metal recovery from electronic waste.

Keywords: acid leaching; copper; e-waste; leaching

1. Introduction

The exponential growth electronic waste (e-waste) has emerged as one of the most pressing environmental challenges of the 21st century. Global e-waste problem is an urgent issue characterized by an alarming increase in the generation of electronic waste, which poses significant environmental and health risks. Due to the swift progress in technology and consumer electronics, the global generation of e-waste reached about 53.6 million metric tons in 2019, indicating a notable growth trend anticipated to persist in the upcoming years, possibly exceeding 57.4 million metric tons by 2023 1,2) . This alarming trend has been further exacerbated by the COVID-19 pandemic, which led to significant shifts in work patterns and increased consumer electronics demand, resulting in a substantial rise in e-waste generation3). The severity of this crisis is underscored by the fact that only 17.4% of total global e-waste was effectively recycled in 2023, highlighting the significantly inefficient management of this waste stream4).

The improper disposal of e-waste poses severe risks to both human health and the environment, contributing to pollution and climate change through the release of hazardous substances5). However, this crisis also represents a substantial loss of valuable materials that could be recovered and reused. The composition of e-waste is particularly significant, as approximately 60% consists of valuable metals, including gold, silver, and copper4). This substantial metal content highlights the urgent need for establishing effective recovery and recycling methods that can mitigate environmental hazards while promoting a circular economy where valuable materials are systematically recovered and reused6).

Among the various components of e-waste, SIM cards represent a particularly rich source of copper that has received limited attention in the literature. Based on previous studies on e-waste characterization, SIM cards have been shown to contain approximately 3-4 times higher copper concentration (75%)7) compared to conventional PCBs (10-29%)8–10) and waste electric cables (4,97%)11). A more recent study confirmed the high copper (Cu) content in SIM cards, reporting 43.6% Cu, 2.56% Ni, and trace amounts of gold and iron12). Despite this variation, both studies confirm SIM cards exceptional copper content

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makes them ideal for metal recovery.

Treatment processes for metal recovery are generally categorized into three groups: pyrometallurgy, hydrometallurgy, and biohydrometallurgy. Pyrometallurgy refers to metal recovery procedures that involve significant energy consumption due to their reliance on high temperatures. The process of hydrometallurgy involves using water-based solutions with various chemicals to extract metals from ores, concentrates, and waste products. In addition, bioleaching is an innovative technology that utilizes microorganisms to directly or indirectly recover metal ions from low-grade ores and mineral nodules[13)]. There is consensus that integrating hydrometallurgical techniques into e-waste management enhances recovery efficiency and aligns with sustainable practices increasingly demanded by regulatory frameworks and societal expectations[14)]. Therefore, the strategic implementation of hydrometallurgical processes represents a pathway to improved metal recovery while mitigating the ecological impacts traditionally associated with metal extraction.

The acid-leaching methods for metal recovery, particularly for Cu from electronic waste, are crucial to the field of hydrometallurgy. Extracting precious metals from electronic waste requires the use of aqua regia or powerful acids like hydrochloric acid (HCl), nitric acid (HNO_3), and sulfuric acid (H_2SO_4) for dissolution[15–18)]. Copper recovery of 99.5% from waste PCBs was achieved using H_2SO_4-hydrogen peroxide (H_2O_2) leaching at optimized parameters: 31ºC, 2.6 mol/L H_2SO_4, 1.87 mol/L H_2O_2, and 0.05 g/mL solid-liquid ratio. The kinetic analysis revealed that the data fit the Avrami equation well, implying that the underlying mechanism for the process is nucleation and growth[19)]. Similarly, Rajahalme et al. (2021) achieved over 92% Cu recovery from waste PCBs using 3.6M H_2SO_4 with 6 vol% H_2O_2 at just 20ºC, demonstrating that high recovery can be achieved without thermal activation[9)].

Beyond H_2SO_4 systems, alternative acids show promise. Recently, an innovative two stage selective recovery process has been developed for nanoscale particles from mobile phone PCBs. Their approach utilized low concentration HNO_3 in the first stage to selectively dissolve tin and base metals while preserving Cu, followed by HCl- H_2O_2 treatment for copper dissolution, achieving 29,437.5 ppm copper in the leachate[20)]. This approach demonstrates the potential for sophisticated separation strategies.

HNO_3 presents significant advantages over other mineral acids for Cu recovery applications. A recent study achieved 99% Cu recovery from oxidized Cu ore under optimal conditions (0.5 M HNO_3, 50ºC, solid-liquid ratio of 0.004 g/mL)[21)]. Kinetic analysis revealed that the leaching process was controlled by both chemical reaction and diffusion mechanisms, with an activation energy of 36.23 kJ/mol. This moderate activation energy indicates the process operates at the boundary between diffusion controlled and reaction-controlled regimes, suggesting limited temperature dependence on process efficiency. In other e-waste applications, Cu recovery of 98.7% was achieved using 10% HNO_3 at 60ºC with solid-liquid ratio of 1:25 g/mL[22)]. This study confirmed the viability of industrial scale implementation and established that nitric acid functions effectively as a standalone leaching agent without requiring additional oxidants..

$HNO_3$was selected as the leaching agent based on three key considerations. Its lower corrosive properties than other strong acids, thereby extending the life of the leaching equipment. The acid can be regenerated after the leaching process, making it a more cost-effective and sustainable option. Moreover, spent nitric acid from the leaching process can be effectively utilized for producing agricultural-grade ammonium nitrate fertilizer, thereby providing additional economic value while ensuring complete waste stream utilization[23)]. These attributes position HNO_3 as a technically and economically viable option for sustainable Cu recovery from e-waste.

Optimizing and scaling up leaching processes fundamentally depends on understanding the reaction kinetics. Consequently, various kinetic models have been applied to describe Cu dissolution behavior. A recent investigation into the leaching of Cu oxide ore in H_2SO_4 determined that the experimental data were best fitted by a mix-controlled mechanism, involving both diffusion and chemical reaction. The activation energy of Cu in this system was reported as 24.0 kJ/mol[24)]. This finding is consistent with observation in HNO_3 systems, suggesting that Cu leaching from oxidized materials generally follows similar mechanistic pathways, regardless of the acid employed[21)]. The shrinking core model (SCM) has been widely applied to describe heterogeneous leaching reactions, considering that the reaction proceeds from the outer surface of the particle toward the center, with either chemical reaction at the interface or diffusion through the product layer as the rate-controlling step. The determination of the rate-controlling mechanism is essential for process optimization, as it dictates whether improvements should focus on enhancing reaction kinetics (through temperature or concentration) or improving mass transfer (through agitation or particle size reduction)[25)].

Despite the extensive research on copper recovery from electronic waste, several critical knowledge gaps persist that limit the development of efficient recovery processes for SIM card waste, which possess a significantly higher Cu content than conventional PCBs. The leaching behavior of this valuable material, particularly concerning the synergistic effects of acid concentration and temperature affect the leaching process, remains largely unexplored[26–29)]. Furthermore, the systematic application of HNO_3 to this specific waste stream, including the determination of fundamental kinetic parameters such as the governing model and activation energy (Ea), has not been reported, which is crucial for process design. This study systematically investigates the impact of HNO_3 concentration (2-6 M) and temperature (40-80ºC) on Cu leaching efficiency from waste SIM cards. Additionally, the research establish the kinetic model and determines activation energy, providing fundamental parameter essential for efficient industrial implementation.

2. Materials and Methods

2.1. Sample collection and characterization

Waste SIM cards are collected in the nearest area. The SIM card consists of a plastic body, and a microchip. To begin, detach the microchip SIM card from the plastic body as shown in Figure 1. The component utilized in the leaching process is a microchip SIM card.

Fig. 1: Component of SIM Card

2.2. Chemicals and Reagents

Nitric acid (65%) from Merck was used in this study. Distilled water is used to dissolve the acid. Nitric acid possesses exceptionally corrosive characteristics. To prevent inhalation and splashing of the resulting vapor, the solution is therefore prepared in a fume cupboard. Additionally, protective eyewear, lab coats, and rubber gloves are utilized to prevent direct contact with the chemicals.

2.3. Experimental Setup

The leaching apparatus consists of a 500 mL three-neck round-bottom flask made of borosilicate glass, known for its chemical resistance and thermal stability. The three-neck design facilitates the installation of critical components for the leaching process. One neck is utilized for the attachment of a reflux condenser, which is connected to a water-cooling system powered by a compressor. This setup ensures effective cooling and prevents the loss of volatile compounds. Another neck is fitted with an alcohol thermometer to monitor the reaction temperature continuously.

In contrast, the third neck serves as an inlet for feeding reagents into the flask during the leaching process. A magnetic stirrer provides the heating with an integrated hot plate, and a magnetic stir bar ensures consistent agitation of the solution at a constant speed, promoting homogeneity during the reaction. This configuration provides an efficient setup for controlled leaching experiments, as shown in Figure 2.

The selection of operating temperatures (40°C, 60°C, and 80°C) and nitric acid concentrations (2 M, 4 M, and 6 M) was based on findings from preliminary studies and existing literature on leaching processes[22)]. Previous research has demonstrated that increasing the temperature enhances reaction kinetics by providing higher energy to the system, thereby accelerating the dissolution of metal compounds. To prevent excessive evaporation of nitric acid and to maintain system safety, the leaching process is conducted in a fume hood. Regarding acid concentration, the chosen range of 2M to 6M reflects an optimal balance between reaction efficiency and material safety. Concentrations below 2M have been shown to result in slower leaching rates. In comparison, concentrations above 6M may lead to increased corrosion of the apparatus and the formation of unwanted oxides that hinder metal recovery. The time intervals (10, 20, 40, 60, 120, and 180 minutes) were selected to capture both the early and later stages of the leaching process, allowing for a comprehensive understanding of how these variables influence leaching efficiency over time.

2.4. Leaching procedure

The leaching procedure used to determine the effectiveness of acid usage employs a qualitative method and involves several systematic steps. Initially, a 4M solution of nitric acid is prepared in a chemical fume hood. Subsequently, 250 mL of the 4 M nitric acid solution was placed into a three-neck flask and heated to the desired temperature. After it was reached, 25 grams of the SIM card sample were placed into a three-neck flask and stirred using a magnetic stirrer for 3 hours. This fixed S/L ratio of 10% was intentionally employed to maintain a near constant concentration of the leaching agent (nitric acid)[30–32)]. This finding aligns with the work of Thubakgale et al[33)] and Prameswara et al[34)], who reported 10% S/L as optimal for metal extraction. After the leaching process is complete, filter to separate the solids and solution. After separating, observe the color of the leaching solution to determine the presence of the highest copper content.

A leaching process with variations in acid concentration and operating temperature was conducted. Initially, nitric acid solutions with concentrations of 2 M, 4 M, and 6 M were diluted to evaluate the impact of different concentrations on the leaching results. Subsequently, 250 mL of 2M nitric acid solution was transferred into a three-necked flask and heated using a hot plate stirrer to the desired temperature. To explore how temperature fluctuations impact leaching outcomes, the leaching process was carried out at three different temperatures: 40°C, 60°C, and 80°C. When the nitric acid solution

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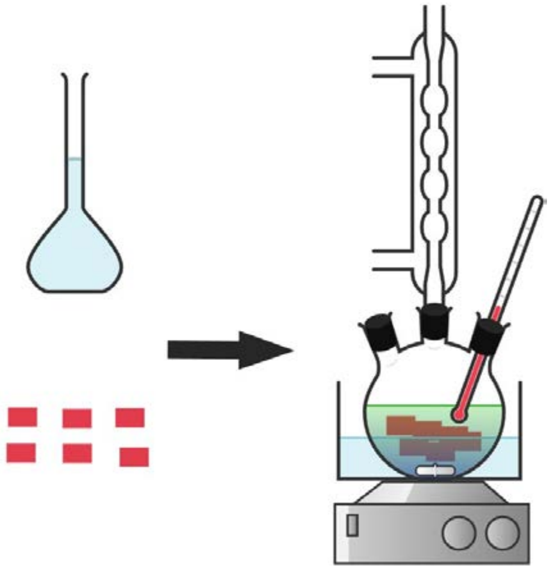

Fig. 2: Leaching SIM card's waste using acid solution

achieved the target temperature, 25 grams of the sample were introduced into the three-necked flask and mixed. At intervals of 10, 20, 40, 60, 120, and 180 minutes, 5 mL samples of the leaching solution were collected using a syringe to determine the copper content using atomic absorption spectroscopy (AAS). The leaching filtrate is filtered using a syringe filter to separate it from the remaining solids before analysis. The same procedure was repeated for leaching using 4 M and 6 M nitric acid solutions.

2.5. Analytical Method

The copper concentration in the leachate is analyzed using atomic absorption spectrometry (AAS). The procedure begins with the preparation of calibration standards at known copper concentrations to generate a calibration curve. The AAS instrument is calibrated using these standards to ensure accurate measurement of copper in the samples. The detection limit for copper is typically in the range of 0.01–0.1 mg/L, depending on the instrument settings and the matrix of the sample. For sample preparation, the leachate is first filtered to remove any solid residues and then diluted appropriately if the copper concentration exceeds the calibration range.

Quality control measures are implemented throughout the analysis to ensure accuracy and reliability. Certified reference materials (CRMs) are used as standards to verify the performance of atomic absorption spectrometry (AAS). At the same time, blanks (samples without copper) are analyzed alongside the actual samples to detect any contamination or background interference. Additionally, measurements are repeated at least three times to ensure consistency, and any deviation from expected results is addressed by recalibrating the instrument or preparing fresh samples. These procedures are essential for preserving the accuracy of the copper analysis process.

Data Analysis

In this research, the influence of nitric acid concentration and temperature on the leaching of copper over time was examined utilizing data acquired from Atomic Absorption Spectroscopy (AAS). The concentration of Cu leached at different time intervals was measured and plotted as a function of time for each acid concentration. The leaching data were then compared by analyzing the percentage of Cu extracted over time for various nitric acid concentrations.

3. Results and Discussion

3.1. Effect of Nitric Acid Concentration on Copper Leaching

Figure 3 demonstrates how varying concentrations of nitric acid influence the extraction of copper from nanosized SIM card waste at a temperature of 60°C. the experimental results clearly show that as the concentration of acid increases, so does the yield of copper, which is consistent with findings in [35,36]. This enhancement is attributed to the increased activity of H^+ ions in the solution, which facilitates the dissolution of copper-containing compounds[6,37]. The higher concentration of nitric acid provides more aggressive leaching conditions, accelerating the dissolution process and improving the overall extraction efficiency.

The leaching behavior exhibits distinct patterns across different time intervals (Table 1), revealing important insights into the process performance. During the initial leaching phase (0-120 minutes), the effect of acid concentration becomes immediately apparent. At the 2M nitric acid, Cu extraction

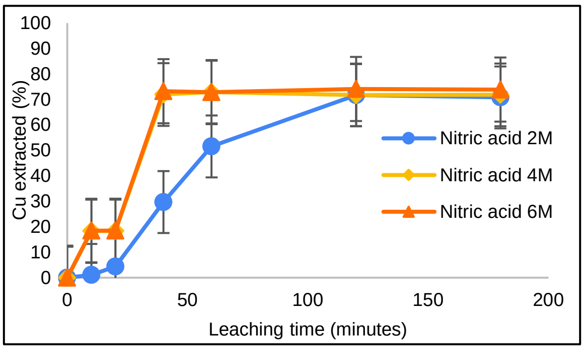

Fig. 3: The effect of nitric acid concentration on copper extraction from waste SIM cards

Table 1: Copper Yield at 60°C In Various Nitric Acid Concentrations

Leaching time (min)	**Copper yield at varying concentrations of nitric acid (%)**		
	2M	4M	6M
20	4.32±0.0013	18.35±0.0004	18.44±0.0008
40	29.70±0.0012	71.94±0.0024	73.24±0.0024
60	51.55±0.0019	72.91±0.0013	72.89±0.0028
120	71.72±0.0021	71.76±0.0007	74.12±0.0015

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progresses slowly, achieving only 4.32% Cu recovery within the first 20 minutes. This low initial recovery can be attributed to the limited availability of reactive species in the solution. In stark contrast, 4 M and 6 M nitric acid demonstrated rapid initial extraction rates, with copper yields reaching 18.35% and 18.44%, respectively, within the same time frame. This dramatic different indicates that higher acid concentrations provide sufficient reactive species to facilitate faster Cu extraction during the early stages of the process.

The most significant changes in Cu extraction occur between 20 and 60 minutes of leaching, representing the intermediate phase where substantial Cu recovery takes place. The 2M nitric acid concentration shows a marked increase in Cu yield from 4.32% to 51.55%, demonstrating that even lower acid concentrations can achieve reasonable extraction efficiency when given sufficient contact time. However, the superior performance of higher concentrations becomes evident as the 4M and 6M solutions reach 71.94% and 72.91% Cu recovery, respectively. This enhanced performance reflects the ability of higher acid concentrations to maintain effective leaching conditions throughout the intermediate phase, achieving higher extraction efficiency within the same time period.

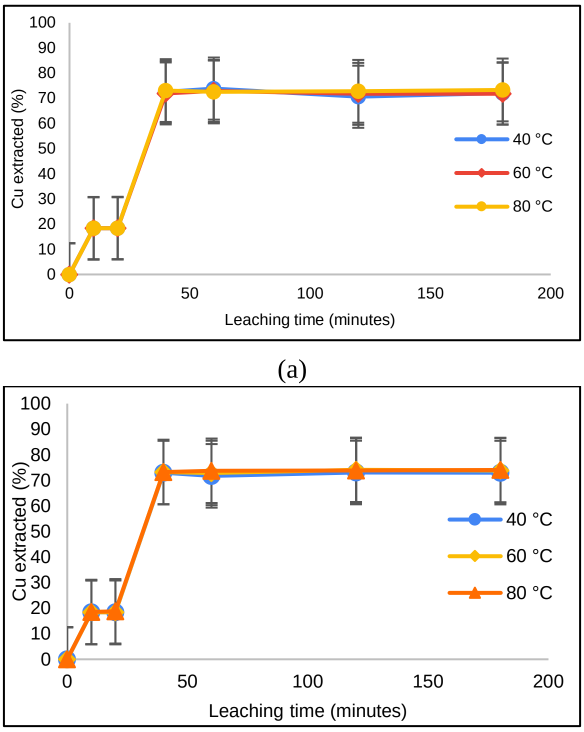
Beyond 60 minutes, the extraction curves begin to plateau, indicating that the leaching process is approaching its maximum efficiency under the given experimental conditions. The 2M concentration continues to show gradual improvement, eventually reaching 71.72% Cu recovery at 120 minutes, demonstrating that extended leaching time can compensate for lower acid concentration. Notably, the performance difference between 4M and 6M concentrations remains minimal throughout the extended leaching period, with both achieving approximately 71-74% Cu recovery by 120 minutes. This behavior suggests that the maximum extractable Cu content under these experimental conditions has benn largely achieved.

The experimental results demonstrate several key factors that influence copper extraction efficiency. Higher acid concentrations enhance the dissolution process by providing more reactive species (H^+ ions and NO_3^- ions) in the solution, which facilitate more effective dissolution of copper from the SIM card matrix. The increased solubility of copper in the acidic medium improves mass transfer characteristics, allowing for better transport of dissolved copper species from the solid surface to the bulk solution. The improved performance at higher concentrations also results from enhanced concentration gradients at the solid-liquid interface, promoting better mass transfer of dissolved copper species from the solid matrix to the bulk solution. Additionally, higher nitric acid concentrations maintain more favorable dissolution conditions throughout the extraction period, contributing to improved overall extraction efficiency.

3.2. Temperature influence on copper extraction

The experimental results, as illustrated in Figure 4, reveal that temperature has a surprisingly minimal impact on copper dissolution efficiency under the investigated conditions. At both 4 M and 6 M nitric acid concentrations, the copper extraction profiles show remarkably similar trends across all tested temperatures. The extraction process exhibits a characteristic two-phase behavior: an initial rapid dissolution period during the first 40 minutes, where copper extraction increases sharply from approximately 18% to 70%, followed by a more gradual increase that reaches equilibrium at around 70-73% after 180 minutes of leaching time.

The temperature-independent behavior observed in this study suggests that the leaching process may be predominantly controlled by factors other than thermal activation. This phenomenon indicates that the dissolution of copper from SIM card substrates in nitric acid proceeds effectively even at the lowest temperature tested (40°C). The minimal temperature dependence is consistent with previous studies on copper dissolution in nitric acid systems, where moderate activation energies around 40 kJ/mol have been reported for similar processes. This activation energy value indicates that the process is at the boundary between diffusion-controlled and reaction-controlled mechanisms, which explains the observed minimal temperature dependence[38,39)].



(a)

(b)

Fig. 4: Temperature's effect on copper extraction from waste SIM cards with nitric acid concentrations of (a) 4M and (b) 6M

The practical implications are significant for industrial implementation. Operating at 40°C provides optimal copper recovery while minimizing energy consumption and operational costs. Lower temperatures enhance thermal stability and reduce the likelihood of uncontrolled exothermic reactions[10,40]. Furthermore, moderate temperature operation enables more effective capture and mitigation of hazardous gas emissions, enhancing overall process safety and environmental performance [41].

These findings align with previous studies on electronic waste processing, where optimal leaching temperatures typically range from 40-60°C[42]. The temperature-insensitive behavior suggests common mechanisms governing copper dissolution from electronic substrates, providing valuable insights for developing standardized recovery processes. Therefore, 40°C is recommended as the optimal operating temperature for copper recovery from SIM card waste, balancing extraction efficiency with energy economy and operational safety.

3.3. Kinetic analysis and activation energy determination

To quantify the temperature dependence observed in the copper leaching, kinetic analysis was performed using the shrinking core model (SCM). In heterogeneous solid-liquid leaching systems, the overall reaction rate is typically governed by one of two primary mechanisms: the interfacial chemical reaction occurring at the solid surface or the diffusion of reactants and products through the accumulated product layer surrounding the unreacted core (equation 1-2)[19,43]. Based on Table 2, the experimental data were fitted to various kinetic models, with the chemical reaction control model showing the best correlation.

If chemical reaction controlled:

$$1-(1-X)^{\frac{1}{3}}=k_r t \qquad (1)$$

Whereas if the reaction is controlled by the diffusion through the product layer

$$1-\frac{2}{3}X-(1-X)^{\frac{2}{3}}=k_d t \qquad (2)$$

Where X is fraction of copper leached, t is the time reaction, kr is the chemical kinetic constant and kd is the diffusion product rate. The apparent rate constant obtained from chemical reaction control were used to determine the activation energy (Ea) using the Arrhenius equation[19]:

Table 2: Correlation coefficients (R^2) for different kinetic models applied to copper leaching data using nitric acid 4 M

Temperature (°C)	Chemical reaction control	Product layer diffusion control
40	0.9493	0.9000
60	0.9662	0.8903
80	0.9598	0.8801

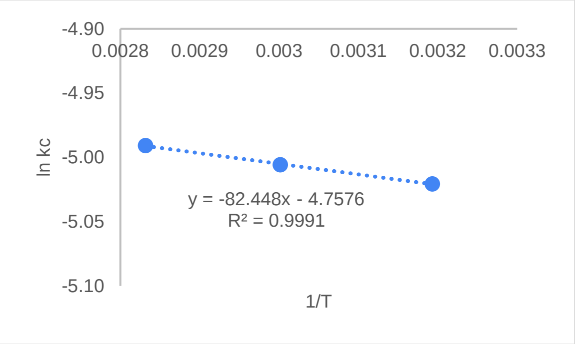


Fig. 5: ln kc vs 1/T

$$\ln k=\ln A-\frac{Ea}{RT} \qquad (3)$$

Where Ea is the activation energy (J/mol), R is the universal gas constant (8.314 J/mol.K), T is the temperature (K) and A is the pre-exponential factor. Figure 5 shows the Arrhenius plot of ln kc versus 1/T, which demonstrates excellent linearity (R2 = 0,9991). From the slope of Figure 5, Ea was calculated to be 0,68 kJ/mol.

4. Conclusions

Copper extraction from SIM card waste using nitric acid has been successfully carried out with > 70% copper recovery efficiency under optimized canditions. The results showed that temperature variations did not significantly affect the leaching rate while the acid concentration increased the leaching rate. Thus, the optimal operating conditions for copper extraction are using 4M nitric acid at a temperature of 40°C, which can efficiently extract copper within 40 minutes.

The quantitative analysis revealed reagent consumption of 9.6 kg nitric acid per kg Cu recovered, with an estimated base cost of $7.20 per kg Cu. Nitric acid regeneration capability provides potential economic advantages over non-regenerable acid systems, offering both cost competitiveness and improved sustainability.

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