



Research article

Effect of sodium acetate additive on gold leaching with cyanide solution: Laboratory and semi-pilot leaching tests

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ABSTRACT

Heap leaching with a cyanide solution is used for processing low-grade ores; however, owing to the chemical, mineralogical, and physical characteristics of ores and their particle size distribution, extraction efficiencies are often low. This study investigated the effects of sodium acetate addition on gold extraction from Akshoky deposit ores under laboratory and semi-pilot laboratory test conditions. The gold-bearing ore used in this study had average gold and silver contents of 1.32 and 3.27 g/t, respectively. The chemical composition of the ore was as follows (wt%): copper: 0.0185, nickel: 0.0090, cobalt: 0.0025, zinc: 0.0470, lead: 0.0095, total iron: 4.10, calcium oxide: 3.08, magnesium oxide: 1.10, sodium oxide: 1.40, potassium oxide: 0.82, silicon oxide: 64.22, aluminum oxide: 13.37, arsenic: 0.023, antimony: 0.0024, total sulfur: 0.24, sulfate sulfur: 0.040, and sulfide sulfur: 0.20. Gold in the ore occurs in different forms: free/native form grains (82%), covered with films (3.28%), associated with sulfides (6.56%), and in fine-grained form (8.20%). Laboratory tests showed that gold dissolution from ground ore by a cyanide solution without sodium acetate addition was 83.08%. However, with sodium acetate addition (0.1; 0.5; 1.0 kg/t), it increased to 84.38–86.61%. Semi-pilot laboratory tests under heap-leaching conditions confirmed the positive effects of sodium acetate. The increase in gold extraction was 7.6% (62.9%) compared with that in the experiments without reagent addition (55.30%).

1. Introduction

The world's rich ore resources are decreasing, leading to a greater focus on low-grade and complex ores. As the gold contents in ores

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decrease and economic and environmental energy costs increase, less energy-intensive metal extraction methods are becoming increasingly appealing. One such method is heap leaching, which has evolved into a key hydrometallurgical technology for gold extraction since its first use in the early 1970s for the extraction of gold from low-grade ores via cyanidation [1–3]. Cyanide heap leaching is globally used for processing low-grade ores such as gold, copper, zinc, nickel, and uranium [3–5].

The commercial application of cyanidation was introduced by MacArthur in 1887, and approximately 65 years after its discovery, gold dissolution was recognized as an electrochemical corrosion process [6,7]. Cyanidation involves leaching with an alkaline solution containing a low concentration of sodium cyanide [8–11].

Cyanidation occurs via two redox half-reactions: gold oxidation (Eq. (1)) as a single-electron reaction and oxygen reduction (Eq. (2)) at an alkaline pH. The mechanism of the cathodic reaction, i.e., the reduction of oxygen, has been controversial for a long time [12, 13]. The direct reduction of oxygen to hydroxyl ions does not usually occur within the potential range of gold dissolution. The reduction of oxygen follows the pathway of sequential two-electron transfer reactions involving the formation of hydrogen peroxide (Eq. (3)) as an intermediate product [14,15]. The overall reaction is described by the Elsner's equation (1846) (Eq. (4)), which is stoichiometrically correct [11,15,16].



The conditions for gold dissolution during cyanidation (or heap leaching) are influenced by the material, mineral composition, accessibility to reagents, permeability, and effective porosity of the ore [17–23]. A significant issue associated with this method is its low leaching rate [24,25]. One reason for this traditionally low gold leaching rate is that residual cyanides cause gold to react with iron sulfide impurities to form a passivating Au/S_x film [26]. The addition of trace amounts of sodium sulfide to a cyanide solution significantly hindered gold leaching, owing to the formation of a passive Au₂S layer on the gold surface [27]. Soluble sulfides impede the rate of gold leaching by forming a protective Au/S_x type layer [28]. The galvanic interactions between gold and minerals also affect leaching. Conducting minerals passivate gold and decrease the dissolution rates.

One of the predominant issues in cyanidation (or heap leaching) is the presence of impurities in ores that can passivate gold. These films can be solid and dense, restricting solvent access to gold. If the films are porous or cover only part of the gold particle surface, they merely reduce the leaching rate [29,30]. For example, metals such as Cu, Zn, Fe, Co, and Ni readily form complexes with cyanide, leading to excessive reagent costs and the prevention of gold extraction [2,31]. Additionally, sulfidic and oxide minerals in gold ore encapsulate gold and block it from cyanide, whereas carbonaceous materials act as adsorbents that re-adsorb leached gold into the ore [32].

Numerous methods have been developed to intensify gold leaching. Air or oxygen is used as an additive during the intensive mixing of the pulp [33–36]. Hydrogen peroxide, as an auxiliary reagent, accelerates leaching and enhances gold extraction [37–40]. Gold leaching involves an electrochemical process that includes the anodic dissolution of gold and cathodic reduction of oxygen and other oxidants [41,42]. Auxiliary leaching with hydrogen peroxide represents an intensified method of cathodic reduction [24,37].

Furthermore, certain heavy metals such as lead [43–45], bismuth [46], silver [47–49], and thallium [50] are effective in intensifying the anodic dissolution of gold. Their catalytic effects on gold leaching have been theoretically analyzed, and studies have examined their electrochemistry [24]. The presence of heavy metal salts in sodium cyanide solutions reduced the gold dissolution time [51]; for instance, a lead concentration of approximately 5 mg/L could quadruple the reaction rate.

The addition of lead(II) ions has been widely used to counteract the negative impact of chemically active sulfide minerals on gold leaching and cyanide and oxygen consumption. In a cyanide solution, lead nitrate, sulfide, and sulfate react with gold, forming intermetallic compounds AuPb₂, AuPb₃, and metallic lead, which intensify gold dissolution. Lead nitrate, owing to partial hydrolysis and affinity for sulfur-containing compounds, forms a hydroxide layer on the surface of pyrite, reducing the rate of pyrite interaction with cyanide and formation of a passivating sulfide layer on the surface of gold [52,53].

A previous study investigated the influence of mercury ions on gold cyanidation [51]. A microstructural analysis revealed that mercury ions enhance cyanide corrosion of the gold surface, resulting in a porous structure with numerous deep crevices and large particles across the gold surface. This porous structure increased the contact surface area between gold and cyanide, accelerating gold dissolution. Moreover, mercury ions prevent the formation of insoluble products, such as AuCN, Au(OHCN), and Au(OH)_x, leading to the formation of a passivation membrane on the surface of gold, reducing the contact between gold and cyanide. These effects induced by mercury ions alter the structure and surface products of gold during cyanidation and promote gold leaching [51].

The disadvantages of such additives include environmental hazards, which require further industrial testing and additional costs [11,12]. Hence, the development of new methods to enhance the leaching efficiency remains a promising and relevant area of research.

Sodium acetate is a promising additive for this purpose. In [54–57], acetic acid was initially investigated as an additive to an alkaline sodium cyanide solution to intensify the leaching process and increase gold extraction from gravity concentrates. Subsequent research [58] focused on the heap leaching of gold from the gold-bearing ore of the Sari Gunay deposit (Iran) with the addition of a sodium acetate reagent. However, the effects of this reagent on other gold-bearing ores have not been studied extensively. However, the effect of sodium acetate addition on the leaching of gold from other ore compositions was studied.

In this study, the effect of the addition of sodium acetate on gold extraction from the Akshoky deposit was investigated under laboratory and semi-pilot laboratory conditions.

2. Materials & methods

2.1. Sample

The gold-bearing ore used in this study was sourced from the Akshoky deposit, located in the Katon-Karagay district of the East Kazakhstan region. This region is known for its gold-bearing areas, with many small and medium-sized gold deposits.

2.2. Analysis

The gold and silver contents in solid products were determined using a fire assay-gravimetric method, whereas those in solutions were measured using atomic absorption spectroscopy. Chemical analysis of the samples was conducted with an atomic absorption spectrometer SavantAA (GBC Scientific Equipment, Australia), with prior chemical decomposition of solid samples. X-ray diffraction was carried out on an automated DRON-3 diffractometer (Russia) with a $\text{Cu}_{\text{K}\alpha}$ -radiation source and b-filter. Briquettes made from the ore and concentrated products (heavy fractions) were studied under a DM2500P microscope (Leica Microsystems, Germany). To identify the presence, form, and composition of gold studies were conducted using an electron probe microanalyzer JXA-8230 (JEOL, Japan).

Additionally, to determine the size of the gold particles, the initial ore and leaching tailings was scintillated at the Grand-Potok atomic emission complex (VMK-Optoelektronika, Russia). This method facilitated the assessment of the quantity and size of gold particles [59,60].

Laboratory bottle-roll leaching tests were conducted under the following conditions: sample weight of 300 g, degree of ore grinding at particle size of P90/-0.071 mm, liquid to solid ratio of 2:1, solution pH of 10.5–11.0 during leaching, NaCN concentration of 0.1 % (1 g/L), and leaching duration of 24 h. Sodium acetate was used as an additive with consumptions of 0.1, 0.5, and 1 kg/t. Each experiment was conducted in triplicates to ensure its reproducibility and reliability. The average values for each test were selected based on the experimental results.

Semi-pilot leaching tests, simulating heap leaching, were conducted on 5 kg of ore with a particle size of $-12 + 0$ mm in columns with a diameter and height of 97 and 515 mm, respectively. The leaching process was carried out in an open cycle. Each cycle involved adding 1.8 L of sodium cyanide solution with a concentration of 0.05 % (0.5 g/L), and pH was maintained at 10.5–11.0 by adding sodium hydroxide (NaOH). The irrigation rate was 10 L/m² per hour. The gold content of the pregnant solutions was analyzed. Each column was subjected to 21 leaching cycles.

For comparison, two series of heap leaching studies were conducted, one with the addition of sodium acetate and the other without. Sodium acetate was added during the first three leaching cycles with no further addition in the subsequent cycles. Each experiment was conducted twice to ensure the reproducibility and reliability of the results. The average values for each test were selected based on the experimental results.

3. Results and discussion

3.1. Physical and chemical composition

According to the results of an assay analysis, the average gold and silver contents in the ore were 1.32 and 3.27 g/t, respectively. The chemical composition of the ore was as follows (in wt%): copper: 0.0185, nickel: 0.0090, cobalt: 0.0025, zinc: 0.0470, lead: 0.0095, total iron: 4.10, calcium oxide: 3.08, magnesium oxide: 1.10, sodium oxide: 1.40, potassium oxide: 0.82, silicon oxide: 64.22, aluminum oxide: 13.37, arsenic: 0.023, antimony: 0.0024, total sulfur: 0.24, sulfate sulfur: 0.040, and sulfide sulfur: 0.20.

According to assay and chemical analyses, gold is the only industrially valuable component of the Akshoky deposit. The remaining metals are of no industrial importance because of their low concentrations. The contents of harmful impurities such as arsenic and antimony were low at 0.023 and 0.0024 %, respectively.

The granulometric composition of the test sample is shown in Table 1.

According to the granulometric analysis data, the gold content was unevenly distributed, slightly favoring fine-grade gold. The

Table 1
Granulometric composition of the ore.

Size (mm)	Yield (%)	Gold content (g/t)	Gold distribution (%)
-12 + 5	69.00	1.11	59.38
-5+2.5	7.68	1.34	7.98
-2.5 + 1.2	5.45	1.74	7.36
-1.2 + 0.63	3.41	1.68	4.44
-0.63 + 0	14.45	1.86	20.84
Ore	100.00	1.29	100.00

lowest gold content (1.11 g/t) was observed within the particle size fraction of $-12 + 5$ mm; however, the majority of gold (59.38 %) was also concentrated within this particular size fraction.

3.2. Mineralogical and phase composition

Mineralogical studies are crucial for the development of gold extraction projects and optimization processes. Technological mineralogy for gold not only involves examining gold minerals and submicroscopic gold with their carriers, but also includes studying ore and rock-forming minerals that might affect the gold leaching process. The characterization of gold minerals and carriers in complex ore samples can be used to diagnose and predict hydrometallurgical reactions, identify potential issues, and assist in designing a more reliable metallurgical testing program [61]. Mineralogical results should be compared with other analyses, such as assays, chemical analyses, and phase analyses [62,63].

The mineral phases identified via an X-ray diffractometric analysis is shown in Fig. 1, and the calculated quantitative ratios of the ore and rock-forming minerals are shown in Table 2.

The rock-forming minerals were represented by an oxidized feldspar-mica-chlorite-quartz composition. Among the ore minerals, iron oxides and hydroxides predominate, amounting to 5.5 % of the sulfide minerals. Approximately 0.3–0.4 % is pyrite, and other sulfide minerals are present in significant amounts. The presence of pyrite, iron oxide, and hydroxide was confirmed through mineralogical analyses (Figs. 2 and 3). These minerals varied in size and were associated with the presence of gold.

Many free/native gold particles of various sizes (from several μm to >100 μm) were observed in the heavy fraction. It had a yellow color with varying intensities and significantly high reflectivity (Figs. 2 and 3). The different coloration intensities can be explained by varying the compositions of gold, such as pyrite and iron oxides. An electron probe microanalysis in the COMPO mode revealed that gold exists as free grains in the ore, with sizes measuring $85.1 \times 36.5 \times 92.6$ μm (Fig. 4). An analysis of this gold grain using the EDS mode indicated a composition of high-grade gold (>90 %), with silver (6.6 %) and iron (1.3 %) present as impurities (Fig. 5). Additionally, gold particles with a composition of 83.5 % gold and 11.8 % silver were found, with a size of $35.6 \times 32.2 \times 48.1$ μm (Fig. 6). Electrum (size: $95.6 \times 66.7 \times 116.6$ μm) containing 60.3 % gold and 39.7 % silver was also identified (Fig. 7). According to the electron probe analysis, these gold crystals contain 6–40 % silver impurities, indicating two distinct types of gold-bearing formations, namely high-grade gold and electrum.

A phase analysis showed that most of the gold (82 %) was in the free/native form. Small amounts of gold were covered with films (3.28 %), associated with sulfides (6.56 %), and in fine-grained forms (8.20 %). The results of the phase analysis of the original ore are shown in Fig. 8.

Conditions favorable for heap leaching occur when free gold has particle sizes below 70–100 μm , with no films or inclusions on the surface. The solvent should have access to the mineral formations. This is ensured by the natural porosity and fracture patterns of the ore. Typically, the fine-grained gold in ores is free. It occurs along fractures and partially forms aggregates with other minerals. These forms and gold locations are easily accessible to solvents, facilitating the relatively quick transfer of the metal to the liquid phase. Fine grained gold in quartz cannot be extracted because diffusion leaching owing to the low porosity of quartz [2,3,30].

The association of gold with sulfide minerals (such as pyrite, chalcopyrite, covellite, galena, and sphalerite) might prevent gold dissolution because the cyanide solution cannot access the gold. Gold in pyrite can be leached if it has a sufficiently coarse-grained structure and exposed gold surfaces or if pyrite is partially oxidized, allowing diffusion leaching through an iron hydroxide film.

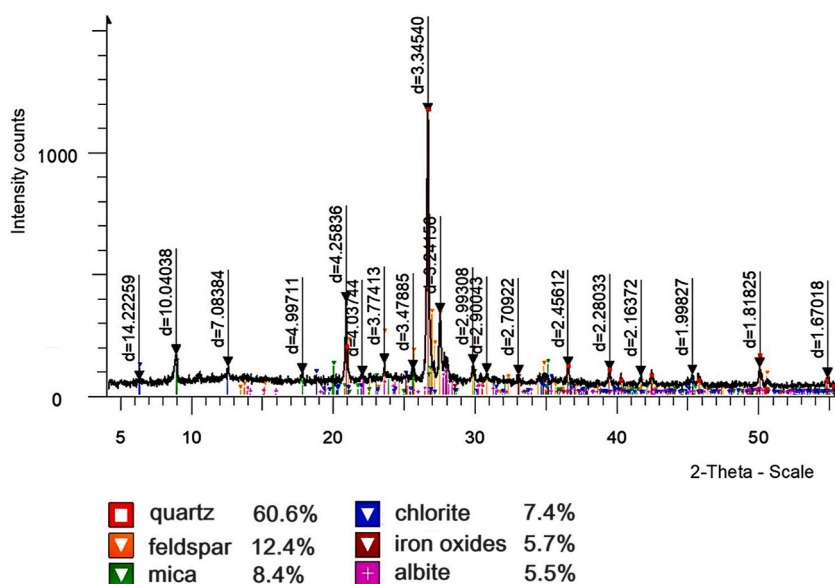


Fig. 1. X-ray diffractometric analysis of the ore from the Akshoky deposit.

Table 2
Mineralogical composition of the ore.

Mineral composition (mass %)			
Ore minerals		Rock-forming minerals	
Oxides and hydroxides of iron	5.3–5.5	Quartz	60–61
Pyrite	0.3–0.4	Feldspar	5
Chalcopyrite, covellite	Isolated grains	Mica	8–9
Galenite	Isolated grains	Chlorite	5–6
Sphalerite	Isolated grains	Plagioclase	15

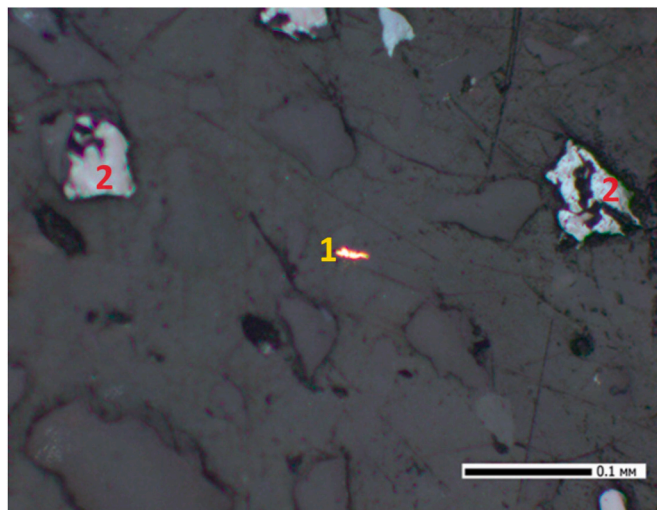


Fig. 2. Gold (1) and iron oxides (2) (Briquette; magnification 200x).

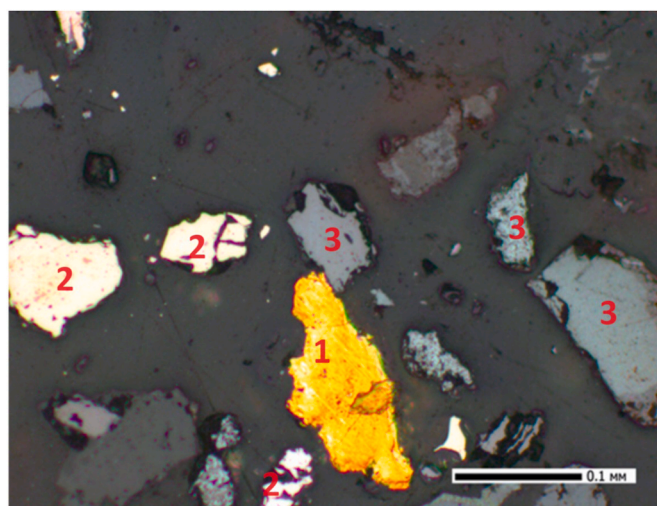


Fig. 3. Gold (1), pyrite (2), and iron hydroxides (3) (Briquette; magnification 200x).

However, if the gold particles are fine grained and sealed in pyrite, an additional treatment (oxidation) is required for extraction [61, 63].

3.3. Laboratory tests for gold leaching

Laboratory studies of ore leaching (bottle tests) showed the maximum gold extraction rates. Therefore, grinded ore with a particle

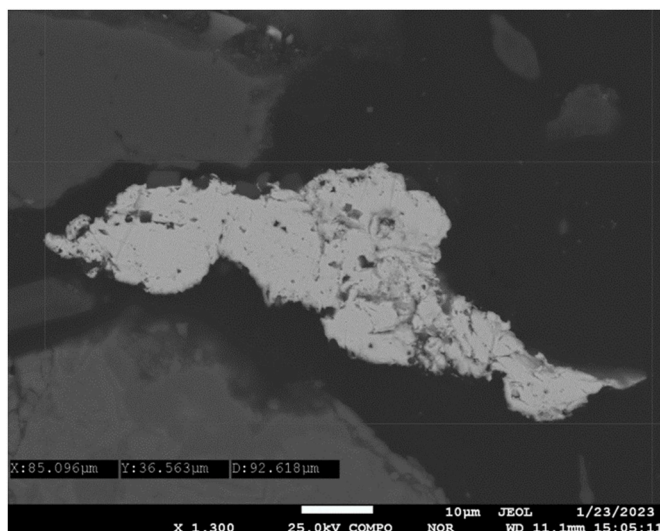


Fig. 4. Micrograph of gold (COMPO mode; magnification 1300x).

size of P90/-0.071 mm was used in these tests to obtain accurate results with reduced mistakes compared to crushed ore tests. This method simulates the behavior of gold during cyanide ore leaching.

Previous studies [58] analyzed gold leaching from the ore at the Sari Gunay deposit (Iran), using various dosages of sodium acetate (from 0.1 to 3 kg/t) as an additive. Results showed that the optimal sodium acetate dosage was 0.5 kg/t, resulting in an average 4 % increase in gold extraction. For the Akshoky deposit ore, which differs in composition, sodium acetate dosages ranging from 0.1 kg/t (minimum) to 1 kg/t (maximum) were chosen for experimentation. The authors concluded that further increase in sodium acetate dosage would not be beneficial.

Table 3 shows the laboratory test results of cyanide leaching from the ore.

The degree of gold dissolution from the ore without additives was 83.08 %. The addition of sodium acetate to the leaching solution had a positive effect on gold dissolution, and the degree of gold dissolution increased to 86.61 % at a sodium acetate consumption of 0.5 kg/t.

Thus, using agitation leaching with the addition of sodium acetate for the ore from the Akshoky deposit resulted in a 3.5 % increase in gold extraction.

A scintillation analysis revealed that gold in the initial ore was primarily in the form of fine particles (0.5 nm). However, single coarse gold particles that were larger than 50 nm were also present (Table 4).

The results of the scintillation analysis showing the effect of sodium acetate addition on the extraction of gold particles of various sizes is presented in Fig. 9.

Fig. 9 shows that coarse- and fine-grained gold particles dissolve. The greatest effect of sodium acetate was observed at dosages of 0.5 and 1 kg/t. The scintillation analysis data of the leaching tails aligned well with the results from bottle-roll tests, with most gold dissolved at sodium acetate consumption rates of 0.5 and 1 kg/t.

However, the scintillation analysis might not capture all gold particles present in a sample, as the ore mass passing through the apparatus is only 0.1 g, with up to 5 or more pieces being analyzed. Given the uneven distribution of gold, as observed in the studied samples, estimating the size of all the particles is impossible. However, this method allows the assessment of the ratio of gold particles of various sizes in the ore [59,60].

For further semi-pilot laboratory tests of gold leaching, a sodium acetate consumption of 0.5 kg/t was selected.

3.4. Semi-pilot laboratory tests for gold leaching

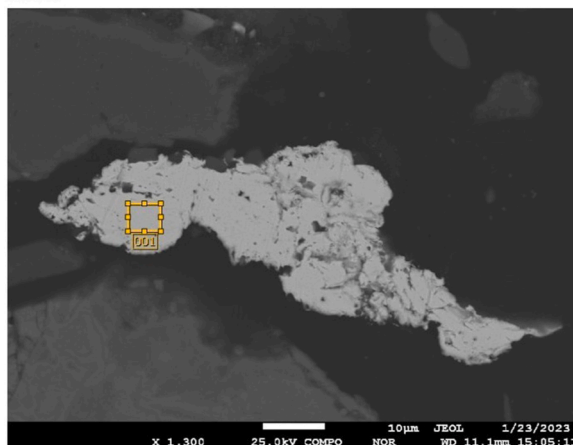
Semi-pilot laboratory heap leaching tests, carried out with ores of $-12 + 0$ mm in size, simulated the heap leaching process. A unique characteristic of the heap leaching technology compared to other technologies is its relatively coarse particle size. Recent experimental data suggest that coarse particle leaching occurs only from surface and subsurface areas accessible through cracks and pores [1,64–66].

The use of a reagent that oxidizes the surface of coarse particles and enlarges cracks and pores for cyanide solution access to the gold particles provides an incentive to test the increase in gold extraction.

Twenty-one leaching cycles were required to dissolve gold from the studied ore. The total amount of pregnant solution without the reagent was 7.23 m³/t of ore. With sodium acetate, the amount of pregnant solution required was 7.22 m³/t of ore.

The changes in the gold concentration in the solution during the leaching process is shown in Fig. 10. The addition of sodium acetate increased the gold content in the pregnant solutions, particularly during the first three leaching cycles.

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Volt : 25.00 kV
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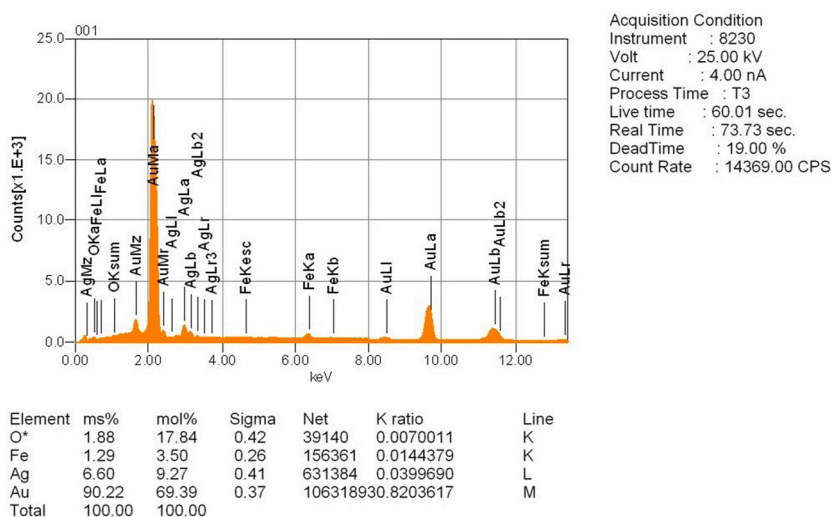


Fig. 5. High-grade gold (EDS mode; magnification 1300x).

Fig. 11 shows the dependence of gold extraction from ores on the leaching duration.

The operational data over 21 leaching cycles showed a gold extraction rate of 60.78 % with sodium acetate, compared to 54.34 % without. Changes in gold extraction were observed starting from the third leaching cycle, with differences between acetate and non-acetate treatments increasing but stabilizing after six to nine cycles (Figs. 10 and 11). This stabilization can be attributed to the addition of sodium acetate during the initial three cycles, with its effects continuing until the sixth cycle.

In [58], the addition of sodium acetate increased gold extraction by only ~4 %, with stabilization occurring after the fourth and fifth cycles. This difference may have been due to the distinct chemical composition of the ore in the Sari Gunay deposit (Iran). Another study [39] on the same ore but with hydrogen peroxide treatment resulted in a modest 1.2 % increase in gold extraction, indicating room for exploring other additives and combinations in future research.

The results of the semi-pilot laboratory heap leaching tests confirmed the positive impact of sodium acetate on the leaching process. The gold balance was calculated based on the obtained data (Table 5).

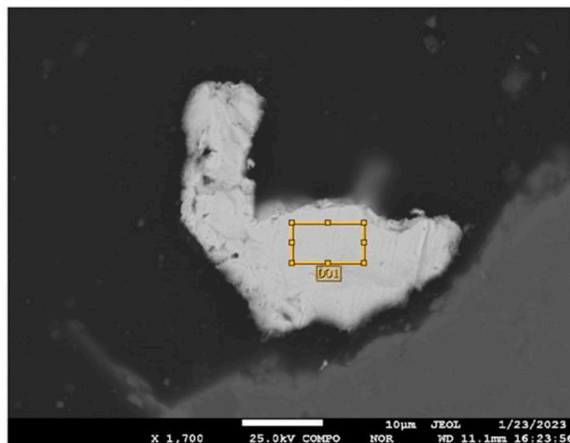
The calculated average gold contents in the ore, according to the balance, were 1.32 g/t without the reagent and 1.29 g/t with sodium acetate. The degree of gold dissolution from the ore with sodium acetate was 62.9 %, which was 7.6 % higher than that without the addition of sodium acetate (55.30 %).

Both laboratory and semi-pilot laboratory tests demonstrated the positive impact of sodium acetate addition on gold leaching from the ore of the Akshoky deposit. A hypothesis regarding the mechanism underlying the effect of sodium acetate is proposed in the following section.

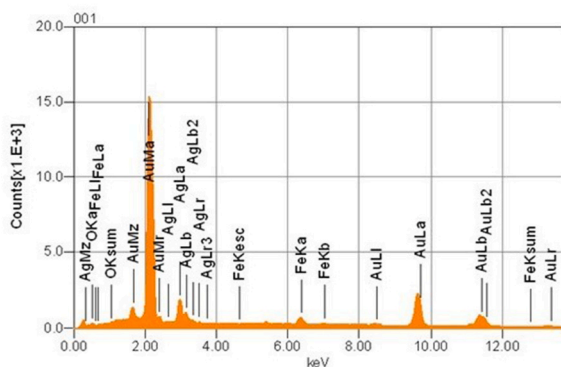
3.5. Approximate mechanism of the influence of sodium acetate addition

Because a significant portion of gold ores contains sulfide minerals, the impact of these minerals on gold dissolution in cyanide

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Acquisition Condition
 Instrument : 8230
 Volt : 25.00 kV
 Current : 4.00 nA
 Process Time : T3
 Live time : 60.00 sec.
 Real Time : 72.24 sec.
 DeadTime : 17.00 %
 Count Rate : 12111.00 CPS

Element	ms%	mol%	Sigma	Net	K ratio	Line
O*	2.51	21.54	0.40	41699	0.0088462	K
Fe	2.15	5.28	0.24	217023	0.0237667	K
Ag	11.81	15.01	0.36	969250	0.0727698	L
Au	83.53	58.17	0.34	8137919	0.7447220	M
Total	100.00	100.00				

Fig. 6. Gold (EDS mode; magnification 1700x).

solutions has been of interest to many researchers [12,14,15,31,32]. Early studies on gold dissolution in cyanide solutions in the presence of sulfide minerals have shown that heavy metal components such as Fe, Cu, and Zn significantly increase the consumption of both cyanide and oxygen. Furthermore, sulfide components strongly influence the kinetics of gold leaching [6,31,32].

Galvanic interactions between gold particles and sulfide minerals may play a crucial role in the behavior of gold dissolution in cyanide solutions (Eqs. (1)–(4)) [12–16].

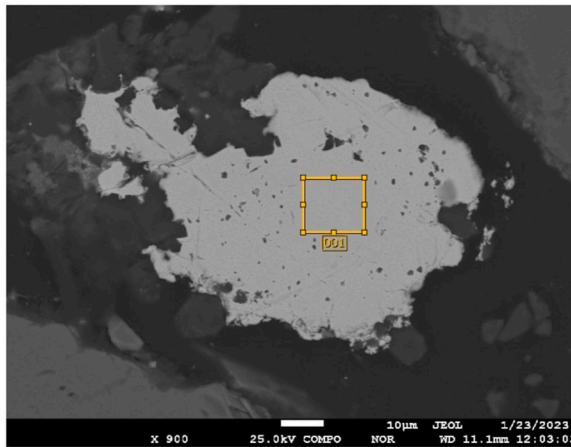
Because gold has a more negative potential in cyanide solutions than certain sulfide minerals, such as pyrite, pyrrhotite, and chalcopyrite, gold is expected to dissolve faster when in galvanic contact with these minerals [67]. However, this is not always true. In [68,69], gold was hypothesized to passivate in close contact with certain conducting sulfide minerals such as pyrite. This phenomenon was explained by postulating that oxygen reduction could occur across the entire mineral surface and that the anodic curve of gold indicates a passive region [68]. Owing to the enhanced cathodic oxygen reduction on the mineral surface, the mixed potential increased to a level that stabilized the passive film on the gold surface. In [69] pointed out that any gold particle embedded in the surface of a much larger pyrite particle and exposed to oxygen and cyanide will be leached at a significantly retarded rate.

In [27], the effect of galvanic interaction due to the formation of a passivating film on the gold surface was studied using a rotating disk made of pure gold, by electrically contacting a mineral disk in one vessel and then in two separate vessels. The authors suggested that when gold comes in contact with conducting minerals, it passivates owing to an increase in the cathodic current density. It has been argued that a higher cathodic current positively shifts the mixed potential to the passive region, thereby reducing the gold dissolution rate.

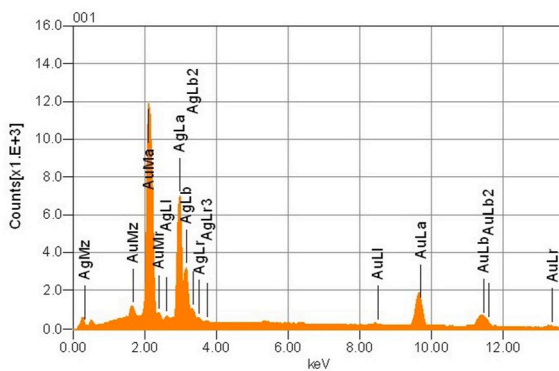
The oxidation of iron sulfide minerals, such as pyrite, present in the investigated ore has been described by many authors through the following reactions. Upon pyrite oxidation, Eq. (5) proceeds intensively [70].



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Mag. : x 900
Date : 2023/01/23
Pixel : 1280 x 960



Acquisition Condition
Instrument : 8230
Volt : 25.00 kV
Current : 4.00 nA
Process Time : T3
Live time : 60.01 sec.
Real Time : 72.45 sec.
DeadTime : 18.00 %
Count Rate : 13366.00 CPS

Element	ms%	mol%	Sigma	Net	K ratio	Line
Ag	39.69	54.58	0.39	4050682	0.2525787	L
Au	60.31	45.42	0.43	6289410	0.4780177	M
Total	100.00	100.00				

Fig. 7. Ectrum (EDS mode; magnification 900x).

Because sulfide minerals are soluble in cyanide solutions to some extent, various forms of sulfur are always present in the leaching solution [71]. Free sulfur, resulting from the partial oxidation of sulfides, reacts with cyanide to form thiocyanates (Eq. (6)).



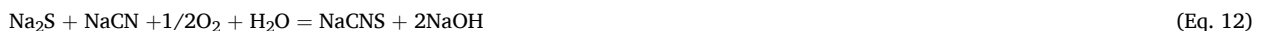
Iron sulfide minerals are classified into rapidly oxidizable sulfides (such as marcasite, pyrrhotite, and pyrite) and slow-oxidizing sulfides (most pyrite differences). The following reactions occur for rapidly oxidizable iron sulfide minerals [72].



Iron compounds react with sodium cyanide in the presence of an alkali, significantly increasing their consumption (Eq. 8, and 9) [30].



The presence of various types of iron sulfides leads to a high consumption of cyanide and oxygen [71]. The slow interaction of cyanide with iron sulfide resulting from the partial oxidation of iron sulfide proceeds according to the following equations [12,30]:



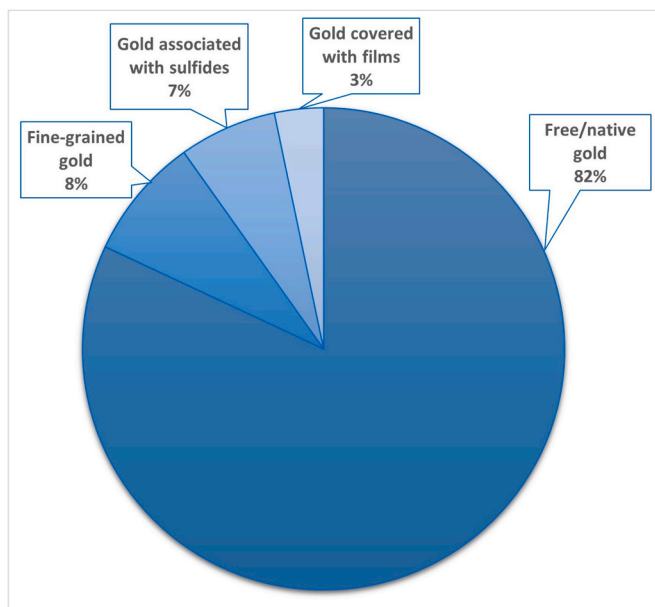


Fig. 8. Results of the phase analysis of gold.

Table 3

Results of laboratory leaching tests.

Indicators	Without reagent	With reagent addition (0.1 kg/t)	With reagent addition (0.5 kg/t)	With reagent addition (1 kg/t)
Au content in the liquid phase of the pulp, mg/L	0.54	0.54	0.55	0.55
Au content in the solid phase of the tailings, g/t	0.22	0.20	0.17	0.19
Au content in ore, g/t	1.30	1.28	1.29	1.29
Au dissolution, %	83.08	84.38	86.61	85.27

Table 4

Distribution of gold particles in the initial ore and leaching tails.

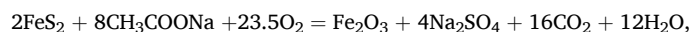
Particle size (nm)	<0.5	<2	<5	<10	<50	Particle Sum
Initial ore	178	110	35	13	10	346
Leaching tails (without reagent)	85	35	16	8	4	148
Leaching tails (with reagent addition 0.1 kg/t)	68	32	13	7	3	123
Leaching tails (with reagent addition 0.5 kg/t)	55	23	6	2	1	87
Leaching tails (with reagent addition 1 kg/t)	59	25	7	2	1	94

The overall reaction can be written as:



Sodium sulfide significantly reduces the extraction of precious metals by cyanidation, as it slows down the dissolution of gold and silver, by acting as a reducer and consuming oxygen and cyanide (Eq. (12)). In [27,73], sodium sulfide in a cyanide solution severely hindered gold leaching, and this was explained by the formation of a passive layer of Au_2S on the gold surface.

We hypothesized that in the presence of sodium acetate, before the formation of iron(II) sulfide (Eq. (7)) and the subsequent formation of sodium sulfide (Eq. (10)), pyrite interacts with sodium acetate to form iron oxide (III), as shown in Eq. (14). The isobaric-isothermal potential is -9608.40 kJ/mol [58]. Iron(III) oxide can be converted into iron(III) hydroxide according to Eq. (15).



$$\Delta G_T = -9608,40 \text{ kJ/mol}, t = 298 \text{ K} \quad (\text{Eq. 14})$$



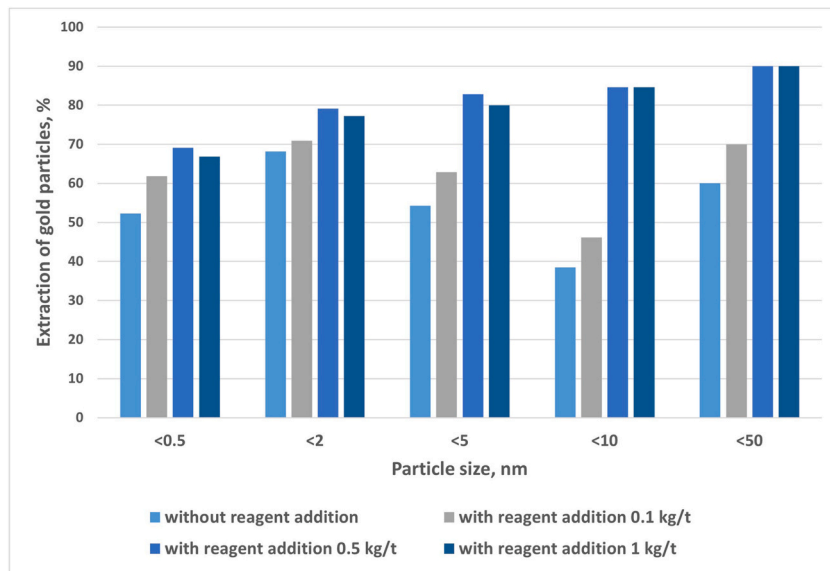


Fig. 9. Effect of the addition of sodium acetate on gold particle extraction.

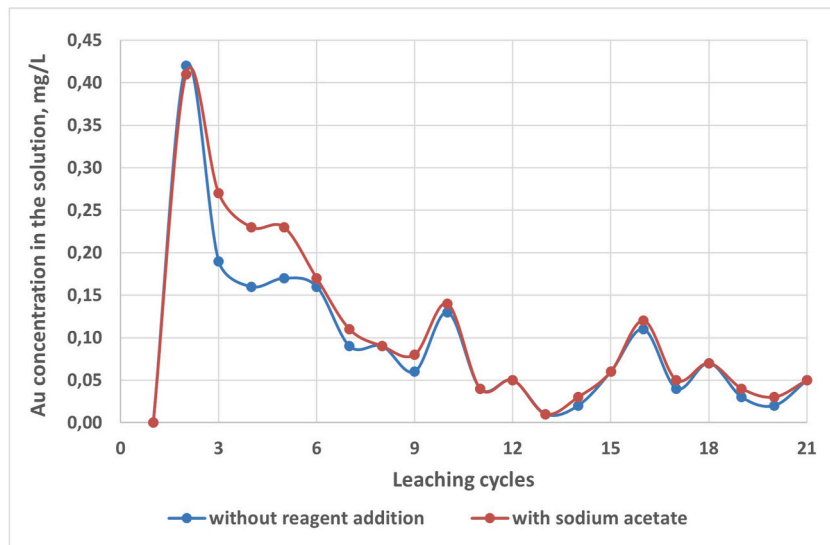
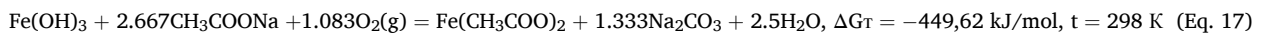


Fig. 10. Changes in the gold content in pregnant solutions during leaching.

During the multistage oxidation of pyrite in an alkaline oxidative environment in the presence of sodium acetate, the probability of iron hydroxide formation is high (Eq. (8)). Iron hydroxide also interacts with sodium acetate to form acetate salts according to Eq. (16, and 17). This reduces the interaction between sodium cyanide and iron hydroxide (Eq. (8)), allowing cyanide to be consumed for gold dissolution, thereby increasing its extraction. Negative values of the Gibbs energy indicate the possibility of these reactions.



The proposed mechanism for gold leaching in an alkaline cyanide medium in the presence of sodium acetate is as follows.

- 1) Sulfide ore minerals interact with a cyanide-alkaline solution to form compounds that block the surface of precious metals and prevent the dissolution of gold.
- 2) In the presence of sodium acetate, it interacts with sulfide ore minerals, and the resulting compounds of impurity metals to form metal acetates.

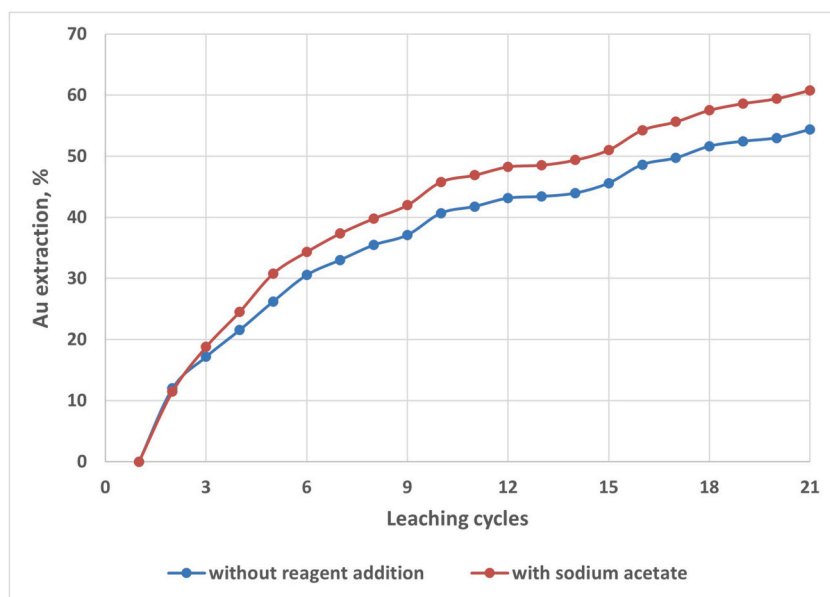


Fig. 11. Dependence of gold extraction on the leaching duration.

Table 5

Gold balance during column tests for heap leaching of gold.

Indicators	Without reagent	With sodium acetate
Extracted gold with a pregnant solution (g/t of ore)	0.717	0.802
Extracted gold with analyzed solutions (g/t of ore)	0.013	0.014
Gold content in column leaching tailings (g/t)	0.590	0.480
Estimated gold content in the initial ore (g/t)	1.320	1.296
Degree of dissolution of gold from ore by balance (%)	55.30	62.97

3) Consequently, the expansion of the intergranular boundaries of compounds blocking the surface of gold promotes the growth of pores and cracks and increases access of the solvent to the surface of gold, leading to an increase in its extraction. The interaction between sodium cyanide and iron sulfide is also reduced (Eq. (13)), and cyanide is consumed to dissolve gold, thereby increasing its extraction.

4. Conclusions

Laboratory and semi-pilot laboratory tests on the heap leaching of gold confirmed the positive impact of sodium acetate addition on the leaching process using a cyanide solution.

Cyanide-acetate solutions can be detoxified using established cyanide detoxification technologies to ensure environmental safety. Because sodium acetate was added only in the first three cycles at a rate of 0.5 kg/t, the concentration of acetate salts in the solutions remained significantly low. However, further research is required to fully understand the potential environmental implications.

Future research should focus on in-depth studies of the mechanism of gold leaching in alkaline cyanide solutions in the presence of sodium acetate, including kinetic and thermodynamic investigations.

Industrial trials at mining sites are necessary to commercialize this technology, considering all nuances and conclusively confirming the results of the tests conducted. Furthermore, cost-benefit analyses and feasibility studies are essential for the commercial implementation of this technology.

Data availability statement

All data generated or analyzed during this study are included in this published article.

CRediT authorship contribution statement

Bauyrzhan Surimbayev: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Yerlan Yessengarayev:** Validation, Methodology, Investigation. **Yerassyl Khumarbekuly:**

Visualization, Investigation. **Lyudmila Bolotova**: Writing – review & editing, Conceptualization. **Yernazar Kanaly**: Data curation. **Mukhitdin Akzharkenov**: Formal analysis. **Shyngys Zhumbai**: Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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