Impacts of cyanide in gold mining and cyanide removal methodologies in liquid waste from gold processing

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ABSTRACT: Cyanide is used in several industries but is widely used for gold extraction due to its ability to complex and stabilize gold ions. The waste generated from this process is of great volume because of low ore grades that requires more processing areas. Also, it is highly toxic due to cyanide being a contaminant of animal life and the environment. The mining sector can recycle the effluents generated in their processes, however, this can affect the gold extraction and treatment methods. There are legal laws that define cyanide levels in effluents for disposal in water bodies. Methodologies for reaching these levels include oxidation degradation processes, physical-chemical, biological processes, adsorption, photocatalysis, among others. In this present review, the use of cyanide in gold mining and some of these methodologies for removing cyanide in effluents generated by gold processing are evaluated.

KEYWORDS: Biological treatment; Cyanide; Effluent treatment; Gold Ore; Mining; Oxidation


RESUMEN. Efecto del cianuro en la minería del oro y metodologías de eliminación del cianuro en los residuos líquidos del procesamiento del oro. El cianuro se utiliza en varias industrias, pero es ampliamente utilizado para la extracción de oro debido a su capacidad para estabilizar los iones de oro. Los residuos generados en este proceso son de gran volumen debido a al bajo grado del mineral que requiere más áreas de procesamiento. Además, es muy tóxico debido a que el cianuro contamina la vida animal y el medio ambiente. El sector minero puede reciclar los efluentes generados en sus procesos, sin embargo, esto puede afectar a los métodos de extracción y tratamiento del oro. Existen leyes jurídicas que definen los niveles de cianuro en los efluentes para su vertido en las masas de agua. Las metodologías para alcanzar estos niveles incluyen procesos de degradación por oxidación, físico-químicos, biológicos, adsorción, fotocatalitis, entre otros. En la presente revisión, se evalúa el uso del cianuro en la minería del oro y algunas de estas metodologías para eliminar el cianuro en los efluentes generados por el procesamiento del oro.

PALABRAS CLAVE: Cianuro; Mineral de Oro; Minería; Oxidación; Tratamiento biológico; Tratamiento de efluentes

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1. INTRODUCTION

In the 18th century, gold production started to increase around the world as it was discovered in Russia and Brazil. In 1900, gold was discovered in South Africa and the United States of America, reaching up to 650 tons of ore per year. With the development of new technologies, more countries started to produce gold, as it was reported in 1994, when South Africa was responsible for 25.4% of the production, followed by the United States of America with 14.4%, Australia with 11.2% and Russia with 7.1%. Brazil represented only 3.2% of the production in 1994. Nowadays, gold is a global business having operations spread in various countries. In 2022, China was the major producer of gold, reaching the mark of 375 tons, followed by Russia with 325 tons, Australia with 314 tons and Canada with 195 tons. Brazil was responsible for producing 87 tons (Andrade et al., 1996; WGC, 2023).

In Brazil, the mineral industry is of great importance, with metals representing about 89% of total production of the country. Among these materials, gold outstands, as it represented the second largest participation of production in Brazil in 2021, according to National Mining Agency (ANM, 2023).

Mining includes steps of research, measurement and extraction through the treatment or transformation of materials into economic and social goods. However, these processes generate tailings that affect the environment when they are disposed. Over time, the demand for minerals increased and, consequently, it was necessary to increase the volume of material in the extraction and processing. Regarding gold ore, besides the increase on market demand, over time high content reserves were exhausted and new low content reserves were discovered. Thus, there was an even higher need for larger ore mass processing to achieve the production levels required, which causes the increasing generation of tailings (Júnior, 2018; IBRAM, 2022).

Water consumption also increases with higher ore volume processing, and gold extraction and processing are processes that consume more water when compared to other minerals extraction (Chaguezac, 2018).

In this way, the need to sustainably allocate these tailings grow. Especially in Brazil, after the disasters with dams, the search for technological solutions that seek to minimize dam content or their extinction increased, such as the disposition method in piles. Dewatered tailings can be arranged in the form of thickened, filtered or paste. Fluids filtered at this stage can be reused in the ore processing plant (Alves, 2020; Costa, 2022).

Effluents containing cyanide have been growing as a problem due to the use of cyanide in different types of industry, especially gold mining companies, whose use is questioned due to the toxicity of the compound. Although alternatives to cyanide are studied, the agent continues to be widely used due to its high capacity to form stable complexes with gold (Riani et al., 2007; Alvillo-Rivera et al., 2021).

The mineral industry is one of the largest polluting sources of the environment, due to issuing a large amount of rejects that often do not receive proper treatment (Costa, 2022). Thus, it is important to develop researches on treatments for effluents that contain this compound, which can be effective and applicable to achieve a more responsible and sustainable mining scenario.

2. CYANIDE

2.1. Cyanide use in industry

Cyanide is defined by an organic molecule that has a functional group of triple-bonded carbon nitrogen (-C≡N), while inorganic cyanide is usually a salt of the anion CN-. Cyanide compounds or complexes are commonly used in mining industries in gold and silver extraction processes, but it can also be applied to other types of processes such as metal recovery of copper, zinc and lead in flotation processes, that uses cyanide as a reagent. In addition, its use is also applied in galvanoplasty industries, paints, plastics, agriculture, pharmaceuticals, food, dyes, among others, as it is illustrated in Table 1 (Botz, 2001; Kumar et al., 2017; Sharma et al., 2019).

When cyanide is in aqueous medium in its form of ion, CN-, or in the form of HCN, it is classified as free cyanide. When associated in the form of metal complexes, cyanide complexes are classified into two classes, namely: WAD (Weak Acid Dissociable), which means it is dissociable in weak acids, and SAD (Strong Acid Dissociable), those that are dissociable in strong acids. WAD complexes are usually with metals such as Cu, Ni, Zn, AG, Hg and Cd, while SAD complexes are usually with metals such as Fe, Pt, Co, Au and Pd. The species in the free or complex form are called total cyanide (Botz, 2001; Jiménez-Prieto et al., 2020).

<table>
<thead>
<tr>
<th>Industrial Application</th>
<th>Cyanide Compounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold Extraction</td>
<td>HCN, NaCN</td>
</tr>
<tr>
<td>Galvanoplasty</td>
<td>NaCN, KCN, ZnCN, CuCN, etc.</td>
</tr>
<tr>
<td>Synthetic Fibres</td>
<td>HCN, ferrocyanide, ferricyanide</td>
</tr>
<tr>
<td>Pharmaceuticals</td>
<td>Ferrocyanide, ferricyanide</td>
</tr>
<tr>
<td>Chemicals</td>
<td>HCN, KCN, thiocyanate</td>
</tr>
<tr>
<td>Agriculture</td>
<td>HCN, metal cyanide</td>
</tr>
<tr>
<td>Food</td>
<td>HCN, NaCN</td>
</tr>
</tbody>
</table>

Table 1. Cyanide Compounds and Their Industrial Application
(Adapted from Kumar et al., 2017)
It is noteworthy that when the cyanide ion is present in aqueous medium, its hydrolysis forming hydrocyanic acid (HCN), which has high vapor pressure and can generate highly toxic vapor. For this reason, processes that use cyanide should be conducted at controlled alkaline pH. The graph represented in Fig. 1 indicates this distribution of species in the system HCN/CN−, in which at pH less than 9.2, hydrocyanic acid predominates and at pH above 9.2, the dissociated form predominates (Ciminelli and Gomes, 2002).

**Figure 1.** Distribution diagram of cyanide species in an aqueous system at room temperature (adapted from Ciminelli and Gomes, 2002).

2.2. Use of cyanide in the beneficiation of gold ore

Gold production around the world has double in the last four decades, as extraction processes were developed consequently, including the hydrometallurgical process involving cyanide and other reagents such as chloride and sulfur. The extraction of gold in Brazil began with the searches for precious metals in the time of colony, being initially in the region of Minas Gerais. At this time, gold was removed from superficial deposits and alluvion, being enriched and found in the form of large particles (Gökelma et al., 2016; Júnior, 2018; ANM, 2023).

Gold occurs in nature in its elementary shape or in alloys with silver, copper and other materials, or in the form of associations with sulfide minerals, such as arsenopyrite (FeS3S), pyrite (FeS2), among others. It is these forms of gold that determine the method of extraction of the mineral (Costa, 2022).

For classification regarding leaching behavior, gold ores can be classified into complexes, free-milling, refractory or placer. Complex ores are associated with sulfides, which imply high cyanide expenditure for leaching. In the case of free-milling ore, 90% of gold can be recovered with conventional leaching. For refractory ore, it is necessary to use reagents or complex processes to achieve the recovery necessary for operational demand. Finally, the placer ores present free gold due to weathering action, so density concentrating processing methods are used to extract the gold (Costa, 2022).

In the process of extraction of gold by conventional leaching, cyanide salts such as sodium (NaCN) and potassium (KCN) are used. It occurs the formation of stable complexes of the released cyanide ion (CN−) with the gold particles. The reaction of formation of this complex, called dicyanoaurate, occurs in the presence of oxygen in an aqueous solution, as described in the equation below. This process requires excess cyanide dosage to increase gold recovery (Ciminelli and Gomes, 2002; Hou et al., 2020).

\[
2\text{Au}_{(s)} + 4\text{CN}^-_{(aq)} + \frac{1}{2}\text{O}_2_{(g)} + 2\text{H}^+_{(aq)} = 2\text{Au(CN)}_2_{(aq)} + \text{H}_2\text{O}_{(l)}
\]

After leaching, gold recovery from the pregnant solution can be done by extraction techniques such as precipitation, solvent extraction, electrowinning and adsorption. Usually, mining companies use processes that involve gold extraction by adsorption with the addition of activated carbon in the solution, processes known as carbon-in-pulp (CIP), adding carbon to the pulp after leaching; carbon-in-leach (CIL), adding carbon to the leaching process; or carbon-in-columns (CIC), using columns stuffed with carbon. After contact time, carbon is removed from the solution to desorb gold. The liquid solution that no longer contains gold is the residue of the process (Altinkaya et al., 2020).

This residue generated may contain other toxic components, which can also form strong complexes with gold, such as ferri cyanide (Fe(CN)63-) and ferrocyanide (Fe(CN)64-), due to the presence of different metals in the mineralogical composition of the ore. Cyanide consumption in leaching can reach up to 2500 g/t of processed material, which can generate effluents with high concentrations of cyanide complexes (Moura, 2005; Vicente, 2014; Chaguezac, 2018; Han et al., 2022).

Compounds containing cyanide are extremely toxic and can cause serious damage to animal life and the environment. The biggest concern about impacts is in relation to aquatic life. Thus, restricted standards were proposed for the disposal of effluents containing cyanide in several countries (Riani et al., 2007; Shin et al., 2019).

According to the federal legislation in Brazil, effluents containing cyanide cannot be discarded in a water body in concentration values above 1.0 mg·l⁻¹ of total cyanide and 0.20 mg·l⁻¹ of free cyanide (CONAMA, 2011).

Cyanide removal treatments are therefore extremely important for maintaining the life of mining companies and to maintain the water quality of the environment and animal life. For the industrial scenario, it is essential that technologies for treatment of cyanide containing are economically beneficial and environmentally friendly (Shin et al., 2019).
Golden mining effluents are commonly found in pH alkaline ranges and high concentration of salts, sulfates (SO$_4^{2-}$), iron (Fe) and other toxic metals such as mercury (Hg), chromium (Cr), zinc (Zn), copper (Cu), nickel (Ni), arsenic (As), among others, because the composition and concentration of the effluent depends on the composition present in the gold ore, which is complex (Yaraghi et al., 2020; Alvillo-Rivera et al., 2021).

In the case of Kinross, in Paracatu - Minas Gerais, because of the ore high sulfide content, between 3% and 5%, the tailings have significant sulfide concentrations, and studies were developed for desulfurization. In addition, there are gold recovery processes in the cyanide tailings, which are impacted by the cyanide content, due to its high depressor potential in the flotation of the auriferous pyrite (Brasil, 2012).

For the effluent stocked in the dam of Geominera Center Enterprises in Cuba, the presence of heavy metals such as zinc, copper, cobalt, arsenic and nickel were evidenced (Jiménez-Prieto, 2020).

In the case of La Quinta and Cepromet Minera S.A.C beneficiation plants in Peru, a characterization of their water was developed by Vuono et al. (2021). In their study it was found total cyanide and a variety of pollutants including heavy metals. Table 2 shows part of the major components found in the water and their concentration as an example of what can occur in gold plants effluents.

Within the scenario of water resources scarcity and environmental requirements, a practice that has been used in mining industries is to recycle the water within the processes, usually from dams, thickening, flowing, filtering, and other processes, returning it to the process of mining and processing. However, the characteristic of this water can be little known to understand the impacts of its application on the process and the increase in recirculation implies the increase in concentration of ions and salinity of this water, requiring additional treatments before recycling (Sampaio et al., 2018).

### 3. COMPARISON OF CYANIDE REMOVAL METHODOLOGIES

To define an effluent treatment methodology, its characteristics and compositions must first be analyzed, together with the quality required for the final product and the costs linked to the treatment operation. Primary, secondary and tertiary systems are commonly used for effluent treatment units, being the primary focused on solids removal, the secondary focused on degradation and oxidation and the tertiary related to physical-chemical operations to remove specific pollutants (Sampaio et al., 2018).

Various methods of treating effluents containing cyanide have been widely studied over the years, such as degradation by oxidative chemical processes, biological treatment, adsorption by activated carbon and resins, alkaline chlorination, oxidation with hydrogen peroxide, Inco process, ozonation, incineration, complexation and precipitation, photodegradation, among others (Riani et al., 2007; Alvillo-Rivera et al., 2021; Han et al., 2022).

When choosing the method to be used, treatment costs and impacts generated on the environment after treatment must be considered, as many cyanide removal techniques generate new products that can also be toxic (Alvillo-Rivera et al., 2021). In this study it will be shown different methodologies with different approaches to treat cyanide effluents.

#### 3.1. Hydrogen Peroxide

The treatment of effluents containing cyanide with hydrogen peroxide (H$_2$O$_2$) is based on the oxidative potential of the reagent, which causes the cyanide to degrade into cyanate (CNO$^-$), a less toxic agent, and, in an alkaline environment, the cyanate oxidizes into ammonia (NH$_3$), according to the equations below (Chaguezac, 2018).

\[
\text{CN}^- + \text{H}_2\text{O}_2 \rightarrow \text{CNO}^- + \text{H}_2\text{O} \\
\text{CNO}^- + 2\text{H}_2\text{O} \rightarrow \text{CO}_3^{2-} + \text{NH}_4^+ + \text{H}^+
\]

This reaction is optimized at pH between 9.5 and 10, but it can stabilize if the pH is in the range of 12. The use of H$_2$O$_2$ is generally applied in cases where the cyanide concentration is low, and the oxidant can remove free ions and WAD cyanide. Its dosage tends to be up to 600% greater than the stoichiometry of the oxidation reaction (Botz, 2001; Chaguezac, 2018).

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**Table 2.** Water Characterization of the Gold Processing Sites of La Quinta and Cepromet (Adapted from Vuono et al., 2021)

<table>
<thead>
<tr>
<th>COMPONENTS</th>
<th>LA QUINTA (mg L$^{-1}$)</th>
<th>CEPROMET (mg L$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Cyanide</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Copper</td>
<td>1.9</td>
<td>800</td>
</tr>
<tr>
<td>Arsenic</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Iron</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>Selenium</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Magnesium</td>
<td>0.9</td>
<td>4</td>
</tr>
<tr>
<td>Boron</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>0.04</td>
<td>5</td>
</tr>
<tr>
<td>Lead</td>
<td>0.07</td>
<td>3</td>
</tr>
<tr>
<td>Sulfur</td>
<td>130</td>
<td>140</td>
</tr>
<tr>
<td>Sulfate</td>
<td>10.5</td>
<td>10</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.15</td>
<td>2.5</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Cobalt</td>
<td>0.3</td>
<td>0.19</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.4</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Examples of use are in the studies by Kamrani et al. (2019), which used pure H₂O₂ with dosages of 0.04 to 4.78 g·L⁻¹ in a solution with 40 mg·L⁻¹ of cyanide at pH 10, indicating the need for a stoichiometric ratio of 300% and suggesting that in the presence of catalysts, such as copper, the reaction is favored. In the study by Tu et al. (2019), oxidation was achieved using 0.010 g·L⁻¹ of H₂O₂, and the pH was evaluated indicating that removal increases above pH 7 and is constant at pH 12.

Cyanide oxidation with hydrogen peroxide is catalyzed when copper is added. That occurs because of the reduction of the copper ion (Cu²⁺) to the tricyanocuprate complex (Cu(CN)₃)²⁻ in the presence of excess cyanide. However, the proportion of copper dosed must be evaluated to increase the effectiveness of cyanide degradation, since when tricyanocuprate becomes the dominant specie in the medium, the reaction is less efficient (Beattie and Polyblank, 1995).

3.2. Inco Process

The Inco Process is called after the name of the company (Inco) that first tried this solution to effluent treatment. The process is based on the use of sulfur dioxide and air in the presence of a copper catalyst, to degrade cyanide into cyanate, according to the equation below. This process is more effective for solutions containing free cyanide and WAD cyanide. However, precipitation of iron and cyanide complexes may occur due to the presence of copper. The reagent dosage in this process is above the reaction stoichiometry, reaching up to 200% (Botz, 2001).

\[
\text{CN}^- + \text{SO}_2 + \text{O}_2 + \text{H}_2\text{O} \rightarrow \text{CNO}^- + \text{H}_2\text{SO}_4
\]

A currently applied variation of the Inco Process is the use of sodium metabisulfite (Na₂S₂O₅), which provides the sulfur dioxide necessary for cyanide oxidation to occur (Botz, 2001; Hou et al., 2020).

To achieve adequate cyanide concentration levels for effluent disposal, a combination of methods can also be applied, such as using Na₂S₂O₅ with H₂O₂ pretreatment. In this reaction, sulfuric acid (H₂SO₄) is formed and must be controlled as the optimum oxidation pH is in the alkaline range (Hou et al., 2020).

According to studies by Han et al. (2022), using 2.0 g·L⁻¹ of Na₂S₂O₅ equivalent to 400% of stoichiometry, working at pH 9, it is possible to remove cyanide from effluents starting from a concentration of 136 mg·L⁻¹ to values below 5 mg·L⁻¹. With the addition of air, the process becomes faster and more efficient, reaching values close to 2 mg·L⁻¹.

3.3. Alkaline Chlorination

Alkaline chlorination consists of the degradation of cyanide by the action of chlorine and involves two steps. In the first, occurs the conversion of cyanide to cyanogen chloride (CNCl) and in the second, through hydrolysis, the conversion to cyanate occurs (Schneider et al., 2019).

\[
\begin{align*}
\text{CN}^- + \text{Cl}^+ & \rightarrow \text{CNO}^- + \text{Cl}^- \\
\text{CN}^- + \text{H}_2\text{O} + \text{ClO}^- & \rightarrow \text{CNO}^- + \text{Cl}^- + \text{2H}^+
\end{align*}
\]

The free and WAD cyanide forms can react with the chlorine gas used in this treatment method. As the name describes, alkaline chlorination reactions occur in pH ranges between 10.5 and 11.5 (Alvarez Rosario, 2017).

However, this is a less used method due to the formation of organochlorine compounds in its reaction, as cyanogen chloride can volatilize at a pH below 8. Furthermore, other oxidizing agents can be used to assist in the reaction, such as hypochlorite of sodium and calcium, which generate chloramines during the reaction, compounds that are extremely toxic to aquatic environments (Alvarez Rosario, 2017; Jiménez-Prieto et al., 2020).

According to Teixeira et al. (2013), the use of alkaline chlorination with sodium hypochlorite by itself can achieve good results of 87% of removal, but it is less effective and slower than other advanced oxidation processes, in the range of pH from 9 to 11 and concentration of cyanide of 1000 mg·L⁻¹. To analyze that, Teixeira et al. (2013) tried the use of sodium hypochlorite and hydrogen peroxide reaching a final removal of cyanide of 99.8%.

3.4. Ozonation

The use of ozone as a cyanide degrader is based on its high oxidizing capacity, being capable of transforming cyanide into cyanate, according to the equation below (Schneider et al., 2019).

\[
\text{CN}^- + \text{O}_3 \rightarrow \text{CNO}^- + \text{O}_2
\]

However, to use this method, it is interesting that the ozone is produced in the effluent treatment plant itself, which further increases the cost of this reagent due to the need to implement the production system (Schneider et al., 2019).

For the studies of Barriga-Ordonez et al. (2006), oxidation with ozone in a countercurrent bubble column can reach up to 90% of removal efficiency when dosing 1.2 mol of O₃ to each mol of CN or in higher dosages, indicating high consumption for this specific technique.

3.5. Complexation and precipitation with iron

Another way to remove cyanide complexes is to use iron ions to precipitate these contaminants. Stable iron ions are formed with cyanide, from the Prussian blue family, which have low solubility and can
be separated from the effluent. In pH ranges from 2 to 11, decomposition of W AD complexes is possible. However, this process is not very efficient for a single treatment as it cannot remove high amounts of cyanocomplexes and the reactions are slow (Riani et al., 2007; Tang et al., 2019).

\[
2\text{Fe}^{2+} + 6\text{CN}^- \rightarrow \text{Fe(CN)}_6^{4-}
\]
\[
\text{Fe}^{3+} + 6\text{CN}^- \rightarrow \text{Fe(CN)}_6^{3-}
\]

The studies of Ghosh et al. (1999) evaluated precipitation of iron cyanide in situ and in column tests and it was concluded that in neutral pH and low flow rates, concentrations of total cyanide of 0.5 mg·L\(^{-1}\) were achieved. The maximum removal efficiency was reached when dosing 10% by weight of iron, not resulting in better efficiency when increasing the dosage of iron. It was also analyzed that, when dissolved iron is in excess, coprecipitation of hydrous ferric oxide can occur.

3.6. Biological treatment

Although chemical treatments are efficient, they are not always able to fully degrade cyanide complexes that are more stable and this may require more expensive and specific equipment and reagents, in addition to the generation of secondary compounds in the reactions, which must be treated later. As a result, biological treatment has become a very attractive alternative for industries (Alvillo-Rivera et al., 2021).

This treatment is based on the use of microorganisms and enzymes that degrade cyanide into carbon dioxide (CO\(_2\)), ammonia (NH\(_3\)), among other less toxic components. The metals released in this decomposition come from weak and strong cyanide complexes and can be removed through precipitation and absorption methods by the biofilm. Enzymes can carry out hydrolytic, reductive, oxidative or substitution and transfer degradation routes, also using oxygen and considering the pH of the medium. Normally, more than one route can be used for complete treatment, and in aerobic treatments, packed bed reactors, batch reactors, biological filters, facultative lagoons and activated sludge are generally used, among others (Sharma et al., 2019; Shin et al., 2019).

In addition to being a highly effective technique, biological degradation can be accelerated and recover energy and health resources through techniques such as electro-biodegradation, anaerobic biodegradation systems and microbial fuel cells, which generate methane, energy and can produce biocompounds (Malmir et al., 2022).

3.7. Comparison between methods

The different methods of treating effluents containing cyanide involve different degradation and transformation techniques into less toxic agents, with cyanate being commonly obtained and, in some methodologies, cyanate decomposition into other agents.

In most cases, a high dosage of reagent in relation to stoichiometry is necessary to remove excess cyanide present in the effluents and balance the oxidation equation. Regarding cyanide species, some methods are more effective for free cyanide and require additional steps or combinations to remove total cyanide, while other methods can remove free and complex cyanide at the same time. Table 3 shows

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen Peroxide</td>
<td>Simple process</td>
<td>High reagent dosage</td>
</tr>
<tr>
<td></td>
<td>Nontoxic</td>
<td>High reagent cost</td>
</tr>
<tr>
<td></td>
<td>Very effective for free cyanide</td>
<td>Requires other steps to remove complexes</td>
</tr>
<tr>
<td></td>
<td>Low reagent cost</td>
<td></td>
</tr>
<tr>
<td>Inco</td>
<td>Can treat cyanide in ore pulp</td>
<td>High reagent dosage</td>
</tr>
<tr>
<td></td>
<td>Efficient for free and W AD cyanide</td>
<td>Can increase sulfate levels in the effluent</td>
</tr>
<tr>
<td></td>
<td>Precipitation of complexes may occur</td>
<td></td>
</tr>
<tr>
<td>Alkaline Chlorination</td>
<td>Oldest and most validated process</td>
<td>Can generate highly toxic compounds during the process</td>
</tr>
<tr>
<td></td>
<td>Efficient for free and W AD cyanide</td>
<td>Ozone must be produced on a gas generation plant</td>
</tr>
<tr>
<td>Ozonation</td>
<td>Effective process for free cyanide</td>
<td>High reagent cost</td>
</tr>
<tr>
<td>Complexation and Precipitation with Iron</td>
<td>Complexes formed are highly stable and insoluble</td>
<td>Depends on additional sludge separation step</td>
</tr>
<tr>
<td></td>
<td>Effective for free and complex cyanide</td>
<td>Slow reaction</td>
</tr>
<tr>
<td>Biological Treatment</td>
<td>Generates much less toxic compounds</td>
<td>The environment must be very well controlled</td>
</tr>
<tr>
<td></td>
<td>Can be accelerated and recover energy</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Comparison Between Cyanide Effluents Treatment Processes
the comparison in relation to the methods evaluated in this study.

4. CONCLUSIONS

• The use of cyanide continues to be a very common practice in the mineral industry, due to its better performance compared to other products used in gold leaching. The demand for mineral goods and the scarcity of resources means that more material is processed. Therefore, alternatives must be increasingly explored for the treatment of waste generated after processing.

• Even though the reuse of effluents in mining is carried out, including those containing cyanide, it must be closely monitored to assess the impacts of the process, suggesting forms of pre-treatment for recycling the effluents.

• In this study, several forms of treatment were explored in this work, such as oxidation with hydrogen peroxide, Inco process, alkaline chlorination, ozonization, precipitation and complexation with iron and biological treatments. Even so, there is no single methodology for treatment and the characteristics of the effluent, operational costs and availability for implementing processes in mining companies must be considered.

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