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Mercury Removal from Glycine Leach Solutions Using Sodium Sulfide (Na₂S) Precipitation

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Abstract

Amino acid leaching has been considered an environmentally friendly alternative for gold recovery; however, the dissolution of mercury (Hg) during the leaching of amalgamation tailings remains a major challenge. This study is a novelty study that focuses on Hg removal by passing the Hg-containing tailings, previously processed by amalgamation, into solution via glycine (NH₂CH₂COOH) leaching. In this regard, a precipitation method using sodium sulfide (Na₂S) was developed to remove Hg from solutions obtained after glycine leaching. The effects of precipitation time, pH, Na₂S dosage, and temperature were investigated. The effects of pH, precipitation time, and temperature were found to be limited within the investigated ranges. The results showed that Na₂S dosage was the most effective parameter in mercury removal. The initial Hg concentration of 12,160 ppb was reduced to 223 ppb at a Na₂S:Hg molar ratio of 60, corresponding to approximately 98% removal efficiency under the selected operating conditions. Increasing the Na₂S:Hg ratio to 80 resulted in a slightly higher removal efficiency (~99%) with a final Hg concentration of 144 ppb; however, a ratio of 60 was considered optimal in terms of reagent consumption and process efficiency. The outcomes indicate that Hg removal with Na₂S is a rapid and effective process under alkaline conditions, while Au remains in solution and Cu and Ag are partially removed, indicating limited selectivity and the need for further optimization. Therefore, this study provides a basis for developing more environmentally friendly processes for amalgamation tailings.

Keywords: Glycine, Heavy Metal Immobilization, Sulfide Precipitation, Hydrometallurgy, Environmental Remediation

INTRODUCTION

Artisanal and small-scale gold mining (ASGM) contributes substantially to global gold production and is recognized as a major contributor to global emissions of mercury (Hg). Recovering the high gold content of the tailings from amalgamation processes is crucial, as is eliminating the dangerous mercury for environmental reasons. Mercury (Hg) is one of the most hazardous heavy metals to human health and the environment due to its high toxicity and potential accumulation. Methylmercury (CH₃Hg⁺), in particular, can result in long-term harm to the nervous system and can be transmitted intergenerationally through breast milk and the placenta. Significant mercury emissions occur due to fossil fuel use, metal mining, tailings incineration, chlor-alkali production, and especially Artisanal and Small-scale Gold Mining (ASGM) (1).

Despite international regulations restricting mercury use, its use in small-scale gold mining has continued. Artisanal and small-scale gold mining (ASGM) employs approximately 15 million miners in over 80 countries, compose of 20% of the world's gold production, and is one of the main sources of global mercury (Hg) emissions. Mercury is widely used because it readily forms an amalgam with gold and is readily available. However, its evaporation, burning in homes, and use in combination with cyanide pose serious risks to human health and the environment. According to the 2018 Global Mercury Assessment (2), ASGM uses 2,059 tons of mercury annually and emits 838 tons into the atmosphere. NAP data show that the average Hg:Au ratio is approximately 1.3:1, that in some countries more than 90% of gold production relies on mercury, and that the goal is to reduce mercury use by 37% by 2025 and by 70% by 2030. However, the largely informal nature of ASGM, limited access to mercury-free technologies and funding, and the lack of knowledge among miners continue to be significant obstacles (3).

During the leaching process of amalgamated gold tailings, mercury dissolves with the gold and passes into the leaching solutions. This poses significant problems not only from an environmental perspective but also in terms of the efficiency of metal recovery processes. In stages such as electrowinning and activated carbon adsorption applied after leaching, dissolved mercury can interfere with precious metal recovery, reduce the adsorption capacity of activated carbon, and make it more difficult to recover target metals such as gold and silver. Furthermore, the volatile mercury species during these processes may create serious occupational health and safety risks (4). Therefore, the effective removal of mercury from leaching solutions before the recovery of valuable metals is of paramount importance.

According to the Minamata Convention on Mercury, which entered into force in 2017, more comprehensive and systematic global efforts are being made to reduce the amount of mercury emitted into the atmosphere and surrounding environments (5) reducing greenhouse gases (GHGs). However, these developments do not negate the fact that the amount of tailings produced by ASGM in the past was quite high, and that much of it was dumped in designated landfills without treatment. Studies have shown that cyanide leaching has been used to reprocess amalgamation tailings (AT) (6). As the demand for gold production increases, the recovery of gold from amalgamation tailings using appropriate techniques such as cyanidation becomes increasingly important for transforming these tailings into valuable and marketable (7). However, according to the Minamata Convention, this practice is considered one of the "worst practices" (8,9). This is because cyanidation of mercury-contaminated tailings lead to the formation of CN/Hg complexes, which can become more mobile and spread more rapidly into the environment (8,10). In this context, it is important to research or develop economic processes for recovering gold and mercury from amalgam tailings and transforming them into a new, environmentally sustainable material.

Due to environmental concerns and economic reasons related to cyanide, a widely used reagent in gold extraction, there is extensive research on the search for alternative reagents. Research has focused on thiosulfates, thioureas, halides, ammonia, and bacteria as alternatives to cyanide for gold leaching (11). However, existing alternatives to cyanide present numerous challenges, including toxicity, economic inefficiency, lack of recoverability, and instability (12,13). Therefore, recovering gold using a simple amino acid (glycine) that is non-toxic, environmentally harmless, has high affinity for gold, silver, and copper, offers potential for recovery and reuse, is thermally stable, non-volatile, and recoverable using conventional carbon adsorption technology, is of considerable importance (14). This approach is particularly prominent in the processing of mercury-containing ores and amalgamation-related wastes, which pose a problem under the Minamata Convention. However, the mobilization of mercury (Hg) into the solution phase during the leaching of amalgamation-related wastes is a critical issue in terms of environmental and process performance.

Glycine leaching may be a different approach to extracting gold, according to recent research (14-24). A carboxylic group and an amino group are present in the amino acid glycine. The simplest amino acid, glycine (NH₂CH₂COOH), has attracted attention as an environmentally friendly solution due to its low toxicity, non-volatility, and capability to combine with metals to form stable complexes in alkaline conditions. According to Eq.1, glycine can exist in three different forms when dissolved in water: H₂NCH₂COO⁻ (Gly⁻, glycinate anion), ⁺H₃NCH₂COO⁻ (H(Gly), zwitterion), and ⁺H₃NCH₂COOH (H₂(Gly)⁺, glycinium cation). Base and precious metals can be extracted from solid resources using an aqueous system called a glycine leaching system (GLS). It usually consists of glycine or one of its alkali metal salts, a pH modifier, an oxidant, and occasionally additional catalysts or modifiers. Unlike cyanide-based systems, glycine-based systems operate at high pH and reduce the formation of toxic metal complexes, making them particularly attractive for sustainable hydrometallurgical processes (25-27). Furthermore, it has been reported that glycine leaching can also dissolve mercury in amalgam structures (17). A method for the concurrent recovery and selective separation of gold and mercury from amalgamation tailing using glycine leaching has been presented in a patent obtained by the authors (28).

Traditional methods for mercury removal are insufficient due to drawbacks including high cost, low efficiency, and secondary pollution. Sulfur-based precipitation methods, especially the use of sodium sulfide (Na₂S), enable the separation of Hg⁺² ions from the solution by converting them into a low-solubility HgS form, thereby immobilizing mercury. In this context, the sulfur precipitation method stands out because of its low residue concentrations and recovery advantages. The precipitation and recovery of Hg⁺² ions from wastewater using Na₂S was evaluated; in a pH 4 environment, with a reaction time of 12 minutes, a sulfur/mercury molar ratio of 1:1 was applied for Hg⁺², and the Hg⁺² concentration was reduced to below 0.03 mg/L, achieving a precipitation

efficiency of over 99% (29). The removal of Hg from water and wastewater using various sulfur-containing precipitants (e.g., TMT, STC, K₂BDET, BDETH₂) has been investigated; it has been reported that the highest efficiency was obtained with K₂BDET (99.98%) and BDETH₂ (99.97%), and that Hg was generally removed by converting it into the insoluble HgS form (30).

Numerous studies have been conducted on the use of sodium sulfide (Na₂S) precipitation to remove mercury (Hg) from cyanide leaching solutions (31-33). However, these studies indicate that mercury may redissolve after precipitation (32). The literature reports that some metals can be successfully removed from glycine leaching solutions using sulfide-based precipitation methods. In particular, metals such as Zn, Cu, and Cd can be precipitated with high yields using sulfide sources like NaHS or Na₂S; the resulting products are generally described as metal sulfide precipitates. However, the vast majority of current studies focus on the recovery/removal of copper, zinc, cadmium, or precious metals (24,34-38). On the other hand, no previous studies have been found in the literature on the Hg removal from amino acid solutions for leaching. In a study on the recovery of Cd from glycine leaching solutions by precipitation with Na₂S, CdS nanoparticles, on average 20 nm in size, can be easily precipitated (36).

This study investigated the effectiveness of removing mercury (Hg) from leaching solutions acquired from the alkaline glycine leaching of AT using Na₂S and explored the effects of various experimental settings on removal efficiency. The findings are expected to contribute to preventing environmental damage caused by mercury-containing leach solutions and to supporting the safe recovery of valuable metals.

MATERIAL AND METHODS

Glycine Leaching and Metal Analysis of Amalgamation Tailings

In this study, the glycine leaching solution obtained from AT in the authors' previous study, with significant potential as a secondary source, was used (39,40). After amino acid leaching, the pulp obtained from the tailings was subjected to solid-liquid separation using a vacuum filtration system with a paper filter. The filtrate was then passed through membrane filters with a pore size of 0.45 μm. In the resulting clarified leaching solution, mercury concentration was determined using a Perkin Elmer AAS Analyst 400 Atomic Absorption Spectrometer (AAS) and the Perkin Elmer/FIAS100 cold vapor technique (Fig. 1). Gold (Au), Silver (Ag), and Copper (Cu) concentrations were also determined using the Perkin Elmer AAS Analyst 400 Atomic Absorption Spectrometer (AAS). For mercury analysis, quality control tests, Limit of Quantification (LOQ) tests and Limit of Detection (LOD), and accuracy tests for the applied analytical method (spike method) were performed using BCR-114R Wastewater Sludge (JRC) and CRM (Certified Reference Material). Detailed information is presented in another study conducted by the authors (41). Glycine was employed as a lixiviant in the dissolution experiments, and leaching tests were performed

under alkaline conditions in the presence of appropriate oxidizing conditions. The metal concentrations in the obtained leaching solution were 12,160 ppb Hg, 1292 ppb Au, 1379 ppb Ag, and 3242 ppb Cu, respectively.

Hg Removal from Pregnant Leaching Solution by Precipitation

After the amino acid leaching process, Na_2S was used as the precipitating agent to remove Hg through precipitation from the pregnant leaching solution. In order to examine the effects of process parameters under circumstances that preserve process continuity, have high operational feasibility, and don't require extra expenses, experimental conditions were created to be compatible with an alkaline glycine leaching system. An orbital shaker with a 100 mL Erlenmeyer flask and 200 rpm was used for the precipitation experiments. A calibrated pH meter was used to measure the solution's pH after it had been adjusted using diluted NaOH and/or HCl solutions. Sodium sulfide nonahydrate ($\text{Na}_2\text{S} \cdot 9\text{H}_2\text{O}$, analytical grade) was used as an inorganic precipitating reagent in the precipitation experiments. The dosage of the precipitant was determined stoichiometrically according to the starting concentration of mercury. The effects of precipitation time (15, 30, 60, 120, and 240 min), pH (10.0, 10.5, and 11.0), Na_2S :Hg molar ratio, and temperature were looked into by varying one parameter at a time where each parameter was varied individually while keeping the others constant in order to evaluate its specific effect on Hg removal efficiency. Unless otherwise specified, precipitation tests were performed under the following conditions: Na_2S : Hg molar ratio of 66, pH 10.5, stirring speed of 200 rpm, shaking time of 30 min. Following sedimentation, the purified solution was passed through a Merck cellulose nitrate membrane filter with a pore size of 0.45 μm . Cold vapor technology was used by Perkin Elmer and FIAS-100 to analyze mercury, while other metal concentrations were measured by Atomic Absorption Spectroscopy (AAS). The mercury removal efficiency (%) was calculated using Eq. (1).

$$\text{Hg Removal Efficiency (\%)} = \frac{C_i - C_f}{C_i} \quad (1)$$

Here, C_i is the initial metal concentration, and C_f is the ultimate concentration following precipitation.

FINDINGS AND DISCUSSION

The Effect of Time on Hg Removal

Precipitation tests were conducted using sodium sulfide at a constant Na_2S :Hg molar ratio of 66 in order to examine the impact of precipitation time on Hg concentration and Hg removal efficiency at various intervals of time (15-30-60-120-240 min). In other studies on mercury removal, it was stated that the appropriate Na_2S or Precipitant/Hg mass ratio is much higher than the theoretical value; this is because ions such as Au^{+2} , Ag^+ , Cu^{2+} , Zn^{2+} present together in the solution consume precipitant (7,42,43). Thus, the initial Na_2S :Hg molar ratio was chosen based on previous studies and experimental experience in removing mercury from cyanide leaching solutions; these studies typically require a large amount of sulfide to achieve high removal efficiencies. Therefore, a relatively high molar ratio was selected to ensure sufficient sulfide availability for mercury precipitation.

As shown in Fig. 1, although the removal efficiency decreased slightly after 60 minutes, Hg removal exceeded 97% within the first 60 minutes. It was found to have the greatest removal efficiency at 30 minutes, reducing the Hg concentration from 12,160 ppb to 223 ppb, corresponding to approximately 98% removal. Based on precipitation tests with sodium sulfide, it can be concluded that precipitation kinetics are rapid, and extending the reaction time beyond 30 minutes does not affect the outcome. For this reason, 30 min was selected as the optimal precipitation time to evaluate the other parameters, in terms of process rate, removal efficiency, and practical applicability.

A decrease in Hg removal efficiency with increasing time has similarly been observed in some studies. This situation has been commonly reported in cyanide systems where the stability of HgS is affected by complexation reactions and solution chemistry. For example, Won (2013) showed that HgS dissolution follows a parabolic leaching pattern and is controlled by the formation of a sulfur-rich product layer, and that precipitated HgS can become unstable over time (44). Furthermore, thermodynamic evaluations by Wang and Forssberg (1990) showed that increasing ligand-metal ratios can shift the equilibrium towards soluble complex formation, which can lead to the re-dissolution of metal sulfides (45).

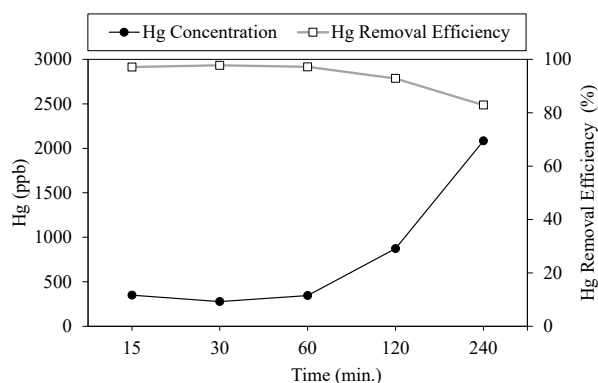


Figure 1 Changes in Hg Concentration and Efficiency of Hg Removal as a function of precipitation time

While there are no studies in the literature on Hg removal from glycine-loaded leaching solutions, there are many studies on Hg removal from cyanide leaching solutions. It has been reported that the effect of time is limited in the use of potassium amyl xanthate (41); that time is decisive in applications carried out with silver sulfide (Ag_2S) and the efficiency of removing mercury rises with time (46,47) and similarly, time is also effective to increase Hg removal in studies using TMT (trimercapto-s-triazine) (48). From this perspective, sodium sulfide used in this study is advantageous for its rapid sedimentation kinetics.

The Effect of pH on Hg Removal

Precipitation tests were conducted under efficient leaching conditions at pH 10-11, consistent with glycine leaching conditions. Test conditions were kept constant (Na_2S : Hg molar ratio of 66, precipitation time of 30 min., agitation speed of 200 rpm), and the effect of pH on Hg concentration.

In this study, the selected pH range was intentionally limited to the values used in the leaching stage in order to maintain process continuity and evaluate the effect of minor pH variations. This approach ensures that the precipitation step remains compatible with the preceding leaching conditions.

Previous studies on Hg removal from cyanide-containing systems have reported varying effects of pH depending on the reagent type and system chemistry. For example, the effectiveness of mercury removal decreased at pH values above 11 in the precipitation process using potassium amyl xanthate (PAX) (41). In Hg removal experiments using TMT (trimercapto-s-triazine), the highest outcome was gained with about 98% efficiency at pH 12, and efficiency decreased as pH decreased; Hg removal could not even be achieved at pH 10 (48). The study using Na₂S and KDDC was conducted at pH values between 8 and 10.5, and the effectiveness of mercury removal was found to increase with pH; however, the effect above 10.5 was not investigated (49). These differences can be attributed to variations in reagent chemistry, complexation behavior, and operating conditions. In addition, Prokkola et al. (2020) stated that sulfide precipitation in acidic mineral water (pH 2-4) carries the risk of H₂S gas formation and therefore the pH should be adjusted to 5.5 before precipitation (50).

The dissolution of Na₂S in water proceeds as follows: ionic dissociation, two-step hydrolysis of the S²⁻ ion, equilibrium of Na⁺, HS⁻, OH⁻ and a small amount of H₂S in solution (51-53);



The limited effect of pH within the investigated range demonstrates that Na₂S and Hg precipitation can occur efficiently under slightly alkaline conditions, compatible with the glycine leaching system, and would also be more suitable for the ongoing process after leaching. In contrast, the present study was conducted within a relatively narrow alkaline pH range (10-11), consistent with glycine leaching conditions. Therefore, the limited effect of pH observed in this study can be explained by the fact that HgS precipitation remains thermodynamically favorable and stable within this range, resulting in consistently high removal efficiency.

In addition, the selected pH range corresponds to the stability region of glycine, where its active species remain ionized (pH>9) and capable of forming stable complexes with metals such as gold (26,54). Therefore, a broader pH range was not investigated in order to preserve both glycine stability and metal speciation in the system.

As shown in Fig. 2, the precipitation test conducted using sodium sulfide showed that increasing the pH had only a limited impact on the effectiveness of removing mercury, and Hg removal approximately 97% was achieved throughout the studied pH range (Fig. 2). The selected operating pH for the precipitation process carried out after leaching was determined to be pH 10.5, regardless of the change.

Effect of Dosage on Hg Removal

The precipitation test conditions were kept constant,

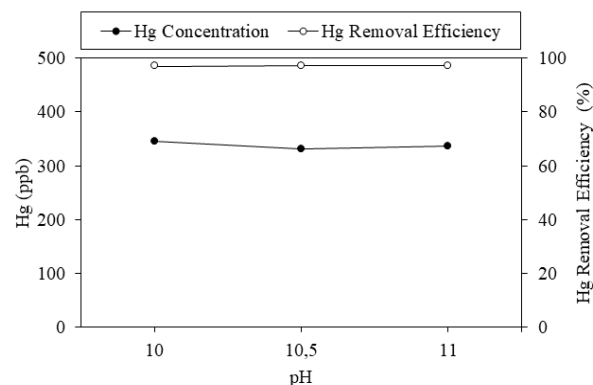


Figure 2 Changes in Hg Concentration and Efficiency of Hg removal as a function of pH

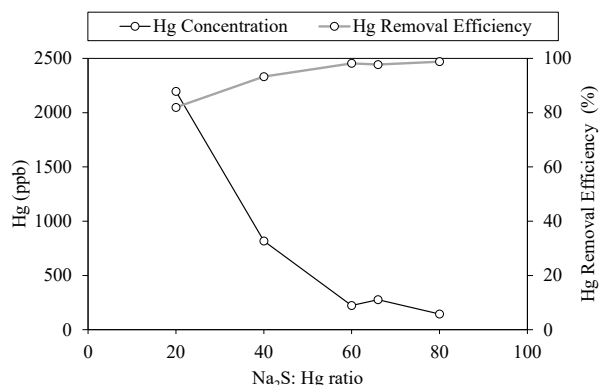


Figure 3 Changes in Hg Concentration and Efficiency of Hg removal as a function of Na₂S:Hg molar ratio

and the effect of dosage on Hg concentration and on Hg removal efficiency was investigated by varying the molar ratio of Na₂S:Hg. Previous studies on Hg in cyanide leaching solutions (7,49,55) have shown that reagent dosage is highly influential parameter; therefore, in this study, the impact on concentrations of Au, Ag, and Cu was also investigated.

The precipitation test results, performed using sodium sulfide, showed that increasing the dosage improved Hg removal efficiency, achieving approximately 99%. It was found to have the most effective removal at Na₂S:Hg molar ratio of 80, at which the concentration of mercury decreased from 12,160 ppb to 144 ppb. In addition, even at a lower dosage (Na₂S:Hg 60), the Hg concentration decreases by 98%, from 12,160 ppb to 223 ppb (Fig. 3). Even though the highest efficiency of Hg removal was attained at a Na₂S:Hg molar ratio of 80, a ratio of 60 was selected to be more appropriate as the ideal condition because it still produced high Hg removal while requiring less reagent consumption.

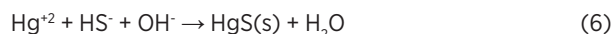
Since the glycine leach solution is alkaline, sodium sulfide can hydrolyze in aqueous solution and generate sulfide species as follows:



Under alkaline conditions, dissolved mercury can be precipitated by sulfide species through the formation of highly insoluble HgS (50):



or, considering HS^- as the dominant sulfide species:



The formation of HgS explains the rapid decrease in Hg concentration after Na_2S addition. However, when sulfide is present in excess, soluble mercury-sulfide complexes may form (56):



Therefore, the Hg removal behavior is controlled by the balance between HgS precipitation and the formation of soluble mercury-sulfide complexes under excess sulfide conditions.

Based on dosage test, the selected precipitating dosage was selected as $\text{Na}_2\text{S}:\text{Hg}$ molar ratio of 60. In the literature, when trimercapto-s-triazine (TMT) and 1,3-benzenediamidoethanetriol (BDET) are employed to remove mercury through precipitation from cyanide solutions (Na/KDTC), the Hg removal efficiency increases with increasing dosage (4,48,49,57,58). In another study, it has also been observed that, during copper removal, excessive amounts of sulfur cause precipitates in solutions to tend to re-dissolve (35,59,60). On the other hand, it has been stated that re-dissolution occurs in case of excessive use of Na_2S (58).

The effect of the $\text{Na}_2\text{S}:\text{Hg}$ molar ratio on Hg removal can be explained by the thermodynamic equilibrium between HgS precipitation and the formation of soluble mercury-sulfur complexes. At low Na_2S doses, insufficient sulfur availability limits HgS formation, leading to incomplete Hg removal. As the Na_2S dose increases, the Hg removal efficiency improves due to the high proportion of insoluble HgS formation. However, it is cautioned that at higher sulfur concentrations, this can lead to the re-dissolution of Hg , and the precipitant dose should be adjusted for each sample (49,61,62). In the presence of excess sulfur ions, the re-dissolution of mercury sulfide can occur according to the following reaction (49):

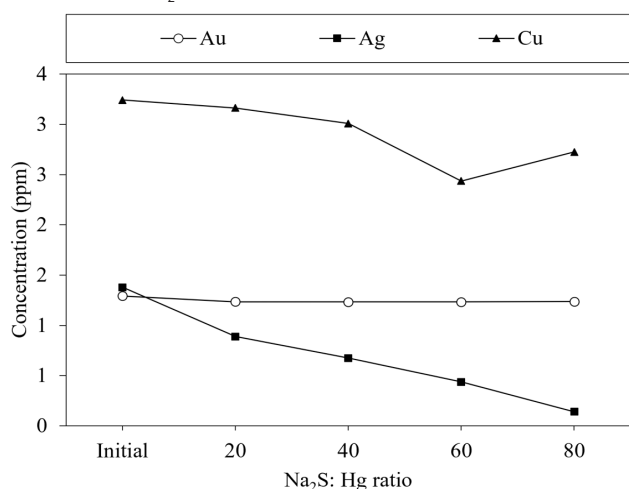


Figure 4 Changes in Concentrations of Au, Ag, and Cu as a function of $\text{Na}_2\text{S}:\text{Hg}$ molar ratio

When the concentrations of Au , Ag , and Cu were examined following precipitation tests, it was determined that the Au concentration did not change significantly when Na_2S was used; however, the Ag and Cu concentrations decreased during precipitation (Figure 4). The decrease in Cu and Ag concentrations can be attributed to the formation of their respective metal sulfides (e.g., CuS , Ag_2S), which have low solubility under alkaline conditions. This behavior is supported by thermodynamic data, indicating that Cu , Ag , and especially Hg form highly insoluble sulfides with very low solubility product constants (50), making their precipitation thermodynamically favorable. It has been reported that gold forms stable soluble complexes such as AuHS^0 and $\text{Au}(\text{HS})_2^-$ in $\text{H}_2\text{S}-\text{HS}^-$ solutions, particularly under alkaline conditions. The formation of these stable aqueous complexes prevents the precipitation of gold as a sulfide phase and maintains it in solution (63). Thus, Au remains largely unaffected due to the stability of its complexes in alkaline glycine systems, which limits its precipitation under the studied conditions. The decrease in Cu and Ag concentrations during precipitation can be explained by the fact that increasing ligand-metal ratios increase complexation, shifting the equilibrium towards soluble metal species (45). These results indicate that Na_2S is not fully selective under the studied conditions. The literature also states that Na_2S is employed in the sulfurization of lead, zinc and copper (64) and isn't selective as a result. Similarly, it is stated that silver also precipitates when CaS is used (65).

Table 1 Solubility product constants (K_{sp}) of selected metal sulfides (50)

Metal Sulfide	K_{sp}
HgS	6.31×10^{-53}
CuS	1.26×10^{-36}
Ag_2S	6.31×10^{-50}

Effect of Temperature on Hg Removal

In the precipitation test, which investigated the effect of temperature, another key parameter, on the efficiency of Hg removal, the experimental conditions were kept constant. The test results were evaluated in terms of changes in Hg concentration and Hg removal efficiency when Na_2S was used as the precipitating agent.

Regarding the effect of temperature, precipitation tests with Na_2S showed that increasing temperature did not significantly affect Hg removal efficiency, although a slight increase was observed. These results indicate that Hg can be efficiently removed at room temperature, with approximately 98% efficiency, without incurring additional heating costs (Fig. 5). In the precipitation study with PAX on a cyanide-loaded leaching solution, it was found that the removal efficiency rose with temperature (41). This finding is advantageous from a practical point of view, as it suggests that effective Hg removal can be achieved under ambient conditions without additional energy input.

The limited effect of temperature on mercury removal efficiency can be attributed to the rapid precipitation kinetics of mercury and the fact that the resulting HgS is a compound

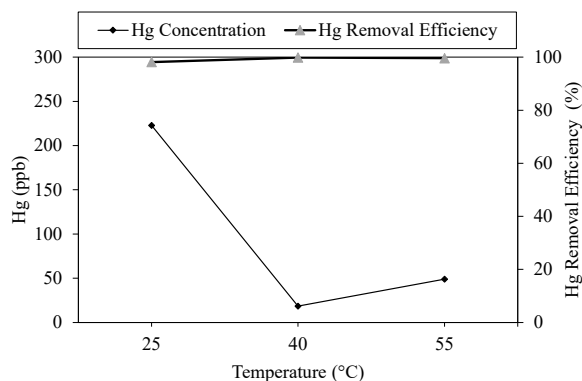


Figure 5 Changes in Hg Concentration and Efficiency of Hg removal as a function of temperature

with very low solubility and high stability (50,66). Therefore, temperature variations do not have a significant effect on solubility and thus on removal efficiency.

CONCLUSION

In this study, Hg removal from glycine leach solutions of amalgamation tailing was achieved by precipitation with sodium sulfide (Na₂S). Precipitation tests showed that Na₂S was highly effective for Hg removal. Specifically, the initial mercury concentration of 12,160 ppb was reduced to approximately 223 ppb with about 98% efficiency under the selected operating conditions, at 30-minute precipitation time, pH 10.5, and a molar ratio of 60 for Na₂S:Hg. Furthermore, the effects of other parameters on Hg removal, such as pH and temperature, were also investigated. It was determined that pH variation within the studied range did not significantly affect Hg removal efficiency, with selected operating pH of 10.5. The effect of temperature was also limited; high-efficiency Hg removal could be achieved even at room temperature. These findings indicate that the process is robust under practical operating conditions and does not require strict control of these parameters, which is advantageous in terms of operational simplicity and cost reduction.

However, when the changes in Au, Ag, and Cu concentrations during precipitation were examined, it was found that Cu and Ag concentrations decreased by precipitation, while Au concentration did not change significantly, indicating that Na₂S was not fully selective under the studied conditions. This behavior indicates that Na₂S is not fully selective under the studied conditions and highlights the importance of considering multi-metal interactions in process design. These results suggest that further optimization is required, particularly in systems where selective Au recovery is desired. In this context, evaluating more selective precipitants or developing sequential separation strategies may improve overall process performance.

Overall, this research has shown that mercury present in the solution obtained after leaching using glycine can be removed in an environmentally and economically effective, rapid, and feasible manner. The data obtained indicate that amalgamation tailings, which are particularly harmful to the environment, can be evaluated as a secondary resource

and support sustainable mining practices in the recovery of valuable metals.

This study provides a fundamental understanding of Hg behavior in glycine-based systems and one of the first reports on Hg removal from glycine leach solutions via Na₂S precipitation. The results indicate that efficient mercury removal following glycine leaching, developed as an alternative to cyanidation, may offer significant practical advantages for treating amalgamation tailings. Further studies are recommended to investigate the potential effects of the precipitation reagent on subsequent process stages, particularly gold recovery by activated carbon adsorption.

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