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Orijinal Original

Cyanidation of Tailings of an Artisanal Small-Scale Gold Mining at Arbaat Region in Red Sea State, Sudan

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A B S T R A C T

In this study, the leaching of gold from an artisanal small-scale gold mining (ASGM) tailings in the Arbaat region of Sudan was investigated by agitated cyanide leaching, considering the parameters stirring speed, NaCN concentration, solid-liquid ratio, temperature and pH. The characterization studies showed that the tailings sample mainly formed from silicate minerals and the sample contained 77.10% SiO2, 8.08% Al2O3, 5.76% Fe2O3, 1.67% CaO, 1.10% Na2O, 0.97% K2O and 4.366% loss on ignition. The results of leaching studies indicated that gold dissolution decreases with increasing solid ratio. Furthermore, the gold leaching positively influenced by the NaCN concentration in the range of 0.05-0.50 g/L and by the pH in the range of 10.00-10.30. However, at pH values greater than 10.30, the gold leaching decreased. The temperature and stirring speed also affected gold leaching in different ways. The leaching studies revealed that it is very simple to apply the cyanide leaching to the tailings and a gold recovery value of 87.5% could easily be reached. Commercially, this study reported an economically feasible process for gold recovery from an artisanal small-scale gold mining tailings in Arbaat.

Keywords: *Agitation leaching. Artisanal small-scale gold mining. Cyanidation. Gold tailings.*

Introduction

Artisanal small-scale mining of gold (Au) is conducted by using traditional or random methods, such as gravity. One of these traditional methods is amalgamation (Hilson, 2009). Amalgamation is a physicochemical process obtained by contacting the gold particles with mercury, because mercury has an excellent affinity for gold particles (Donkor et al., 2006). Artisanal small-scale mining accounts for 15-20% of global gold production each year (Velásquez-López et al., 2011). It directly contributes more than 20 billion U.S. dollars to the global economy, while indirectly contributing around 20 billion U.S. dollars (Persaud and Telmer, 2015). As it is known, the performance of this method does not achieve acceptable industrial recovery, which means that a residual amount of gold still exists in the tailings of this process (Esdaile and Chalker, 2018). Sudan is one of the countries located in Sub-Saharan Africa (Ahmed, 1998). Geologically, in Sudan, gold can be found in oxide minerals such as quartz, carbonates and silicate minerals. On the other hand, the sulfide minerals in the region are pyrite, arsenopyrite, chalcocite and chalcopyrite (Fadlallah et al., 2020).

In general, artisanal small-scale mining of gold mining in Sudan does not have extensive scientific literature (West et al., 2015). Artisanal mining of small-scale gold mining has been practiced in Sudan since the third century BC in the Merowe and Nubian kingdoms. The Bijah and some Arab immigrants have engaged in gold mining operations in the eastern Sudanese Red Sea Mountains (Ahmed et al., 2019). Northern Sudan, the Red Sea Hills, and the upper Blue Nile regions have a long mining history dating back to Pharaonic times (Hussien and Mohamed, 2020).

Historically, mercury was used in the amalgamation process to separate the coarse-librated gold particles (Moreno-Brush et al., 2020). Port Sudan has a huge reserve of gold ores, categorized as oxide, sulfide, and carbonate minerals (Bakr, 2018). Amalgamation is a physicochemical process that can be obtained in the desired medium of gold ore, as seen in Equation-1.

$$Au + 2Hg \rightarrow AuHg_2 \quad (1)$$

Finally, an Au_3Hg solid will develop when the resultant solid substance, mercury, volatilizes into an elemental form when

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heated, while the gold exists as sponge gold (Callister, 2007). Gold mining production depends on the price of gold, but deposits containing 1 g/ton of gold are considered economically viable (Kiriş, 1994). According to the data for March 2019, there were approximately 900000 tons of pulp accumulation in the Arbaat region. As a result of the chemical analyses made in the pulp, it was determined that there was an average of 3 g/ton of Au.

These enterprises carry out processes, including the process of extracting gold from the mine, transportation, size reduction operations, etc. Considering the expensive processes and the importance of these residues, which contain an average of 3 g/ton Au and are ready for cyanidation processes, small enterprises in the aforementioned region operate continuously throughout the day (24 hours) (Ibrahim, 2015). The amount of amalgamation residue accumulated in the tailing area is increasing day by day. Thus, 900000 tons are equivalent to 2.7 tons of gold, and the current (in 2023) economic value is calculated as approximately 165000000 U.S. dollars.

Since its advent at the end of the nineteenth century, cyanide processing has facilitated the intensification and global expansion of industrial gold mining (Marsden and House, 2006). There are significant signs that the artisanal and small-scale gold mining industries are about to experience a similar cyanide revolution. While mercury-based processing is primarily connected to artisanal small-scale gold mining, the cyanidation process is rapidly replacing mercury amalgamation (Verbrugge et al., 2021).

The cyanidation process, which chemically dissolves in cyanide, is defined by the 'Elsner Equation', as shown in Equation 7 (Ferdana et al., 2018). The metallic gold does not oxidize in the air, but the dissolved oxygen is more important in the process of cyanidation in an alkaline solution (Marsden and House, 2006). The dissolution of gold is an oxidation-reduction process that forms strong complexes in the presence of CN^- ions and dissolved oxygen. On the gold surface, gold is oxidized while dissolved oxygen is reduced, and then oxidized gold complexes with CN^- ions.

oxidation of gold:

$$Au \rightarrow Au^+ + e^- \tag{2}$$

reduction of oxygen:

$$O_2 + 2H_2O + 2e^- \rightarrow H_2O_2 + 2OH^- \tag{3}$$

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \tag{4}$$

complex formation:

$$Au^+ + 2CN^- \rightarrow [Au(CN)_2]^- \tag{5}$$

overall reactions:

$$2Au + 4CN^- + O_2 + 2H_2O \rightarrow 2[Au(CN)_2]^- + H_2O_2 + 2OH^- \tag{6}$$

$$4Au + 8CN^- + O_2 + 2H_2O \rightarrow 4[Au(CN)_2]^- + 4OH^- \tag{7}$$

Extensive work on gold extraction from ores has been carried out, but there is a limited literature review on artisanal small-scale mining. For this reason, we used tailings.

A study was conducted on tailings from an artisanal gold mine located in northern Brazil. According to leaching experiments, the tailings are resilient to mild organic acids but soluble in alkaline and aqueous cyanide solutions. These solutions recovered 89% of the gold and removed 100% of the mercury in 24 hours. Electro-leaching tests using sodium chloride as an electrolyte showed that mercury was removed and a gold recovery rate of up to 70% in 4 hours (de Andrade Lima et al., 2008).

A study was conducted on the stated perspectives on tailings trade between large-scale and small-scale gold mining in Ghana. During this study, field visits were made to 13 ASGM sites where improper handling of gold tailings was carried out. Interviews were conducted with the stakeholders, and the results indicated that the waste was reprocessed using cyanide (Bansah et al., 2017).

Investigated socio-technical innovation and changing production relations in artisanal small-scale mining of gold in Burkina Faso, specifically focusing on gold processing, and switched from mercury amalgamation to cyanidation for processing. The outcome was an increase in output in Burkina Faso's artisanal small-scale gold mining industry (Lanzano and di Balme, 2021). Industrially, the demand for gold is increasing day by day, in contrast to the source of gold, which is decreasing. Thus, this paper focuses on the recovery conditions for extracting gold from the Au tailings of artisanal small-scale mining using the cyanidation method.

1. Materials and methods

1.1. Materials

Approximately 50 kg of tailing sample was collected from the residual stocks of the enterprises located about 60 km north of the city of Port Sudan, where private artisanal and small-scale mining is very widespread in that region. The provided sample was reduced according to the sampling rules at the Mining Engineering Mineral Processing Laboratory of the Faculty of Engineering and Natural Sciences of Konya Technical University and reserved for the experiments planned to produce approximately 25 kg of sample. A representative sample of about 5 kg was analyzed by X-ray fluorescence spectroscopy (XRF) and X-ray diffraction (XRD, X-ray wavelength: 1.54056 Å – Cu Kα1) to determine the chemical and mineralogical compositions of the samples.

1.2. Methods

The experimental works were carried out in a one-liter beaker which placed in a temperature-controlled water bath placed on a speed-controlled mechanical stirrer having a Teflon-coated mixer as seen in Figure 1. The effects of temperature (25-85 °C), stirring speed (0-600 rpm), pH (10.0-12.30), percent solids (20-50%) and NaCN concentration (0.05-1.0 g/L) were investigated. The pulp was prepared by setting the desired test conditions and then leached for 120 minutes. The atomic absorption spectrometer (AAS-GBC Sens AA model) was used for gold analysis.

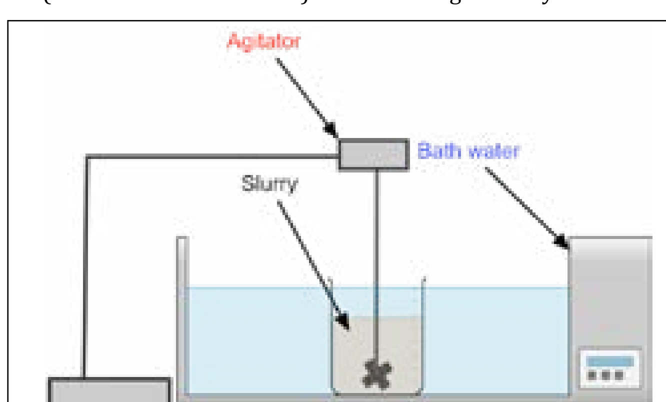

Figure 1. Experimental set-up

2. Results and Discussion

2.1. Sample characterization

Table 1 showed that the contents of the sample are mostly silicate minerals, with a mass percentage of 77.10%. Furthermore, XRD analysis also confirmed the same results with the mineral phase of SiO_2, as shown in Figure 2.

Table 1. Chemical composition of the tailings sample

Component	Amount (%)
SiO_2	77.10
Al_2O_3	8.08
Fe_2O_3	5.76
CaO	1.67
Na_2O	1.10
K_2O	0.97
SO_3	0.392
TiO_2	0.345
As_2O_3	0.054
MnO	0.049
ZrO_2	0.005
Loss on ignition	4.366

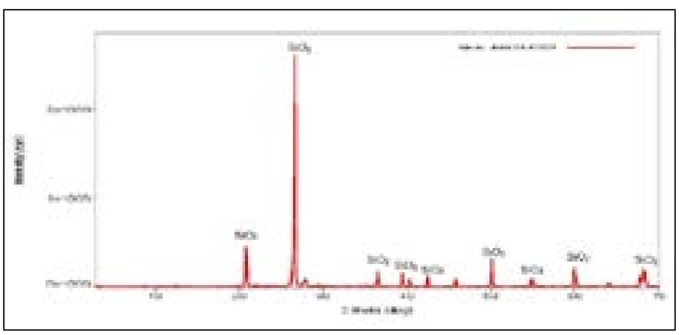

Figure 2. XRD pattern of the tailings sample

In microscopic studies, as seen in Figure 3, the results demonstrate that the sample contains free gold, silicates, copper oxides, and magnetite minerals. The magnetite mineral was detected by a low-intensity magnetic pole. However, due to the low concentration of copper and the limited detection of XRF, copper oxides were not determined in XRF analysis.

The sieve analyses (Figure 4) were performed to determine the gold concentration in each particle size fraction (Table 2). The calculated gold concentration is about 16.86 g/ton.

Table 2. The gold concentration in particle size fractions of the tailings sample

Size fraction (µm)	Au content (g/ton)
-1 mm +850	19.4
-850 +600	15.68
-600 +500	15.08
-500 +425	16.16
-425 +300	14.4
-300 + 212	11.32
-212 + 150	12.08
-150 + 106	13.56
-106 + 75	9.64
-75	30.16

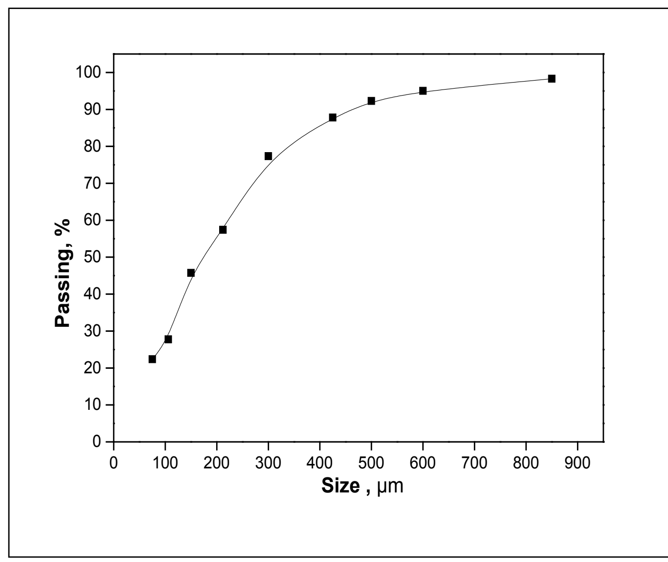

Figure 4. Sieve analysis of the tailings sample

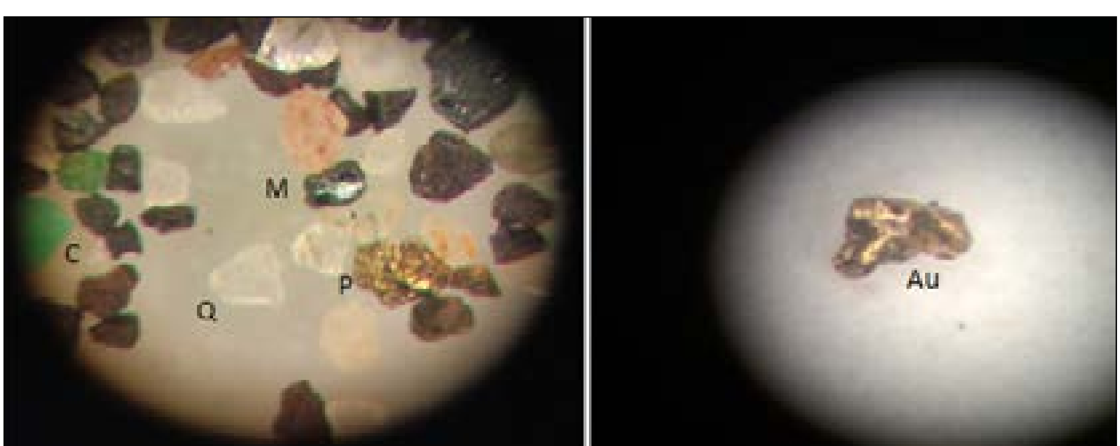

Figure 3. Mineral microscope view (60x) (C:copper oxide, Q:quartz, M:magnetite, P:pyrite, Au:gold)

2.2. Effect of stirring speed on Au dissolution

The effect of stirring speed at 0, 100, 200, 400 and 600 rpm were studied on solutions containing 0.5 g/L NaCN. The solid/liquid ratio was 40%, the temperature was 25 °C and the pH, adjusted by $Ca(OH)_2$, was 10.30. The results of the experiments investigating the effects of stirring speed were given in Figure 5. As seen in Figure 5, when the stirring speed increases, the Au dissolution rate also increases. For example, as a result of a 15-minute leaching process, the Au dissolution efficiency values obtained at 0-600 rpm stirring speeds are 52.2%, 61.7%, 62.3%, 63.6% and 64.0%, respectively. Very similar values were obtained in gold dissolution efficiencies at 400 rpm and 600 rpm stirring speeds. In other words, no significant gold dissolution efficiency was observed at values above 400 rpm stirring speed.

Dissolution of gold in cyanidation processes is normally a lengthy process. However, approximately 84% of the gold can be dissolved after 120 minutes at a stirring speed of 100 rpm. It is known that mercury greatly enhances the rate of gold dissolution. However, the XRF analysis performed on the sample revealed no presence of mercury. Due to the small grain size of gold, there is a large surface area in contact with the solution, which explains the high dissolution rate (Marsden and House, 2006). The stirring speed was adjusted to 400 rpm to investigate other parameters, as there was no noticeable difference in the extraction of gold between 400 and 600 rpm.

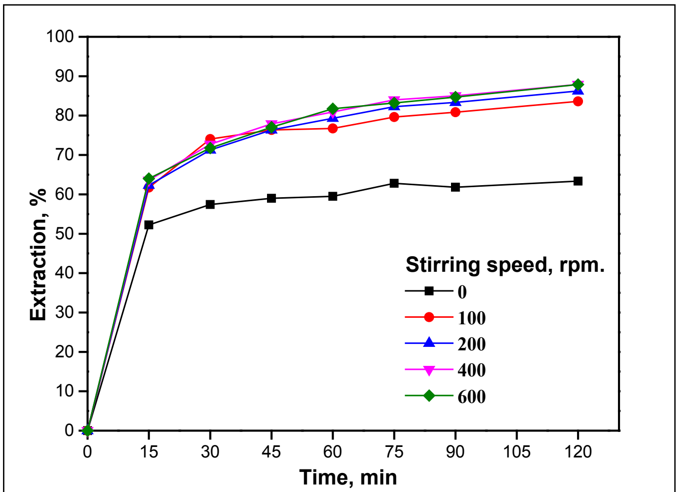

Figure 5. Effect of stirring speed on gold recovery

2.3. Effect of pH on Au dissolution

Experiments investigated the pH in the range of 10 to 12.30 in a solution containing 0.5 g/L NaCN, 400 rpm, 25 °C, and a solid/liquid ratio of 40%. Gold ore cyanidation is known to be affected by pH (Brittan, 2008). The results are given in Figure 6. As shown in Figure 6, as the pH increases in the pH range of 10-10.10, the Au dissolution rate also increases. In the results of the leaching process at pH 10.10 and pH 10.30, the Au dissolution rate is almost the same, but after pH 10.30, the Au dissolution rate decreases. The reason why the dissolution rate decreases rapidly at pH values greater than 10.30 is because $Ca(OH)_2$ is used as a pH adjuster. The H_2O_2 formed as a reaction product (Equation 6) reacts with Ca^{2+} ions on the gold surface and forms CaO_2 (calcium superoxide) (Habashi, 1999). To investigate other parameters, the pH value was chosen as 10.30.

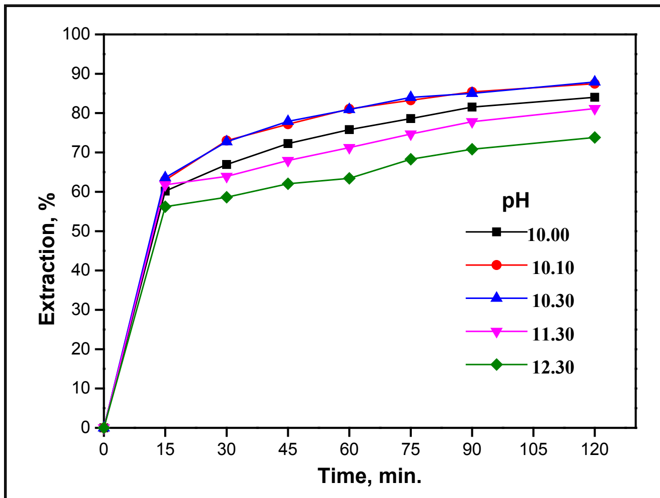

Figure 6. Effect of pH on gold recovery

1.4. Effect of NaCN concentration on Au dissolution

The effect of sodium cyanide concentrations on the dissolution of Au in the cyanidation process depends on cyanide and oxygen concentrations, leading to the opinion that solubility will increase with an increase in both (Equation 6 and Equation 7) (Lorenzen and Tumilty,1992). The effect of NaCN concentration on Au dissolution was investigated. The sodium cyanide concentration was between 0.05 and 1.0 g/L NaCN, the solid/liquid ratio was 40% at a temperature of 25 °C, the pH was 10.30, and the stirring speed was 400 rpm. The results are given in Figure 7. As shown in Figure 7, the gold extraction increased with increasing NaCN concentration. For example, as a result of a 15-minute leaching process, the Au dissolution efficiency values obtained in the 0.05-1.0 g/L NaCN concentration range are 14.5%, 53.4%, 54.5%, 63.6%, 65.8% and 71.9%, respectively. As a result of the 120-minute leaching process, the Au dissolution efficiency remained around 88% in the 0.25-1.0 g/L NaCN concentration range. It has been concluded that the dissolution rate of coarse-grained gold remains slow due to the nature of cyanidation processes, while fine-grained gold in the studied sample dissolves rapidly (Corrans and Angove, 1991).

Detailed studies have shown that the rate of gold dissolution increases linearly with increasing sodium cyanide concentration until a maximum is reached, beyond which further increase in sodium cyanide has no effect. At the end of 120 minutes, there was no significant change between the concentrations in the range of 0.5-1.0 g/L NaCN, so a concentration of 0.5 g/L NaCN was chosen for other experiments.

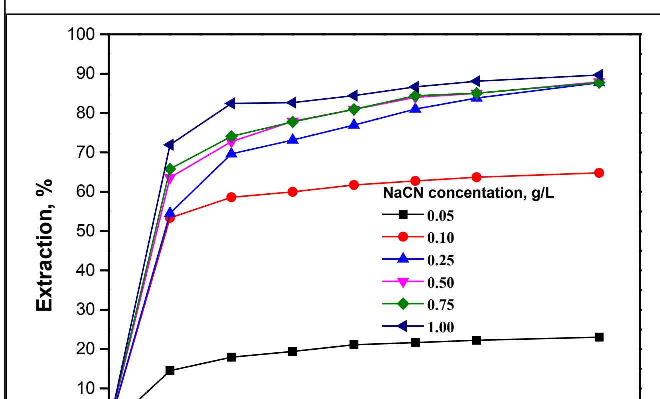

Figure 7. Effect of NaCN concentration on gold recovery

1.5. Effect of solid/liquid ratio on Au dissolution

The effect of solid/liquid (S/L) ratio experiments was conducted between 20 and 50%, stirring speed of 400 rpm, NaCN concentration of 0.5 g/L, temperature of 25 °C and pH of 10.30. The results are presented in Figure 8. As shown in Figure 8, the gold extraction decreased with an increasing solid/liquid ratio. When the S/L ratio percentage was 20%, the value of Au dissolution efficiency was 98%. As the S/L ratio increases, the amount of CN^- ions required per unit weight decreases. Similarly, the amount of oxygen dissolved in the solution reduces the oxygen required per unit weight. Normally, leaching processes experience a decrease in the S/L ratio, leading to an increase in dissolution efficiency, but this does not hold in industrial conditions. A higher S/L ratio increases the amount of ore processed per unit of time, thereby increasing the capacity. In other words, doubling the S/L ratio under suitable conditions leads to an increase in facility capacity at the same rate, increasing the amount of ore processed per unit of time. This, in turn, reduces initial investment expenses and other expenses (employee expenses, energy expenses, etc.) (Ahtiainen and Lundström, 2019). So, the S/L ratio of 40% was selected for the study of other parameters.

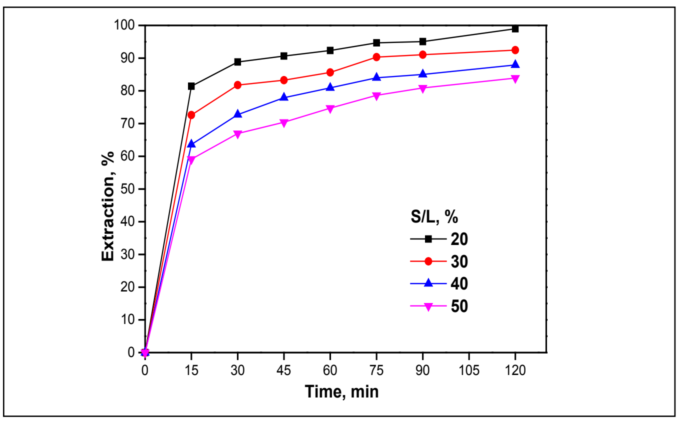

Figure 8. Effect of solid/liquid ratio on gold recovery

1.6. Effect of temperature on Au dissolution

The effect of temperature was investigated in the range of 25-85 °C in a solution containing 0.5 g/L NaCN, 400 rpm, pH 10.30 and an S/L ratio of 40%. The results are given in Figure 9. As seen in Figure 9, as the temperature increases, the Au dissolution rate also increases. For example, as a result of a 45-minute leaching process, the Au dissolution efficiency was 77.9% at 25 °C and 98.7% at 85 °C. At the end of 60 minutes at a temperature of 85 °C, the gold extraction was 100%. In the literature, when the temperature increases, the extraction rate of gold increases until 85 °C; after that, the extraction rate of gold decreases because dissolved oxygen decreases in the solution (Habashi, 1999; Ahtiainen and Lundström, 2019).

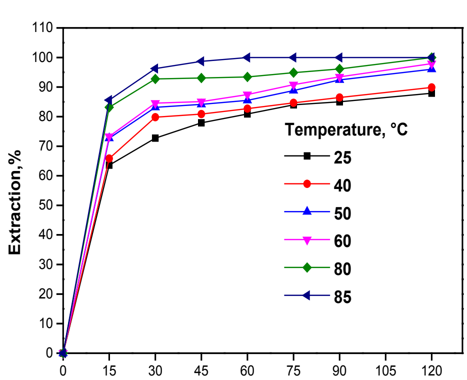

Figure 9. Effect of temperature on gold recovery

3. Conclusions

The XRF and XRD analyses revealed that the tailings sample used in the leaching studies had an oxide composition and formed from mainly silicate minerals. The tailings sample had average gold grade of 16.86 g/ton, which is good for agitation cyanide tank leaching. The maximum recovery of gold (87.5%) was obtained at a stirring speed of 400 rpm, a temperature of 25 °C, a solid percentage of 40%, a pH value of 10.30 and a sodium cyanide concentration of 0.5 g/L. The metallurgical tests showed that artisanal small-scale gold mining tailings from Arbaat region are amenable to cyanide leaching in an agitated tank.

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