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Use of Alternative Lixiviants to Cyanide for Gold Recovery: Sustainable Mining Processes

Uso de Lixiviantes Alternativos al Cianuro para la recuperación de Oro: Procesos mineros Sostenibles

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Resumen

La cianuración es un método comúnmente empleado para extraer oro, ya que es eficaz, económico y adaptable a distintos tipos de mineral. Sin embargo, los peligros ambientales y de toxicidad que conlleva han fomentado la búsqueda de lixiviantes alternativos que sean más seguros, sostenibles y compatibles con normativas ambientales más estrictas. Este artículo ofrece un análisis técnico de varios reactivos que pueden sustituir al cianuro, tales como yoduro, tiourea, tiosulfato, tiocianato, glicina y productos derivados del cianato, examinando su efectividad, condiciones de operación, toxicidad, costos y viabilidad a escala industrial. Los hallazgos indican que ciertos compuestos logran recuperaciones superiores al 90% en condiciones controladas, especialmente en minerales oxidados o complejos, lo que sugiere un futuro prometedor para su uso a gran escala. Además, se discuten los desafíos técnicos asociados a cada alternativa, como la estabilidad química, regeneración de reactivos, manejo de residuos y adaptación a circuitos existentes. La selección del lixiviante óptimo depende en gran medida del tipo de mineral tratado, la infraestructura disponible y los criterios económicos y ambientales de cada operación minera. Este estudio busca contribuir a la discusión sobre minería responsable, proponiendo soluciones tecnológicas viables que equilibren eficiencia metalúrgica, seguridad operativa y sostenibilidad ambiental.

Palabras clave: Lixiviación; oro; cianuro; alternativas sostenibles; recuperación de metales.

Abstract

Cyanidation is a commonly used method for extracting gold, as it is effective and economical. However, the environmental and toxicity hazards involved have prompted the search for alternative leaching agents that are safer and more sustainable. This article provides a technical analysis of several reagents that can replace cyanide, such as iodide, thiourea, thiosulfate, thiocyanate, glycine, and cyanate derivatives, examining their effectiveness, operating conditions, toxicity, and feasibility in industry. The findings indicate that certain compounds achieve recoveries of over 90% under controlled conditions, suggesting a promising future for their use in the industry.

Keywords: Leaching; gold; cyanide; sustainable alternatives; metal recovery.

1. Introducción

Gold is a valuable metal prized for its physical and chemical characteristics, including its chemical stability, excellent conductivity, malleability, and visual beauty. These properties make it indispensable in the jewelry industry, as well as in industry and financial markets (Liu et al., 2022). In hydrometallurgy, the most common methods for its extraction include pretreatment, leaching, and purification, with cyanidation being the most widely used procedure throughout history. (Johnson, 2015).

This method involves dissolving gold using a dilute acid mixture of cyanide, which facilitates its effective extraction. However, although effective, cyanidation also poses considerable environmental risks, as misuse or improper handling of cyanide can lead to high levels of pollution in surrounding ecosystems.

Over time, technological innovations have fostered the emergence of alternative techniques that eliminate the need for cyanide, representing a significant advance toward more environmentally friendly mining. These new methodologies not only aim to reduce ecological damage but also optimize the profitability of the extraction process, reducing costs associated with hazardous waste management. (León-Cueva et al., 2024).

Today, the mining and metallurgical industry faces the challenge of implementing more responsible practices, adopting clean technologies that allow for the extraction of valuable metals without jeopardizing the health of the ecosystem or surrounding communities.

This shift toward more sustainable techniques symbolizes a growing commitment to environmental conservation and economic efficiency in the mining sector. The use of cyanide in gold extraction has been common for many years due to its effectiveness in dissolving the metal. However, the dangers of cyanide and its negative impacts on the environment have prompted research into safer alternatives. (Li et al., 2025).

Within this framework, this bibliographic review examines recent progress in the development and use of alternative lixiviants to cyanide, paying particular attention to their technical and ecological feasibility. Additionally, several reagents, such as thiosulfate, thiourea, iodide, and thiocyanate, among others, are discussed, which have demonstrated their ability to recover gold under safer and more sustainable conditions. The review covers comparative research on their efficacy, toxicity, and industrial utility, with the aim of providing a comprehensive perspective on current trends and the challenges associated with the application of these technologies in the mining industry.

2. Metodología

A systematic literature review was conducted of scientific articles published in journals recognized in databases such as ScienceDirect, Springer, and ResearchGate. The search included keywords such as gold extraction, cyanide substitutes, and environmentally friendly metal recovery. Studies that provide experimental data, recovery rates, thermodynamic analysis, and environmental studies on reagents such as thiourea, thiosulfate, glycine, iodide, thiocyanate, and other novel compounds were selected.

Cyanide in gold mining

Cyanide is more versatile and widely used due to its low cost. Gold is a noble metal and therefore insoluble in water. Cyanide is needed to dissolve it, which is especially responsible for stabilizing gold and silver. Despite its high efficiency in dissolving gold and oxygen being used as an oxidant,

cyanide is a highly toxic substance, representing a major environmental impact as well as a health problem for populations near mining areas. (Galvan Lira et al., 2023).

Therefore, the impact of cyanide on plants and organisms varies according to the absorbed dose, which as I also mentioned (Galvan Lira et al., 2023), It is highly toxic; however, in small quantities it can be transformed into a less harmful compound such as thiocyanate. When ingested, cyanide reacts with gastric acid to form hydrogen cyanide, which blocks cellular respiration and causes cell death. The estimated lethal dose is 1.5 mg of CN- per kilogram of body weight. (Gökelma et al., 2016).

Figure 1 shows the general heap leaching process, where the previously crushed ore is piled and sprayed with a sodium cyanide solution. This solution percolates through the material, dissolving any gold present. The gold-rich solution is then collected on an impermeable platform and sent to a recovery plant, where the precious metal is precipitated or adsorbed. Finally, the solution is recycled or treated for proper disposal. (Morales Bernardino, 2018).

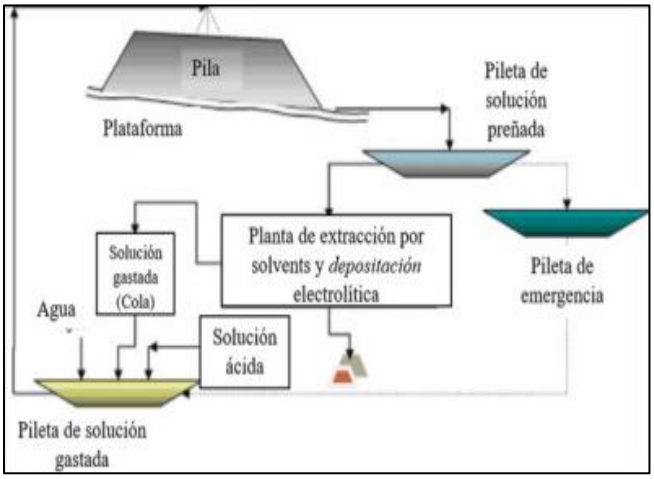

Figure 1. Cyanide leaching system for gold recovery

Documented cases of cyanide contamination

The cyanide leaching process is frequently used in the mining sector to extract gold and other valuable metals from low-grade ores. Despite the environmental and health concerns it poses, it remains a preferred alternative due to its efficiency and low cost. (Valarezo Tenesaca et al., 2024).

On the other hand, various spills worldwide demonstrate the danger of this reagent, according to (Earthworks.org., n.d.) He mentions the following:

- In Mexico (2014), five hundred thousand gallons of cyanide solution were spilled at the Magistral Project Mine, caused by heavy rains..
- In Romania (2000), a dam collapsed, spilling 3.5 million cubic feet of cyanide-laced waste into the Tisza and Danube rivers, thus causing water pollution.
- In Kyrgyzstan (1998), a truck loaded with sodium cyanide crashed into the Barskoon River, forcing a total of 2,000 people to seek urgent medical attention.
- In the United States (1982), fifty-two thousand gallons of cyanide solution were spilled, contaminating the drinking water supplied to a community. It was discovered when an employee noticed the smell of cyanide in his home's drinking water.

Alternative reagents to cyanide as gold leaching agents

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Growing interest in minimizing the environmental impacts and risks associated with the use of cyanide in gold extraction has prompted research into safer and more environmentally friendly alternative reagents. Figure 2 shows some reagents used as gold lixiviants, as well as the electrochemical conditions that promote their reaction with gold.

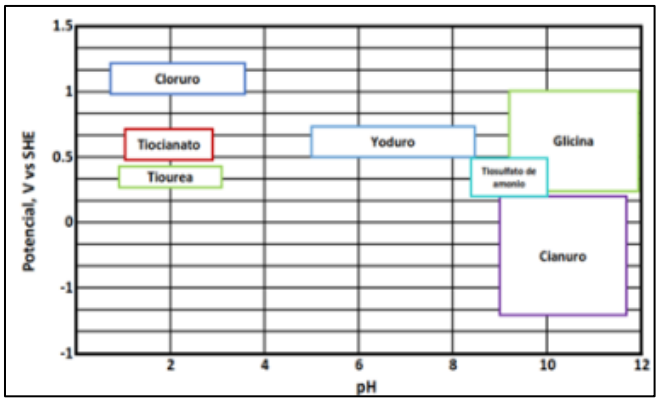

Figure 2. Potential diagram as a function of pH for potential solutions for leaching gold

In this section some of the main alternative reagents are presented and analyzed:

Iodide

This article (Galvan Lira et al., 2023) It indicates that the iodination technique offers multiple benefits such as greater operational safety, good selectivity towards precious elements such as gold and silver, and recovery levels comparable to those obtained through cyanidation.

This article, based on experimental research, applied this technique to a mineral under controlled conditions of temperature, pH, and agitation, achieving gold recovery of up to 99.92%, surpassing cyanidation, which required an alkaline pH (10-12) and longer treatment time. This result demonstrates the potential of the iodine-iodide system as an effective and more sustainable alternative, although its large-scale application still requires improvements in its economic viability.

Among the most notable alternatives for gold extraction is the iodine-iodide combination, appreciated for its effectiveness and lower environmental impact compared to cyanide. This option is presented as a viable substitute; however, its use in industry is restricted due to the high price of iodine, leading to the need to find methods to reduce its use. (Wang et al., 2020).

Thiourea

This article mentions that thiourea (NH2CSNH2) It has emerged as a promising agent for the extraction of precious metals such as gold and silver, offering an alternative with a lower environmental impact compared to traditional cyanidation. This approach has several significant advantages, such as reduced toxicity, greater selectivity toward valuable metals, rapid dissolution, and safer handling of the chemical.(Ubaldini et al., 1998)

Furthermore, it is particularly beneficial in the treatment of difficult sulfide minerals, since its acid leaching allows the mineral to be processed directly without the need for prior neutralization, unlike cyanidation which requires alkaline solutions. (Isaí Santamaría Roncancio -Robinson de Jesús Torres Gómez -Mario Parra Pinilla -César Armando Ortiz Otálora et al., 2013)

However, its use is restricted due to the need to use expensive oxidants, such as ferric ion, and the greater use of reagents compared to cyanide. In these laboratory studies, such as that of Ubaldini et al. (1998), Recoveries of up to 80% gold were achieved using optimal thiourea

concentrations, adjusting variables such as temperature, concentration and leaching time. Despite its potential, this process requires improvements in efficiency and cost reduction, in addition to the implementation of complementary techniques such as adsorption on activated carbon to optimize gold recovery. (Lin et al., 2024).

Ammonium thiosulfate

The use of ammonium thiosulfate for leaching has been the subject of extensive research as a strategy for the extraction of gold and silver, exploring elements such as its chemical mechanism, stability, thermodynamic conditions and methods for recovering the precious metal. (Aylmore & Muir, 2001). This process, which uses copper as a catalyst, offers multiple benefits compared to cyanidation, as it is less toxic, allows for faster gold dissolution, and offers better recovery rates in complex or high-carbon minerals due to the reduced involvement of other ions. Furthermore, from an economic perspective, ammonium thiosulfate may prove to be more cost-effective than cyanide. (Grosse et al., 2003).

Thiocyanate

It is considered one of the most alternative agents for obtaining gold, although its research is not yet as extensive as that of other reagents. This substance is less harmful than cyanide and has a great capacity to dissolve gold. Leaching involves thermodynamic chemical processes and different methods to recover gold from the resulting mixture. One of the main reasons why it has not been commercialized is that it requires a higher redox potential compared to leaching using cyanide, and it also uses iron ions to facilitate gold dissolution. This technique is adaptable and can be used in both heap and tank leaching processes. (Azizitorghabeh et al., 2021).

Wisteria

Glycine has emerged as an alternative to cyanide for leaching, gaining significant interest recently due to its low environmental impact, its effectiveness in dissolving metals and its high selectivity towards precious metals. (Cuesta Gregory et al., 2024). In research conducted by Altinkaya, gold leaching was analyzed in a stirred reactor using alkaline glycine solutions and applied to minerals that presented a certain resistance. Using an experimental design that modified glycine concentration and temperature for a fixed period of 24 hours, the findings showed that glycine concentration did not significantly influence efficiency, while temperature did help accelerate the leaching process, achieving an experimental extraction of 90%.(Altinkaya et al., 2020).

Current advances in alternative lixiviants and sustainable methods for gold extraction

Growing concerns about the environmental impacts of cyanide have prompted the development of safer and more efficient options for gold extraction. Below, we highlight some recent methods that focus on reagents and technologies designed to improve extraction processes, prioritize sustainability, and reduce hazards. This progress includes the development of novel reagents, the application of innovative approaches to different types of minerals, and improved development of materials that effectively restore the metal, as demonstrated by subsequent research.

Development of a reagent for gold leaching as an alternative to cyanide: Synthesis and performance evaluation

They developed a cyanide substitute for gold extraction, using materials from a sulfide concentrate containing a high percentage of gold and sulfur. This new reagent was made from sodium cyanate, sodium hydroxide, and sodium ferrocyanide, resulting in a compound with lower toxicity compared to conventional cyanide. Tests indicated that this reagent achieved effective extraction, and after pretreatment, extraction rates of up to 87.56% were obtained. Furthermore,

its effectiveness was tested on gold-coated electronic waste, where it managed to dissolve more than 90% of the metal in just a few hours. (Altinkaya et al., 2020).

Thiosulfate leaching in carbonaceous gold ores in Ethiopia

The use of thiosulfate was studied as an environmentally friendly alternative to cyanide for gold extraction from carbonaceous ores obtained from the MIDROC Legadembi open-pit mine, located in the Oromia Region of Ethiopia. In laboratory tests, thiosulfate showed a gold recovery of 91.54%, being more efficient than cyanide, which recovered 61.70%. This article highlights the technical and economic disadvantages of thiosulfate, in addition to its potentially lower environmental impact, given that the main reagents are also fertilizers used in agriculture. However, the difficulties associated with the use of thiosulfate are also highlighted, such as the high reagent requirement, surface passivation of gold, and slow kinetics at room temperature, which are influenced by factors such as pH, dissolved oxygen, and ore type. (Chaka & Rupprecht, 2024).

The use of novel modified activated carbon in thiosulfate solution: a green gold recovery technology

This article presents a novel method for obtaining gold through the alteration of activated carbon, incorporating functional groups containing nitrogen and sulfur. This system is notable for its ease, efficiency, and commitment to ecosystem conservation, presenting a cyanide-free option for the extraction of the precious metal. The activated carbon was altered using a thioglycolic acid impregnation procedure, achieving a gold adsorption capacity of up to 25.8 kg/t, which represents an important advance toward more sustainable mining and reduces dependence on cyanide. (Chen et al., 2020).

Activated carbon plays an essential role in the gold recovery process, as its high porosity makes it a highly efficient adsorption material. During the process, the previously crushed ore reacts with the cyanide solution, forming a gold cyanide complex, which is subsequently adsorbed by the activated carbon, thus enabling the extraction of the metal. Figure 3 shows the physical appearance of the activated carbon commonly used in this type of process. (Carbón Activado Para La Recuperación de Oro., 2022).

Figure 3. Activated carbon used for roro recovery

Thiourea as an environmental alternative to the use of Cyanide: computational and experimental thermochemical comparison of Leaching

The research focuses on the dissolution of acanthite using thiourea as a more environmentally friendly option compared to cyanide. Analyses and computer simulations were carried out to measure the spontaneity of the reaction and its effectiveness in obtaining silver. The experimental results indicated that, at the same concentration (5 g/L), thiourea was able to capture 3% more silver than cyanide over a 3-hour period, in addition to consuming 13.6 times less reactive substance. With 7 g/L of thiourea, almost 100% recovery of the metal was achieved.

However, the effluent produced exceeded permissible limits in terms of pH and suspended solids. (Bernaola Flores, 2018).

3. Resultados

Recent experimental findings support the potential of alternative lixiviants to replace cyanide in gold and silver leaching processes:

In the case of thiosulfate, studies conducted on carbonaceous gold ores in Ethiopia reported a maximum gold recovery of 91.54% after 48 hours of leaching, which is significantly higher than the 61.70% obtained with cyanide under the same conditions.

Thiosulfate leaching was also associated with a lower environmental impact and the potential for agricultural reuse of tailings due to the lower toxicity of its chemical compounds.

Despite these advantages, researchers identified several challenges, including:

- High thiosulfate consumption
- Passivation of the gold surface
- Slow reaction kinetics at room temperature

Regarding thiourea, both computational and experimental approaches demonstrated that:

- It can extract up to 3% more silver than cyanide when used at equal concentrations.
- It achieves complete metal removal (100%) at optimized concentrations.
- It requires significantly less lixiviant—up to 13.6 times less than cyanide.

Environmental assessments of thiourea leaching revealed that, although some effluents exceeded the allowable limits for pH and suspended solids, the overall toxic impact was lower than that of cyanide.

4. Discusión

The presented results illustrate a clear trend toward more sustainable leaching technologies in the mining industry. While cyanide remains efficient, its environmental risks and toxicity continue to drive the development of alternative systems.

Thiosulfate demonstrates strong potential for industrial gold recovery due to its high extraction rates and comparatively low environmental footprint. Its suitability for processing refractory ores adds to its appeal. Nevertheless, its widespread adoption is currently limited by technical challenges such as:

- Excessive reagent use
- Kinetic inefficiencies
- The passivation of gold surfaces

These issues necessitate further optimization, particularly to improve reaction rates and reduce operating costs under standard conditions.

On the other hand, thiourea has proven effective in the leaching of silver ores like acanthite. Its lower toxicity, reduced reagent requirements, and high recovery efficiency position it as a compelling alternative to cyanide. However, its environmental profile is not entirely benign, given the occurrence of effluent parameters exceeding regulatory thresholds. This calls for improvements in effluent treatment and process control.

Overall, the shift towards thiosulfate and thiourea reflects a broader movement in hydrometallurgy toward greener, less hazardous processes that preserve or enhance metallurgical performance. Continued research is crucial to resolve remaining limitations, particularly regarding electrochemical behavior, operational conditions, and long-term environmental impact.

5. Conclusión

Although the use of cyanide in gold mining has historically proven effective, it constitutes one of the most significant environmental risks associated with the mining industry. The numerous reported incidents of cyanide contamination, along with its detrimental impacts on ecosystems and human health, have prompted the search for safer and more sustainable extraction technologies. In this context, the analysis of alternative lixiviants becomes essential for progress toward conscious mining.

The research reviewed shows that reagents such as thiosulfate and thiourea offer considerable benefits compared to cyanide, both in terms of metallurgical efficiency and environmental impact. Thiosulfate has demonstrated high gold recovery even in refractory ores, while thiourea has been able to obtain higher percentages of silver with reduced reagent use. Furthermore, the use of modified activated carbon in cyanide-free solutions enhances metal adsorption and recovery, establishing it as a technology with significant potential.

However, the industrial implementation of these processes still faces technical challenges such as reagent stability, mineral surface passivation, and the requirement to comply with environmental limits for effluents. Despite all this, these advances represent a solid step toward greener mining and confirm that environmentally friendly technologies can be developed without sacrificing the efficiency of extracting valuable metals.

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Conflicto de Intereses: Los autores declaran que no tienen conflictos de intereses relacionados con este estudio y que todos los procedimientos seguidos cumplen con los estándares éticos establecidos por la revista. Asimismo, confirman que este trabajo es inédito y no ha sido publicado, ni parcial ni totalmente, en ninguna otra publicación.