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Removal of Impurities from Refractory Gold Ore using Bio-reduction and Bio-oxidation processes

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ABSTRACT

Gold in refractory gold ore is difficult to be extracted by conventional metallurgical methods due to the presence of sulfide minerals with elevated levels of iron (Fe), sulfur (S), and arsenic (As) as impurities, resulting in low gold (Au) recovery. Conventional methods such as cyanide leaching has been proven ineffective for gold extraction from refractory ore due to gold being intricately bound within the sulfide minerals. Consequently, this study explores the application of bioleaching as an alternative to conventional cyanide leaching. Shewanella oneidensis (S. oneidensis) and Acidithiobacillus ferroxidans (A. ferroxidans) serve as bio-reduction and bio-oxidation agents, respectively in the bioleaching process. The composition of minerals in the ore was determined through XRD analysis (Model: Rigaku's Miniflex 600) and EDX analysis (Model EDX 3). Meanwhile, SEM analysis (Zeiss EVO LS15 SEM) was utilized to examine the morphology structure. The concentrations of impurities (Fe, S, and As) were assessed using a spectrophotometer (Model: DR3900 Hach) meanwhile the Au concentration was determined through ICP-OES (Model: G8015A5110 ICP-OES). Sieved refractory gold ore samples with less than 32 um and varying in weight (0.5 g, 1.0 g, 1.5 g, 2.0 g), underwent bio-reduction and bio-oxidation processes. The results indicated a rougher surface morphology of the raw sample as observed through SEM analysis. Furthermore, XRD and EDX results demonstrated a decrease in impurity concentrations, suggesting a potential increase in gold purity. Notably, the bio-reduction process exhibited a superior enhancement in Au concentration with the value of 138.89% compared to biooxidation with the value of 122.22%. Thus, the bio-reduction process proved more effective in increasing Au concentration compared to bio-oxidation.

Keywords: Bioleaching, *S. oneidensis*, *A. Ferroxidans*, gold, ICP-OES.

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Introduction

Metallurgists commonly divide gold ores into two primary categories: free milling ores and refractory ores. Refractory gold ore, recognized as a preg-robbing mineral, contains gold intricately intertwined with sulphide minerals like pyrite, pyrrhotite, arsenian pyrite, stibnite and arsenopyrite [1]. This complex composition poses challenges in extracting gold [2].

Refractory gold ore, a valuable material primarily composed of sulphide minerals like arsenian pyrite and arsenopyrite (ultrafine gold), poses a challenge for gold recovery through conventional cyanide leaching methods, which can typically retrieve over 90% of gold from free-milling ore [3]. However, refractory gold ore often exhibits traits that hinder gold separation from sulphides, resulting in a lower gold recovery rate (less than 20%) using the same conventional method [4]. As an alternative, bioleaching is a method employing microorganisms has gained significant attention from gold miners and researchers worldwide. This approach aims to break down preg-robbing minerals by eliminating metal impurities, leading to an increased concentration of gold [5].

Bioleaching methods are increasingly being utilized for Au recovery from refractory ore that cannot be processed effectively by conventional methods [5]. It proposed a greener method by using microorganisms to dissolve the impurities from the refractory gold ore to ensure higher Au concentration recovery achieved. This process implied the conversion of an insoluble element to soluble compound followed by the selected metal recovery via either the metabolic activities or microbe's products [6].

In addition, bioleaching has been widely adopted in industry for gold recovery [7], primarily because its effectiveness hinges on the efficient ability of microorganisms to extract gold from ores. Therefore, microorganisms like *A. ferrooxidans* and *S. oneidensis* have been utilized to enhance the purity of gold compared to traditional methods like cyanidation or carbon-in-pulp (CIP), which rely on optimized chemical processes for achieving high gold recovery rates [8]. Bioleaching methods offer cost-effectiveness in terms of operational expenses due to reduced chemical usage and lower energy consumption when contrasted with conventional techniques [9]. From an environmental perspective, bioleaching is often favored as it minimizes the use of toxic substances such as cyanide, thereby mitigating risks associated with acid mine drainage and related environmental hazards in sulfide-containing ores [10]. Furthermore, ongoing research in bioleaching focuses on improving efficiency, optimizing microbial strains, and developing innovative bioreactor designs, indicating the continual advancement of these methods [11].

In the course of this research, *S. oneidensis* and *A. ferroxidans* were employed respectively as bio-reduction and bio-oxidation agents in the bioleaching process. The aim was to break down preg-robbing minerals by extracting Fe, sulfur, and arsenic [12] which are the predominant elements in the sample leading to a heightened concentration of Au. Furthermore, bioleaching is recognized as an environmentally sustainable and cost-effective method in gold production [13]. Conversely, bioleaching is perceived as a rapid and efficient means of eliminating [14].

The primary objectives of this research are to identify and characterize the mineral composition of refractory gold ore, specifically focusing on elements such as arsenopyrite, hematite, magnetite and quartz. Meanwhile, the Scanning Electron Microscopy (SEM) used to examine the morphology structure of the refractory gold ore. Furthermore, the effectiveness of bio-reduction and bio-oxidation processes in enhancing gold concentration of the refractory gold ore was assessed by examining the removal efficiency of metal impurities.

Experimental part

Sample Preparation

The refractory gold ore was obtained from Benua Sunda Cari Gali. The samples were broken down into small particles using a geological hammer and sieved using a RETSCH Sieve Shaker AS 200 (China) until size <32 *u*m.

Characterization of refractory gold ore

The sieve samples were sent to XRD and EDX to determine the percentage composition of the mineral. Meanwhile, the samples were sent to SEM to analyze the morphology structure of the mineral.

Preparation of inoculum using S. oneidensis MR-1 strain

S. oneidensis MR-1 strain was cultured in Luria–Bertani broth. A single colony of bacteria from the LB agar plate was inoculated into 5 mL of LB media and shaken overnight at 30°C and 150 rpm [15]. Subsequently, the microbial culture was transferred

to the autoclaved conical flask containing 50 mL of LB media and cultivated aerobically for 5 hours at 30 °C and 150 rpm. The optical density of the seed culture was 5 which was measured by using Genesys 20 Spectrophotometer at the wavelength of 600 nm.

Preparation of inoculum using A. Ferroxidans strain

A. ferrooxidans strain was cultured in Leptospirillum (hh) media [16]. 1 ml of pure strain bacteria was added into 50 mL of Leptospirillum (hh) media and shaken in an incubator shaker for 14 days at 30°C and 170 rpm. After 14 days, the colour of the medium was changed to reddish brown with 5 OD measurements and 600nm of wavelength.

Incubation of sample for bio-reduction process using S. oneidensis

The sterilized refractory gold samples with different weights consist of (5 g,1.0 g, 1.5 g, and 2.0 g) were placed into 50 ml of LB media in serum bottles. Subsequently, 0.5 ml of inoculum was added and incubated for 19 days of bio-reduction process at 30°C with 170 rpm. The incubation period was 19 days which microbial growth had reached its stationary phase. The concentration of Fe (II) and sulphate were measured every 3 to 4 days using the ferrozine assay and sulfatVer 4 reagent.

Incubation of sample for bio-oxidation process using A. ferroxidans

The sterilized refractory gold samples with different concentrations (5g, 1.0 g, 1.5g, 2.0g) were placed into 50 ml of Leptospirillum (hh) media. After that, 10 ml of inoculum was added and incubated for 19 days of bio-oxidation at 30°C with 170 rpm. The concentration of Fe (II) and sulphate were measured every 3 to 4 days for 19 days using the ferrozine assay and sulfatVer 4 reagent.

Determination of Fe (II) using Ferrozine assay

The ferric iron reduction is represented by production of ferrous iron by ferrozine assay. 200 µl of bioleached sample from serum bottles were transferred into 2 ml of microcentrifuge tube and added with 1000 µl of 0.5 M of hydrochloric acid. During the assay, 0.5 M hydrochloric acid is applied to keep the pH low to prevent oxidation of Fe (II) and to dissolve Fe (III) particles so that Fe (II) that is absorbed in Fe (III) particles were released. The microcentrifuge was placed in the dark places for 30 minutes and then 50 µl sample from the microcentrifuge was transferred into a cuvette containing 950 µl of ferrozine assay. Subsequently, A spectrophotometer (DR3900, HACH) was then d using equation 3.1 used to take the reading using 562nm of wavelength. The final absorbance reading of the sample obtained [17].

Fe (II) concentration (mM):

$$\frac{(final\ absorbance\ reading - 0.016)}{0.1999} \quad (1)$$

Determination of iron (Fe), arsenic (As), gold (Au) via ICP-OES

After characterization, the treated and untreated samples were proceeded with total digestion technique by microwave digester. The process of digestion was followed [18], in which the samples have been weighed about 0.5 g and placed into the white flask. Subsequently, added 68% of nitric acid HNO3, 48% of hydrofluoric acid (HF), and 50% of hydrogen peroxide (H_2O_2) were with the ratio of 4:3:2. Later, the digested samples were sent to ICP-OES to analyse the concentration of total Fe, As, and Au.

Analyzation using ICP-OES

The determination of the gold, total iron and arsenic were measured by taken 5-10 mL of the digested samples and then measured using ICP-OES from Agilent Technologies 5110 (California, U.S). The calibration curve of Au was recorded in the range of 1 mg/L to 5 mg/L using 242.794 nm of Au wavelengths. The data obtained indicated the value of the composition mineral left in the refractory gold ore.

Removal Percentage

The analysed results were recorded to determine the removal percentage (R%) of the impurities by applying the formula as shown in the equation 3.2 [19].

$$R\% = \frac{C_o - C_e}{C_o} \times 100\% \quad (2)$$

Where C_o is the initial impurity concentration, C_e is the impurity final concentration.

Results and Discussion

Characterization of ore using XRD

Refractory gold ore was analysed using XRD and DIFFRAC EVA software. The aim of this characterization was to identify the S-Q value's

percentage of minerals presented in the refractory gold samples. As shown in Figure 1, the percentages in the S-Q value of impurities i.e., arsenopyrite, magnetite, and hematite in the raw sample were 14.2%, 12.1%, and 13.4%, respectively, followed by 60.3% of quartz as the remaining mineral in the samples. Hematite and magnetite were considered as the principle's ore of iron. In addition, magnetite is a primary component of an iron oxide that contains equal amounts of Fe (II) and Fe (III) [20]. On the other hand, the detection of arsenopyrite by XRD indicates Au was present in the sample [21]

. Meanwhile, the presence of quartz in the samples denotes low Au content, defining them as refractory gold ore [22].

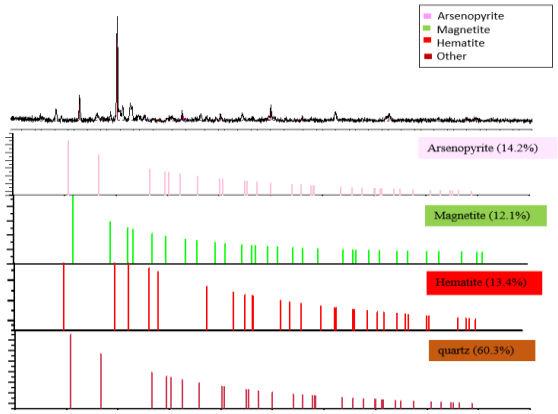

Figure 1 - The percentage in the S-Q value of mineral composition in the raw sample

Characterization of ore by Energy Dispersive X-ray analysis (EDX)

The characterization using EDX was performed to determine elemental composition of refractory gold ore. Figure 2 illustrates the percentage of iron (Fe) and sulphur were 37.7% and 12.4%, respectively. The presence of iron (Fe) and sulfur (S) in the refractory gold ore was regarded as impurities that required removal to enhance the concentration of Au.

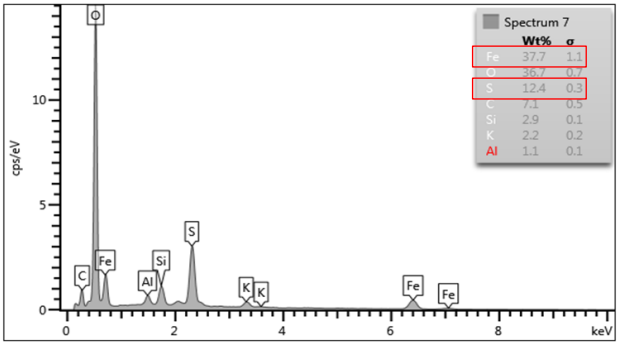

Figure 2 - The elemental composition of solid surfaces for the raw sample

Characterization of ore by scanning electron microscope (SEM).

The morphology structure of the samples was analyzed by SEM analysis. The surface morphology of the raw sample is shown in Figure 3 which the pyrite surface was relatively smooth without treatment.

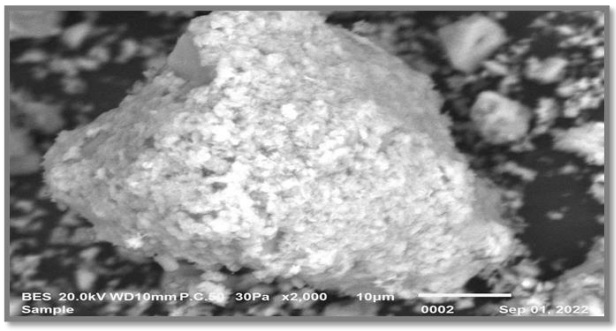

Figure 3 - SEM photograph of raw sample

Removal of metal impurities (Fe, S, As) from refractory gold ore

(a) Iron removal through reduction of Fe (III) to Fe (II) from refractory gold ore

In this study, the removal of Fe applied the usage of *S. oneidensis MR-1* and *A. Ferroxidans* as the bacteria that undergo bio-reduction and bio-oxidation processes, respectively. Bio-reduction process for Fe removal involved the reduction of insoluble Fe (III) to soluble Fe (II). Meanwhile, bio-oxidation implies the oxidation of Fe (II) to Fe (III). The produced Fe (III) acts as an oxidant to oxidize the metal sulphide forming the sulphur metal and soluble Fe (II) ion.

Figure 4 and 5 showed a Ferrozine assay reading at 562 nm to determine the concentration of Fe (II) ion for bio-reduction and bio-oxidation processes, respectively. The weight samples in both processes are 0.5 g, 1.0 g, 1.5 g, and 2.0 g, with abiotic serving as the control in the absence of bacteria strains. The concentration of Fe (II) was increased by days for both processes. The result for the Abiotic sample showed a constant reading, indicating that Fe reduction did not occur without bacteria strains. Based on observation for both processes, the incubation of 2.0 g of weight sample has a higher Fe (II) concentration reading as compared to other samples.

In the bio-reduction process, Fe (III) was reduced to Fe (II) by *S. oneidensis* which used organic carbon or hydrogen as an electron donor [23]. The transfer of electrons from the cell to the iron minerals is performed through direct contact between the cell

and the mineral surface [24]. It means the Fe (III) ion gained an electron forming the soluble Fe (II) ion to be discarded from the refractory gold ore.

On the other hand, the concentration of Fe (II) in the bio-oxidation process using *A. ferrooxidans* also showed an increased value as days increased. The Fe (II) was removed by oxidation of *A. ferrooxidans* which these bacteria take up O_2 and CO_2 and oxidize Fe (II) (energy source) to Fe (III), which dissolve metal ions. Fe (III) was reacted with Sulphide mineral and metal, and reduced to Fe (II). The purple color was produced when the ferrozine reagent reacted with the Fe (II) in the solution. The darker purple in the solution corresponds to a higher concentration of ferrous iron (Fe II). Fe (II) concentration was chosen as a crucial parameter to regulate the procedure for both bio-reduction and bio-oxidation.

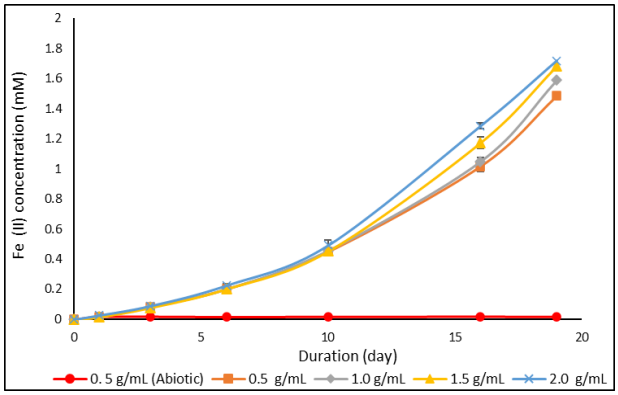

Figure 4 - Fe (II) concentration obtained during bio-reduction process within 19 days

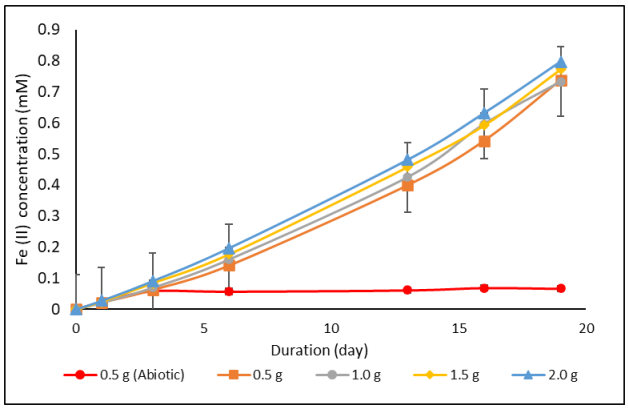

Figure 5 – Fe (II) concentration obtained during bio-oxidation process within 19 days

In addition, the remaining Fe in the refractory gold ore after bioleaching was measured and the result presented in Figure 6. Obviously, the concentration of Fe in the refractory gold ore was decreased for both bio-reduction and bio-oxidation processes compared to the raw sample. The lowest value of Fe concentration was shown by the weight sample of 2.0 g indicating high removal of Fe had been achieved compared to 0.5 g, 1.0 g and 1.5 g. This was due to the high amount of weight sample consisting of a large value of Fe resulting in the increment of Fe dissolution in the ore. Moreover, the remaining Fe in the ore after the bio-reduction process for 2.0 g of weight sample exhibited lower value than the bio-oxidation process. It means that bio-reduction proposed a better process in Fe removal compared to the bio-oxidation as Fe (III) was well-dissolved in bio-reduction causing the low value of Fe left in the ore.

Therefore, Figure 7 and Figure 8 revealed the increment of Au concentration from refractory gold ore when the removal percentage of Fe increased via bio-reduction and bio-oxidation, respectively. In detail, bio-reduction with 70.12% of Fe removal shows higher Au concentration can be achieved with 0.23 ppm rather than bio-oxidation with 0.21 ppm with 61.81% of Fe removed.

(b) Sulphur removal from refractory gold ore through formation of sulphate.

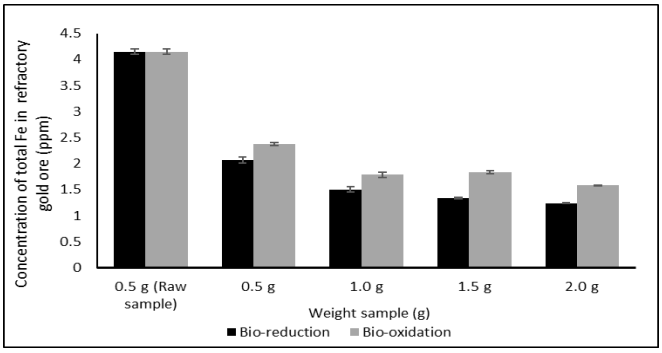

Figure 6 - The concentration of total Fe in refractory gold ore after 19 days of bioleaching process

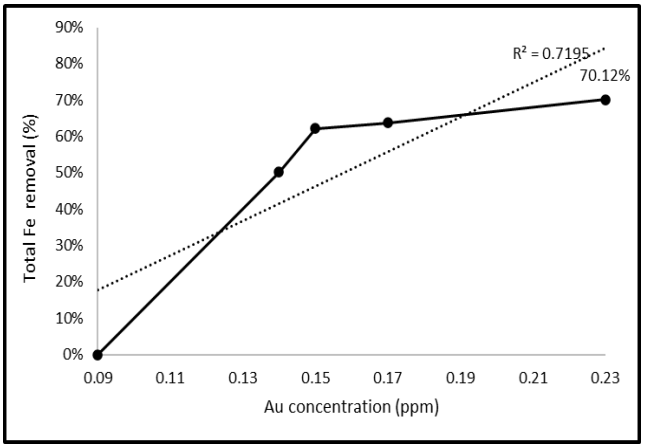

Figure 7 - Correlation between Au concentration and Fe removal for bio-reduction process

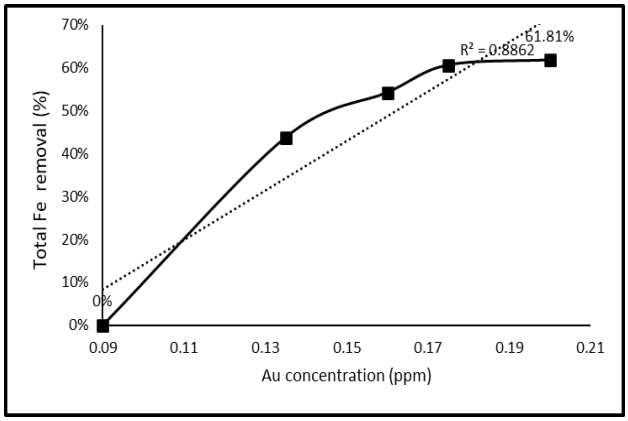

Figure 8 - Correlation between Au concentration and Fe removal for bio-oxidation process

Bio-reduction and bio-oxidation were able to dissolve sulphur from ore samples and formed sulphate (soluble) by following sulphur cycle and direct contact mechanism. The concentration of sulphate was checked by a spectrophotometer using SulfatVer 4 sulphate reagent. From the observation, when the sample becomes cloudy, it possibility determined that sulphate was present. Figures 9 and Figure 10 illustrated the concentrations of sulphate for bio-reduction and bio-oxidation, respectively. From the analysis results of both processes, the biotic samples had higher sulphate concentrations compared to the abiotic sample.

Sulfate ion is primarily produced when metal sulphide dissolves. *S. oneidensis* was used in the bio-reduction experiment to produce ion sulphate from the mineral sulphide (insoluble). Previous studies revealed that specific *Shewanella* species link the oxidation of organic substances (or hydrogen) to the dissimilatory reduction of S_0, a reaction that doesn't require the cell and S_0 particle to come into direct contact with each other [25]. There are two mechanisms for microbial respiration of oxidizing bacteria based on an interspecies sulphur cycle and extracellular cell. In this study, extracellular cell was interacted with S0 and SO_3^{2-} to generate thiosulphate ($S_2O_3^{2-}$) [26].

Meanwhile, the bio-oxidation process involved oxidation of element S from refractory gold ore. This process required the presence of both water and oxygen [27]. Sulphur oxidation (S, S_2^-, $S_2O_3^2$) can generate energy for bacterial growth. Sulphur is a better energy substrate than Fe (II) because it produces more ATP at the same molar level [28]. The CO_2 fixation process of *A. ferrooxidans* requires both sulphur oxidation and high redox potential electron transfer. Bacteria can adsorb sulphur intocell surface and transport it to the periplasmic space via bacterial outer membrane protein [29]. After a series of biological oxidation pathways, it is finally oxidised to sulphate ions and released on the cell's surface. Besides that, sulphur also can be oxidized to sulfuric acid. Sulphur oxidation mechanisms are classified into two types. The first one is when sulphur is the only substrate under aerobic conditions and is oxidised to sulfuric acid by sulphur dioxygenase. The second one occurs when both Fe (II) and Sulphur are used as substrates in anaerobic conditions and Sulphur is converted to sulfuric acid by the combined action of hydrogen sulphide Fe (III) oxidoreductase, sulfuric acid Fe (III) oxidoreductase, and Fe (II) oxidoreductase [30].

Moreover, the increment of sulphur removal via bio-reduction by *S. oneidensis* and bio-oxidation by *A. ferroxidans* resulting to the enhancement of Au concentration left in refractory gold ore as shown in Figure 11 and Figure 12, respectively. The bio-reduction and bio-oxidation had removed 97.21% and 97.70% of sulphur from the refractory gold ore with 0.23ppm and 0.21ppm of Au concentration obtained, accordingly. The results of removal of sulphur only show a slight difference for both processes. However, bio-oxidation by *A. ferroxidans* was more effective as it was sulphur-oxidizing bacteria that productively for removing sulphur where the strain cell interacted directly with the sulphur surface affecting to the enhancement of sulphur dissolution from refractory gold ore [31].

(*C*) *Arsenic removal from refractory gold ore*

The reduction of arsenic was measured by ICP-OES after 19 days of bioleaching. Figure 13 results showed the removal of arsenic for each weight sample was increased after bioleaching process with the percentage removal from 82.01% (0. 5 g of weight sample) to 84.93% (2.0 g of weight sample) for the bio-reduction process and 91.65% (0.5 g of weight sample) to 93.87% (2.0 g of weight sample) for the bio-oxidation process.

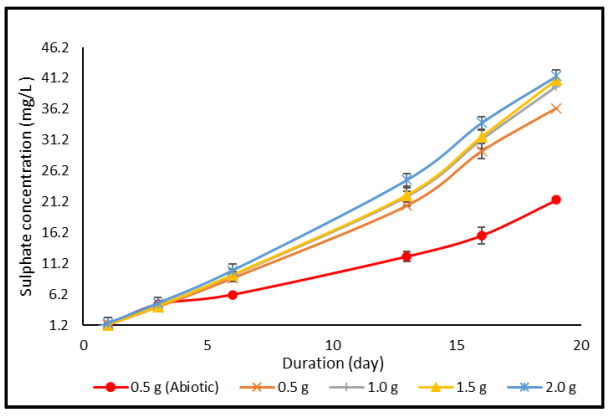

Figure 9 - Sulphate concentration obtained during the bio-reduction process within 19 days

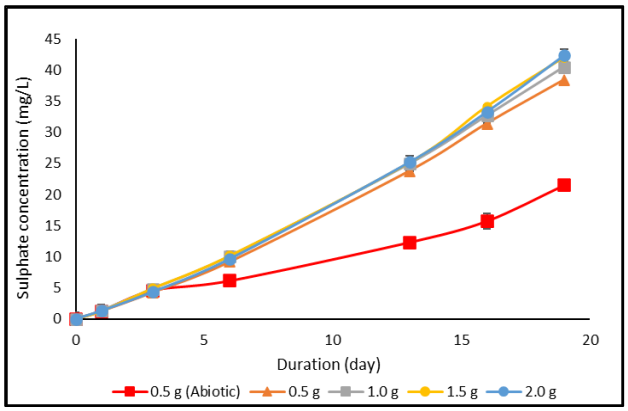

Figure 10 - Sulphate concentration obtained during the bio-oxidation process within 19 days

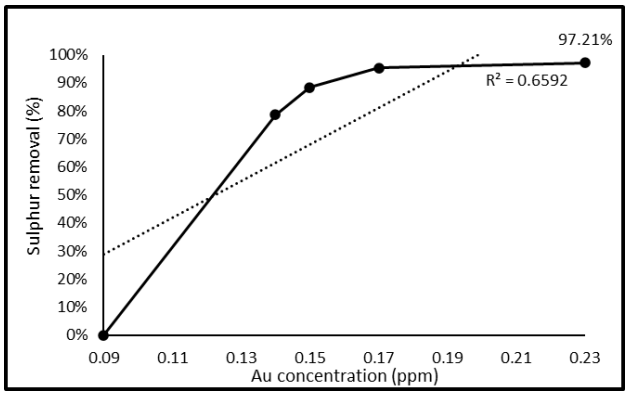

Figure 11 - Correlation between Au concentration and S removal for bio-reduction process

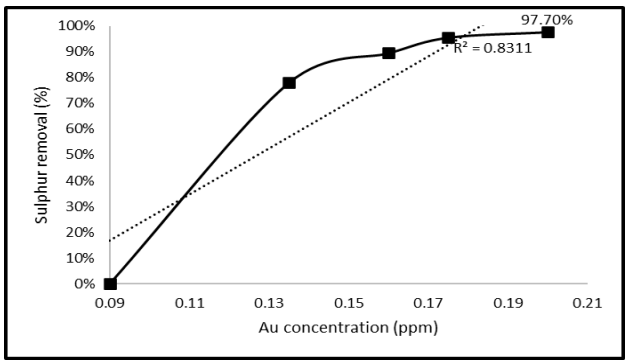

Figure 12 - Correlation between Au concentration and S removal for bio-oxidation process

The breakdown of Fe and S from arsenopyrite (FeAsS) via bio-reduction and bio-oxidation processes released free arsenic such as As (III) and As (V). In bio-reduction, As (V) undergoes a reduction process by gaining electrons from the *S. oneidensis* and producing soluble As (IIII) [32]. In this case, the removal of arsenic higher by bio-reduction compared to bio-oxidation process because the rate of As (V) reduction was more rapid than other electron acceptors such as nitrate, thiosulfate, manganese (IV) oxide, and iron resulting to the increment of the arsenic removal [33]. Meanwhile, the removal of arsenic from the bio-oxidation process was not efficient compared to bio-reduction due to the removal of As (III) is more difficult than the removal of As (V) [34]. This reaction occurred through the oxidation of Fe (II) to Fe (III) ions and simultaneously oxidation of As (III) to As (V) producing some ferric arsenate [35]. Subsequently, the removal of arsenic from refractory gold ore affected the enhancement of Au concentration with the value obtained 0.23 ppm and 0.22 ppm via bio-reduction and bio-oxidation processes as shown in Figure 14 and Figure 15, respectively.

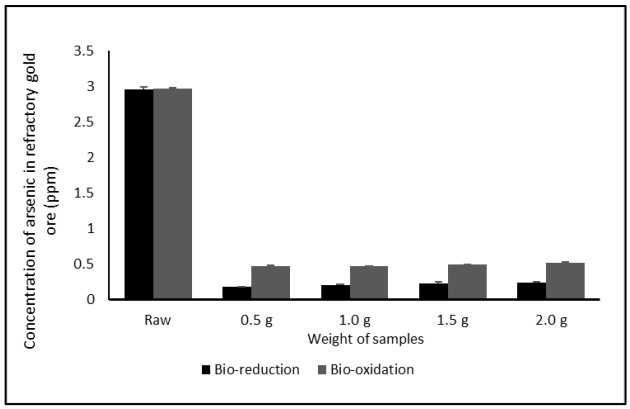

Figure 13 - The concentration of arsenic in refractory gold ore after 19 days of bioleaching

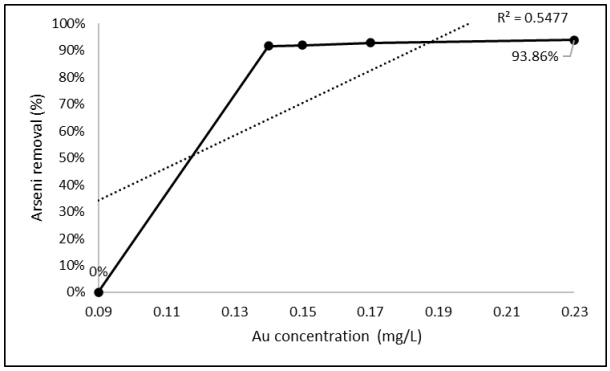

Figure 14 - Correlation between Au concentration and arsenic removal for bio-reduction process

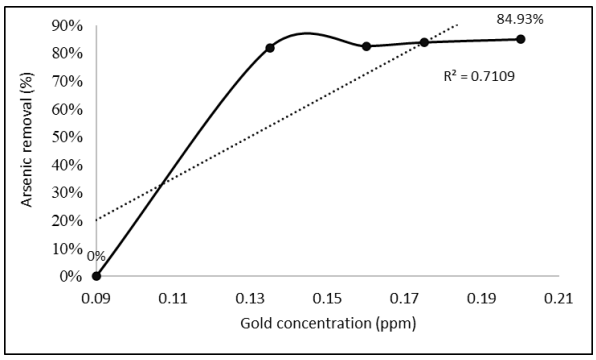

Figure 15 - Correlation between Au concentration and arsenic removal for bio-oxidation process

Conclusions

As a conclusion, the impurities of refractory gold ore namely Fe, S, As were successfully reduced by bioleaching technique using *S. oneidensis* and *A. ferroxidans* as a bio-reduction and bio-oxidation agents, respectively. The results from XRD and EDX show As, Fe, S exist in the refractory gold ore. In addition, the SEM analysis has shown a rough morphological structure that indicates the presence of pyrites.

The Au concentration was enhanced by the bioleaching process, yielding values of 138.89% for bio-reduction and 122.22% for bio-oxidation, respectively. The bio-reduction has been proven more effective, primarily due to its enhanced removal of impurities in comparison to bio-oxidation. This was supported by significant correlation values between Au concentration and the percentage removal of impurities (Fe, S, and As) with respective R^2 values of 0.7109, 0.6261, and 0.953.

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Қиын өңделетін алтын кенінен қоспаларды биототықсыздану әдістерімен жою және биототығу процестері

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ТҮЙІНДЕМЕ

Қиын өңделетін алтын кеніндегі алтынды кәдімгі металлургиялық әдіспен алу қиын, себебі қоспалар ретінде құрамында темір (Fe), күкірт (S) және мышьяк (As) болатын жоғары сульфидті минералдар бар, нәтижесінде алтын (Au) аз бөлінеді. Цианидті шаймалау сияқты дәстүрлі әдістер алтынның сульфидті минералдармен күрделі байланысқандығына байланысты қиын өңделетін кеннен алтын алу үшін тиімсіз екендігі дәлелденді. Бұл зерттеуде әдеттегі цианидті шаймалауға балама ретінде биошаймалауды қолдану зерттеледі. Shewanella oneidensis (S. oneidensis) және Acidithiobacillus ferroxidans (A. ferroxidans) биошаймалау процесінде сәйкесінше биототықсыздану және биототығу агенттері ретінде қызмет етеді. Кендегі минералдардың құрамы XRD талдауы (Модель: Rigaku's Miniflex 600) және EDX талдауы (EDX 3 үлгісі) арқылы анықталды. Сонымен қатар, SEM талдауы (Zeiss EVO LS15 SEM) морфологиялық құрылымды зерттеу үшін пайдаланылды. Қоспалардың концентрациясы (Fe, S және As) спектрофотометрдің (үлгі: DR3900 Hach) көмегімен бағаланды, ал Au концентрациясы ICP-OES (үлгі: G8015A5110 ICP-OES) арқылы анықталды. Ірілігі 32 мм-ден аз және салмағы әртүрлі (0,5 г, 1,0 г, 1,5 г, 2,0 г) електен өткізілген қиын өңделетін алтын кенінің үлгілері биототықсыздану және биототығу процестерінен өтті. Нәтижелер SEM талдауы арқылы байқалған өңделмеген үлгінің бетінің кедір-бұдырлы морфологиясын көрсетті. Сонымен қатар, XRD және EDX нәтижелері қоспа концентрациясының төмендегенін анықтады, бұл алтын тазалығының ықтимал жоғарылауын байқатады. Атап айтқанда, биототықсыздану процесі 122,22% мәні бар

	биототығумен салыстырғанда 138,89% мәндерімен Au концентрациясының жоғары деңгейін көрсетті. Осылайша, биототықсыздану процесі биототығумен салыстырғанда Au концентрациясын арттыруда тиімдірек болды.
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Удаление примесей из упорной золоторудной руды методами биовосстановления и процессы биоокисления

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АННОТАЦИЯ

Золото из упорной золотой руды трудно извлечь традиционным металлургическим методом из-за присутствия сульфидных минералов с повышенным содержанием железа (Fe), серы (S) и мышьяка (As) в качестве примесей, что приводит к низкому содержанию золота (Au). восстановление. Традиционные методы, такие как цианидное выщелачивание, оказались неэффективными для извлечения золота из упорной руды из-за того, что золото сложно связано с сульфидными минералами. Следовательно, в этом исследовании рассматривается применение биовыщелачивания в качестве альтернативы традиционному цианидному выщелачиванию. Shewanella oneidensis (S. oneidensis) и Acidithiobacillus FerrOXIDANS (A. FerrOXIDANS) служат агентами биовосстановления и биоокисления соответственно в процессе биовыщелачивания. Состав минералов в руде определялся с помощью рентгеноструктурного анализа (модель: Miniflex 600 компании Rigaku) и анализа EDX (модель EDX 3). Тем временем для изучения морфологической структуры использовался анализ СЭМ (Zeiss EVO LS15 SEM). Концентрации примесей (Fe, S и As) оценивали с помощью спектрофотометра (модель: DR3900 Hach), а концентрацию Au определяли с помощью ICP-OES (модель: G8015A5110 ICP-OES). Просеянные образцы упорной золоторудной руды с крупностью менее 32 мкм и различной массой (0,5 г, 1,0 г, 1,5 г, 2,0 г) подверглись процессам биовосстановления и биоокисления. Результаты показали более шероховатую морфологию поверхности необработанного образца, наблюдаемую с помощью SEM-анализа. Кроме того, результаты XRD и EDX продемонстрировали снижение концентрации примесей, что указывает на потенциальное увеличение чистоты золота. Примечательно, что процесс биовосстановления продемонстрировал превосходное увеличение концентрации Au со значением 138,89% по сравнению с процессом биоокисления со значением 122,22%. Таким образом, процесс биовосстановления оказался более эффективным в увеличении концентрации Au по сравнению с биоокислением.

	Ключевые слова: Биологическое выщелачивание, S. oneidensis, A. Ferroxydans, золото, ICP-OES.
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