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Treatment of Gold Mining Wastewater: A Review of Current Technologies and Future Perspectives

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Abstract

Gold mining wastewater poses significant environmental risks due to its complex composition, including high concentrations of heavy metals, cyanide, sulphates, and acidic discharges. Effective treatment before release into the environment is essential to prevent long-term ecological and public health damage. This manuscript reviews the environmental impacts of gold mining wastewater and highlights current industrial-scale treatment technologies such as SAVMIN (Sulphate Removal Process), Slurry Precipitation and Recycle Reverse Osmosis (SPARRO), Biogenic Sulphide, and DESALX, which have been successfully commercialised in gold mining operations. These technologies integrate multiple separation processes for the efficient recovery of salts and over 95% of water for reuse, supporting sustainable mining practices. In addition, the study presents modern pilot-stage systems and laboratory-scale methods, particularly adsorption-based technologies, developed for the removal and recovery of precious and toxic metals from gold mine effluents. While many adsorbents have shown high removal efficiency, challenges remain in terms of adsorbent reusability, toxic sludge management, and economic feasibility. The need for integrating treatment systems that enable the simultaneous reclamation of water and recovery of gold and other valuable metals at low concentrations is emphasised as a step toward circular mine water use. The study concludes that for long-term sustainability, future gold mining wastewater treatment must address not only contaminant removal but also resource recovery, waste minimisation, and cost-effectiveness.

Keywords: *Gold mining, heavy metals, technologies, treatment, wastewater.*

1.0 Introduction

The gold mining industry is a significant contributor to the global economy, but it also generates substantial amounts of wastewater that can harm the environment and human health [1]. The extraction and processing of gold require large volumes of water, which is often released into the environment after use, containing toxic pollutants such as heavy metals and other hazardous substances. The discharge of untreated or inadequately treated gold mining wastewater can lead to severe environmental pollution, affecting aquatic life, soil quality, and human health. In particular, soil contamination occurs through the accumulation of heavy metals (such as arsenic, lead, cadmium, and mercury) and cyanide compounds, which degrade soil fertility, alter pH, reduce microbial diversity, and inhibit plant growth—ultimately rendering the land unfit for agriculture or natural regeneration. The treatment and purification of gold mining wastewater are crucial to mitigate water scarcity, reduce environmental pollution, and recover valuable metals such as gold, silver, copper, zinc, and rare earth elements, which are often present in low concentrations in mine effluents. Various methods have been employed to treat gold mining wastewater, including physical, chemical, and biological processes [2,3,4]. However, many of these methods have limitations, such as high energy consumption, high maintenance costs, and the generation of toxic sludge.

Recent research has focused on developing more efficient and cost-effective treatment technologies that can remove toxic pollutants and recover precious metals from gold mining wastewater [5.6]. This review aims to provide a comprehensive overview of the current state of gold mining wastewater treatment technologies, including commercialised, pilot-scale, and laboratory-scale methods. We will discuss the effectiveness and limitations of these technologies, as well as future perspectives for improving the treatment of gold mining wastewater and recovering valuable metals.

1.1 Effects of Gold Mining Wastewater on the Environment

Gold mining activities generate large volumes of wastewater that pose serious environmental threats if not properly treated or contained. See Figure 1 for details on the environmental impact of gold mining wastewater. Similar to the broader impacts of mining wastewater reviewed by Heliyon [7], gold mining wastewater is often characterised by elevated concentrations of heavy metals, suspended solids, cyanide, acids, and other harmful

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substances that significantly impact terrestrial and aquatic ecosystems. Gold mining wastewater frequently contains arsenic, mercury, lead, cadmium, and cyanide—all of which are highly toxic to aquatic organisms and humans [9]. These contaminants can leach into nearby rivers, streams, and groundwater, degrading water quality and making it unsafe for consumption, irrigation, or recreational use. Acidic pH levels, often resulting from acid mine drainage (AMD), further enhance the mobility and bioavailability of these pollutants, intensifying their ecological effects [13]. Gold ores often contain sulphide minerals, such as pyrite, which oxidize upon exposure to air and water, producing sulfuric acid. This acid not only lowers pH in receiving waters but also promotes the dissolution of heavy metals into the environment. AMD is persistent and can continue for decades after mine closure, causing long-term damage to water bodies and aquatic biodiversity. When gold mining effluents seep into surrounding soils, they can alter pH, reduce nutrient availability, and introduce heavy metal contamination. This affects crop growth, reduces agricultural productivity, and can lead to food safety issues due to metal uptake by edible plants. In areas where untreated wastewater is used for irrigation, either intentionally or due to lack of alternatives, the risks to human health and food security are even higher. High levels of suspended solids, metal toxicity, and cyanide can disrupt aquatic ecosystems by reducing oxygen levels, damaging gill tissues of fish, and affecting reproductive systems. Over time, this leads to loss of species diversity and collapse of food chains, especially in sensitive habitats downstream of gold mining operations. Improper management of gold mining tailings can result in leachate infiltration into groundwater. Once contaminated, aquifers are difficult to remediate, posing prolonged risks to drinking water supplies. Communities relying on shallow wells near gold mining sites are particularly vulnerable to metal poisoning and chronic health effects. The accumulation of toxic metals such as mercury and arsenic in drinking water sources can cause severe health problems, including neurological disorders, cardiovascular challenges, developmental issues in children, organ damage, and increased cancer risks. In artisanal and small-scale gold mining (ASGM) areas, the use of mercury for gold amalgamation directly contributes to mercury pollution in both aquatic and atmospheric environments [14].

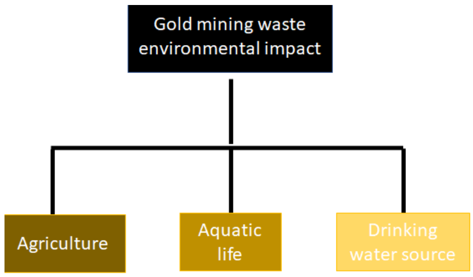

Figure 1: Environmental impacts of gold mining wastewater on agriculture, aquatic ecosystems, and drinking water sources [14].

Table 1: Reported environmental impacts of mining wastewater.

Impact Category	Description and examples	Environmental Consequences	Reference
Water Pollution	Discharge containing heavy metals (e.g., arsenic, lead, cadmium), cyanide.	Toxicity to aquatic life; water unsuitable for human/agricultural use	[8]
Acid Mine Drainage (AMD)	Sulphide oxidation produces acidic effluents, lowering pH and releasing metals › China, EU.	Fish kills, impaired ecosystems, corrosion of infrastructure	[9].
Sedimentation & Turbidity	Erosion from tailings and waste dumps increases sediment in rivers.	Habitat smothering, reduced light penetration, altered flow regimes	[10]
Acid Mine Drainage (AMD)	Sulphide oxidation produces acidic effluents, lowering pH and releasing metals › China, EU.	Fish kills, impaired ecosystems, corrosion of infrastructure	[11]
Sedimentation & Turbidity	Erosion from tailings and waste dumps increases sediment in rivers.	Habitat smothering, reduced light penetration, altered flow regimes	[11]
Heavy Metal Contamination	Metals dissolve into groundwater/surface water—Pb, Cu, Zn, Hg.	Bioaccumulation in food chains, soil/water degradation	[12]

Impact Category	Description and examples	Environmental Consequences	Reference
Biodiversity Loss	Plant/animal species decline in contaminated zones (e.g., sulphide, metal-laden areas).	Loss of aquatic and terrestrial species, reduced ecosystem resilience	[13]
Soil Erosion & Land Degradation	Removal of vegetation and land destabilization near mine sites.	Declining agricultural productivity, landscape fragmentation	[14]
Groundwater Contamination	Pollutants leaching into aquifers from mine effluents.	Long-term water quality degradation, risks to drinking water supplies	[15]

Gold mining wastewater poses significant environmental challenges, especially in regions with inadequate regulatory enforcement, as outlined in Table 1. The issue requires attention and effective management strategies. Countries such as South Africa, Ghana, Peru, and China are known to experience significant levels of illegal gold mining, both on the surface and underground, including in closed, abandoned, and even active mining sites. Artisanal and small-scale gold mining (ASGM) is of particular concern globally due to its informal nature and widespread environmental impacts. A common practice in ASGM involves the use of mercury (Hg) to extract gold from sediments and soil. Fine gold particles are amalgamated with mercury to form a solid mixture, which is later heated to vaporize the mercury and isolate the gold. This rudimentary extraction method, though inexpensive and accessible, results in significant mercury pollution of soils, water bodies, and the atmosphere. Numerous studies have reported contamination of both terrestrial and aquatic ecosystems due to mercury used in ASGM. For instance, Niane et al [25]. documented high concentrations of mercury (Hg) and methylmercury (MeHg) in soils, rivers, and water ponds surrounding mining sites in the Kedougou region of Senegal. Similarly, Achina-Obeng and Aram assessed the environmental effects of ASGM in Ghana, where samples collected from the Offin River and nearby abandoned mine sites revealed that pH, turbidity, conductivity, and the concentrations of arsenic (As), lead (Pb), and cadmium (Cd) exceeded WHO permissible limits. Table 2 shows WHO permissible limits for selected water quality parameters. Elevated levels of other metals such as manganese (Mn), copper (Cu), mercury (Hg), and iron (Fe) further rendered the water unsafe for domestic or agricultural use and made the soil unsuitable for farming. Interviews conducted with illegal miners revealed that while they are aware of the environmental hazards associated with their activities, many continue due to unemployment, lack of alternative livelihoods, and political interference. As a way forward, respondents suggested inclusive stakeholder engagement and policy development that includes financial support, technical training, and access to cleaner technologies [4]. In contrast, legal gold mining operations have made progress in reducing the environmental footprint of their wastewater. These efforts include treating mining sludge and wastewater, recycling treated effluents for ore recovery, and adhering strictly to regulated discharge limits to protect surrounding ecosystems.

Table 2: WHO permissible limits for selected water quality parameters

Parameter	WHO Permissible Limit	Unit	Remarks
pH	6.5 – 8.5	-	Acceptable range for palatability and safety
Turbidity	≤ 5	NTU	Preferably <1 NTU for effective disinfection
Electrical Conductivity	≤ 1500	µS/cm	Not a health concern but indicates salinity
Arsenic (As)	≤ 0.01	mg/L	Carcinogenic at higher levels
Lead (Pb)	≤ 0.01	mg/L	Neurotoxic, especially in children
Cadmium (Cd)	≤ 0.003	mg/L	Toxic to kidneys and bones

2.0 Treatment of Gold Mining Wastewater using Industrial-Scale Technologies

While numerous treatment methods for gold mining wastewater have been developed and tested at the laboratory scale, their transition to industrial-scale application remains limited. Many laboratory-based technologies, despite demonstrating high removal efficiencies, often face challenges related to scalability, high operational costs, and the generation of secondary pollutants that may be toxic or unsuitable for reuse [16]. These limitations reduce their environmental and economic viability for large-scale implementation [12, 15]. In contrast, this section highlights treatment technologies that have been successfully deployed at operational gold mining sites. These industrial-scale systems have demonstrated effectiveness, reliability, and cost-efficiency in managing the complex contaminants typically found in gold mining effluents, such as cyanide, heavy metals, and suspended solids [16]. Their real-world application underscores their suitability for sustainable and compliant gold mining wastewater management.

2.1. SAVMIN technology

Mintek, South Africa, developed the SAVMIN process specifically to address the challenges of treating acidic and metal-laden wastewater from mining activities, including gold mining operations as shown in Figure 2. The technology was successfully demonstrated through pilot-scale implementations at various sites across South Africa, notably at the Witwatersrand gold fields [17,18]. These demonstrations confirmed the system's effectiveness in treating different types of mine wastewater—including that from gold, coal, platinum, and base metal mines—at a treatment capacity of approximately 4 m³ per hour.

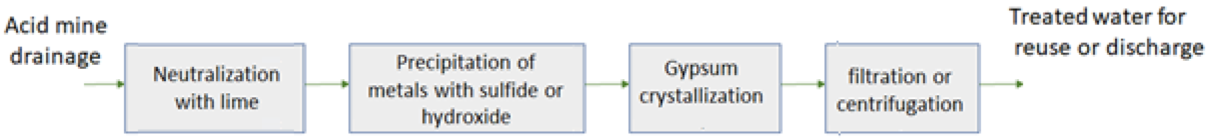

Figure 2: Flowchart for SAVMIN process [18].

The SAVMIN process is a multi-stage chemical treatment system designed to neutralize acidity, remove heavy metals, and reduce sulphate concentrations in gold mining wastewater. In the initial stage, acidic wastewater (typically pH 3–4) is treated with lime in a reaction tank to increase the pH above 10, resulting in the precipitation of metals as metal hydroxides. During this stage, gypsum (calcium sulphate dihydrate) also forms and begins to settle. A thickener is then used to separate the precipitated solids, which can either be disposed of or further processed for metal recovery. The partially treated effluent moves into a second stage, where additional lime is added to increase the saturation of gypsum in solution, further promoting gypsum precipitation. This gypsum may be collected as a usable by-product or discarded. In the third and final stage, aluminium hydroxide is dosed into the gypsum-rich solution to further raise the pH [19, 20]. This step leads to the formation of ettringite—a stable calcium-aluminium sulphate compound—which helps in the removal of residual calcium and sulphate ions from the solution. The overall result is a significant reduction in acidity, heavy metal concentrations, and sulphate content.

2.2 SPARRO technology

The Slurry Precipitation and Recycle Reverse Osmosis (SPARRO) process is a patented membrane-based desalination technique designed for the treatment of mining wastewater characterised by high concentrations of calcium and sulphate—common constituents in gold mining effluents as shown in Figure 3. This technology integrates seeded precipitation with reverse osmosis (RO) to address scaling challenges and improve water recovery efficiency. It was successfully demonstrated at a pilot scale using wastewater from the East Rand Proprietary Mines (ERPM) Hercules Shaft in South Africa. In the SPARRO process, the gold mining wastewater undergoes chemical conditioning by adjusting the pH with lime or caustic soda, followed by the addition of gypsum seed crystals [20, 21, 23]. These crystals promote the precipitation of scaling compounds like silica and calcium sulphate before the water reaches the RO membranes. This seeded precipitation step ensures that scale forms on the seed crystals rather than fouling the membrane surfaces. To optimise membrane performance, all precipitates are retained in a slurry suspension tank. A cyclone separator is then employed to isolate the crystal slurry from the treated solution. The separated gypsum crystals are recycled back into the feed stream to maintain a continuous cycle of precipitation and reuse [21]. This enhances the overall recovery rate of the RO system and minimises brine volume, thus reducing waste disposal requirements. SPARRO was specifically developed to lower the high operational costs typically associated with gold mining wastewater treatment. Its energy efficiency, effective control of calcium sulphate seed and brine mass balance, and ability to recycle treatment chemicals make it a promising option for industrial-scale application [22]. The system is particularly suited for treating large volumes of gold mining wastewater while achieving high water recovery and minimising environmental impact.

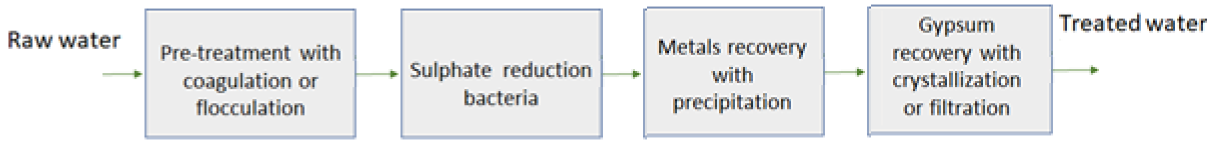

Figure 3: SPARRO technology schematic diagram [19].

2.3 Biogenic sulphide technology

BioteQ Environmental Technologies (BQE Water), a Canadian company, has developed an innovative biogenic sulphide technology that not only treats gold mining wastewater but also focuses on the recovery of valuable metals, particularly in sites where copper contamination complicates gold extraction. This dual-purpose system has been successfully applied at several gold mining sites, including the Lluvia de Oro gold mine in Sonora, Mexico [22].

In many gold mines, especially those with copper-rich ore bodies, cyanide leaching from gold extraction becomes inefficient due to the dissolution of copper, which consumes large amounts of cyanide. This raises operational costs and introduces additional environmental risks. Biogenic sulphide technology works by selectively removing copper from cyanide solutions, allowing the cyanide to be regenerated and reused in gold leaching, which in turn reduces overall cyanide consumption, lowers treatment costs, and minimises ecological damage [23]. At the core of the system is an adaptation of the Sulphidization-Acidification-Recycle-Thickening (SART) process, originally developed by SGS Lakefield and TeckCominco Ltd. However, instead of using chemical sulphides like sodium hydrosulphide (NaHS), this approach utilizes biogenic hydrogen sulphide (H_2S), a low-cost alternative produced biologically by sulfur-reducing bacteria.

The process consists of two main stages:

i. Biological Stage:
Elemental sulfur is metabolized by anaerobic bacteria (typically *Desulfobacter* spp.) in the presence of a carbon source such as acetic acid. This reaction occurs in a bioreactor, producing biogenic H_2S gas [35].

ii. Chemical Stage:
The H_2S gas is transferred into a gas-liquid contactor tank containing copper-laden gold mining wastewater. In this stage, metals such as copper, zinc, and others are selectively precipitated as metal sulphides. The precipitates are then separated through filtration or clarification. The treated effluent—now low in metals and cyanide—is either recycled for use in the leaching circuit or safely discharged to the environment [36].

2.4 DESALX technology

Clean TeQ Water Company has developed a zero liquid discharge (ZLD) water treatment technology known as DESALX as shown Figure 4, which has been successfully implemented at a gold mining site in Victoria, Australia to address the challenge of excess underground water generated during mining operations. The primary goal of this system was to treat gold mining wastewater to a quality suitable for aquifer re-injection, thereby preventing environmental contamination and promoting sustainable water management [23].

Gold mining wastewater from the site contained elevated concentrations of arsenic (As), magnesium (Mg), antimony (Sb), calcium (Ca), and sulphate (SO_4^{2-})—all of which require removal prior to safe discharge or reuse as illustrated in Figure 4. Before entering the DESALX® unit, the feedwater undergoes pre-treatment to reduce toxic elements such as Sb and As through chemical precipitation, minimising their concentrations in the system. The core DESALX process utilizes a two-stage continuous ion exchange system, optimized for the selective removal of cations and anions responsible for water hardness and salinity. In the adsorption column, the resins capture metal cations (e.g., Ca^{2+}, Mg^{2+}) and anions (e.g., SO_4^{2-}) from the gold mine wastewater [25]. These resins are then transferred in a counter-current flow through a wash column and into a desorption column, where they are regenerated using acid for cation exchange and lime for anion exchange [26].

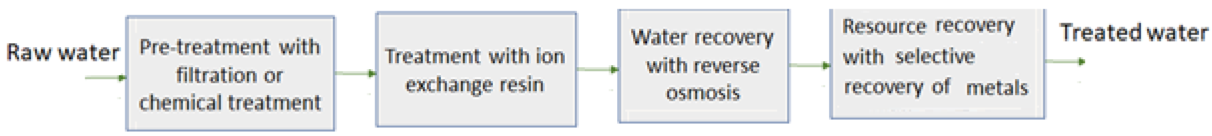

Figure 4: The Clean TeQ Water company (DESALX®) process.

Once regenerated, the resins are cycled back to the adsorption column to repeat the process, ensuring high system efficiency and operational continuity. While the system effectively removes heavy metals and sulphate, sodium and chloride ions are not captured, avoiding the accumulation of saline brine and reducing the need for further desalination.

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The DESALX system is designed to operate under variable flow conditions, handling feedwater rates ranging from 20 to 80 m^3/h, and maintains over 90% water recovery. Its automated control system ensures stable performance across fluctuating influent compositions, making it ideal for the dynamic conditions typical of gold mining wastewater [27].

This case demonstrates how advanced Zero Liquid Discharge (ZLD) systems like DESALX can provide robust, sustainable, and cost-effective solutions for treating complex gold mining effluents while minimising environmental risks and maximizing water reuse.

3.0 Overview and Critical Analysis of Industrial-Scale Technologies

Several advanced treatment technologies discussed earlier have been effectively deployed for the removal or recovery of these contaminants, particularly Cu, Pt, As, Sb, Au, Mg, Ca, and sulphate. The emphasis on gold (Au) stems from its central economic importance in natural currency systems and international markets, while platinum (Pt), as a valuable Platinum Group Metals (PGMs), adds strategic value in recovery processes. PGMs include Pt, Pd, Rh, Ru, Ir, and Os. Hazardous elements like As and Sb are included due to their high toxicity and carcinogenicity; Sb, for example, has been found to bioaccumulate in fish tissues [28].

The SAVMIN technology, deployed in the Witwatersrand gold fields of South Africa, has shown strong performance in removing contaminants and recovering valuable metals such as Au and Pt from gold mine effluent. As a chemical precipitation method, SAVMIN efficiently eliminates high sulphate concentrations commonly associated with gold ore processing, while also reducing heavy metal loads. The technology is praised for its operational safety, simplicity, and ability to use relatively low-cost reagents. However, its limitation lies in the generation of large volumes of toxic sludge due to the extensive use of chemicals. Nevertheless, gold mines—often discharging effluents rich in sulphates and metals—are ideal candidates for this technology.

Similarly, the SPARRO technology integrates a two-step process involving chemical precipitation (for pre-treatment) and reverse osmosis (RO) (for polishing). This dual approach minimises membrane fouling and extends the membrane lifespan while producing high-quality permeate. SPARRO is particularly effective in treating gold mining wastewater with elevated levels of calcium and sulphate and is also adaptable for heavy metal removal in pump-and-treat remediation scenarios. The chemical precipitation step facilitates the conversion of soluble metals into insoluble forms that are easily filtered, and the final RO step ensures potable water quality.

Biogenic sulphide technology, developed by BQE Water, offers a hybrid biological-chemical method that not only treats wastewater but also enables the recovery of valuable metals, particularly from cyanide-rich effluents in gold mines. This system has been implemented at the Lluvia de-Oro gold mine in Mexico to selectively remove copper from cyanide solutions, thus regenerating cyanide for reuse in gold leaching processes. By reducing cyanide consumption, the technology significantly mitigates environmental risks. Instead of using synthetic sulphide, this process generates low-cost biogenic hydrogen sulphide via sulfur-reducing bacteria in an anaerobic bioreactor, making it more sustainable. The treated water can either be safely discharged or recycled, depending on site needs [29].

The DESALX system, developed by Clean TeQ Water, represents an advanced Zero Liquid Discharge (ZLD) solution that has been successfully deployed at a gold mine in Victoria, Australia. It targets contaminants such as As, Sb, Mg, Ca, and sulphate—common constituents in gold mining wastewater. DESALX® operates through multiple stages: pre-treatment via precipitation to reduce Sb and As levels, followed by ion exchange for removing hardness and sulphates. The process ensures that water is purified to levels suitable for aquifer re-injection or reuse within mining operations, while also recovering salts and minimising environmental impact. Despite its high cost, DESALX offers robust, consistent performance across varying wastewater compositions and is among the most comprehensive treatment options currently available for the gold mining sector.

4.0 Treatment of Gold Mining Wastewater using Pilot-Scale Methods

The application of pilot-scale treatment methods for gold mining wastewater remains relatively limited in the literature. However, the transition from laboratory-scale techniques to pilot-scale systems offers valuable opportunities for bridging research and practical implementation in the mining sector [36]. Developing and operating pilot plants based on promising lab-scale technologies provides critical insights into the design parameters required for full-scale deployment, and allows for the economic assessment of treatment processes, including operational costs, maintenance needs, and energy efficiency [37].

Pilot plants also enable researchers and engineers to gather performance data under realistic environmental conditions, facilitating continuous process optimization and validating the feasibility of emerging treatment methods. Moreover, these setups offer a controlled platform for testing alternative or hybrid technologies—especially for treating complex mixtures of heavy metals, cyanide, arsenic, and sulphate that are prevalent in gold mine effluents [31].

This section reviews selected pilot-stage treatment systems documented in the literature, with a focus on their application to pollutants commonly found in gold mining wastewater, such as mercury (Hg), arsenic (As), cyanide

(CN^-), and sulphate (SO_4^{2-}). These pilot trials serve as important precursors to scaling up sustainable, efficient, and regulatory-compliant wastewater treatment solutions in gold mining operations.

4.1 Granular ferric oxyhydroxide (CFH-12)

Coagulation techniques have been widely used in conventional water treatment, but their application in gold mining wastewater treatment is limited. A notable pilot-scale study by Zhang et al. focused on the removal of vanadium from mining effluent at the closed Mustavaara mine in Finland using granular ferric oxyhydroxide (CFH-12). Although the case involved vanadium, the method is relevant to gold mining effluents where similar metal contaminants (e.g., arsenic, iron) are present. Two pilot filter systems were tested: Pilot A (51 days) and Pilot B (127 days), with varying influent vanadium concentrations. Both systems demonstrated effective removal of metals without full saturation of the CFH-12 media [37]. The sorbent also captured organic matter, as evidenced by increased carbon content. As shown in Table 3, the CFH-12-based method achieves high gold purity (>95%), effectively removes arsenic and antimony, and offers operational simplicity, sorbent stability, low maintenance, and potential reusability—features desirable for application in treating gold mine wastewater [38].

Table 3: Comparative analysis of selected gold mining wastewater treatment technologies

S/N	Treatment System	Gold Purity Achieved	Metals Removed / Present	Techniques Adopted	Similarities	Differences
1	Granular Ferric Oxyhydroxide (CFH-12)	High (>95%)	Arsenic (As), Antimony (Sb), potentially other metalloids	Adsorption	Removes toxic metalloids; operates at low pH	Selective for metalloids; limited capacity for bulk metals
2	Microfiltration /Ultrafiltration –Reverse Osmosis	High (>98%)	Heavy metals (Pb, Cd, Zn), sulphates, cyanide	Membrane filtration (MF/UF), RO	Efficient in water purification; suitable for water reuse	High energy cost; sensitive to fouling; requires pre-treatment
3	Sedimentation Tank + Cocopeat Filter Bed	Moderate (80–90%)	Suspended solids, Pb, Fe, Mn, some organics	Physical settling and biofiltration using natural media	Low-cost, eco-friendly; suitable for rural/mining communities	Lower purification efficiency; limited effectiveness for dissolved heavy metals
4	Adsorption and Constructed Wetlands	Moderate to High (85–95%)	Cd, Zn, Cu, Pb, As, organic contaminants	Biosorption, microbial remediation, phytoremediation	Nature-based; supports ecological restoration	Slow treatment rate; climate-sensitive performance

A hybrid treatment system combining CFH-12 for metalloids, membrane processes for high purity and water reuse, and constructed wetlands for ecological restoration could offer an optimal solution, with pre-treatment such as sedimentation incorporated before membrane systems to reduce fouling, and further improvement could be achieved through enhancements to the Cocopeat Filter Bed System by combining it with granular activated carbon or biochar to enhance adsorption capacity, introducing a pre-treatment oxidation step to convert dissolved metals into filterable particulates, and monitoring pH to ensure optimal adsorption performance.

4.2 Microfiltration/ultrafiltration-reverse osmosis

Grossi et al. assessed a membrane-based treatment system for gold mine effluent collected from the blasting stage in Minas Gerais, Brazil. The setup integrated microfiltration/ultrafiltration (MF/UF) as pretreatment and reverse osmosis (RO) as a polishing step. Unlike other technologies that rely on chemical precipitation (e.g., SPARRO®), this approach aimed to reduce membrane fouling and improve RO performance. The MF/UF-RO system operated steadily at 6 bar and achieved a water recovery fraction of approximately 80%. After pH and nitrogen level adjustments, the treated effluent met reuse standards for industrial operations. This membrane configuration is promising for gold mining wastewater due to its efficiency in removing dissolved contaminants like ammonia and cyanide while minimising chemical usage.

4.3 Sedimentation tank and Cocopeat filter bed

Amaniego and Tanchuling piloted a simple but effective treatment system using sedimentation and a Cocopeat filter bed to treat gold mining wastewater from an artisanal site in Paracale, Philippines. The wastewater contained elevated concentrations of Cd, Pb, As, Ba, and Hg, alongside physico-chemical stressors. Operating over 50 days at 40 L/h, sedimentation alone removed significant portions of metals: 74.24% (Cd), 98.82% (Pb), 97.11% (As), 39.75% (Ba), and 97.02% (Hg). The Cocopeat bed further polished the effluent, reducing these contaminants to within national Class C water standards. Heavy metals accumulated in the top 25 cm of the filter bed, which remained unsaturated, highlighting its adsorption potential. This low-cost, natural approach is particularly suited for decentralized gold mining operations.

4.4 Adsorption and constructed wetlands

In another pilot study relevant to gold mining wastewater, Nguyen et al. developed an integrated treatment system using natural adsorption and constructed wetlands to remediate wastewater containing As, Cd, Zn, Mn, and Pb from the Pb–Zn Cho Don mine in Vietnam. Though not a gold mine, the target pollutants are often found in gold mining effluent. The setup included a settling tank, an adsorbent tank filled with modified iron-ore sludge, and a series of constructed wetlands planted with Phragmites australis. Removal efficiencies were substantial—As (up to 89.9%), Cd (93.3%), Zn (80.1%), Mn (99.5%), and Pb (66.7%)—depending on substrate type (laterite or limestone). This modular, eco-based treatment strategy shows promise for treating gold mine wastewater, especially in regions with low resources and high environmental vulnerability.

5.0 Treatment of Gold Mining Wastewater using Laboratory-Scale Methods

Extensive laboratory-scale research has been conducted to develop novel materials for the removal and recovery of both precious and toxic metals from gold mining wastewater. Among the many treatment approaches explored, adsorption has gained significant attention due to its versatility, efficiency, and potential for low-cost application. In the adsorption process, pollutants in wastewater—including heavy metals and residual cyanide—adhere to the surface of solid adsorbents through mechanisms such as physisorption, chemisorption, and biosorption [33].

Physisorption is governed by weak interactions such as van der Waals forces, hydrogen bonding, polarity, and dipole–dipole interactions [34]. It allows for multilayer adsorption and offers advantages such as reversibility, high adsorption capacity, and ease of regeneration [35]. In contrast, chemisorption involves stronger chemical bonds or electron exchange between the adsorbate and the surface of the adsorbent, resulting in monolayer adsorption that is often irreversible, limiting adsorbent reusability [36].

Biosorption represents an environmentally friendly and cost-effective alternative, particularly relevant to gold mining wastewater treatment in artisanal and small-scale mining regions. It involves the binding of metal ions onto functional groups present on the surface of biomass-derived materials, such as agricultural or industrial waste [37]. Mechanisms underlying biosorption include ion exchange, absorption, complexation, and precipitation [38].

The efficiency of adsorption processes in treating gold mine effluents depends significantly on the characteristics of the adsorbent. Ideal properties include high porosity (and thus large surface area), strong selectivity for target pollutants, abundant active sites, fast adsorption kinetics, and chemical and thermal stability [82]. Operational parameters—such as solution pH, contact time, adsorbent dosage, and temperature—also influence adsorption performance [39].

Various materials have been investigated for their suitability in removing contaminants from gold mining wastewater, including natural materials, biosorbents, agricultural residues, industrial waste byproducts, and synthetic sorbents [40]. Overall, physical, biological, and physico-chemical adsorption processes are often preferred over purely chemical treatments due to their lower environmental impact, reusability, and adaptability to decentralized wastewater treatment scenarios [41].

5.1 Recovery of precious metals in gold mining wastewater

The demand for precious metals such as gold (Au), silver (Ag), platinum (Pt), palladium (Pd), rhodium (Rh), and iridium (Ir) has significantly increased in recent decades due to their critical applications across medical, technological, and industrial sectors. These metals are highly valued for their exceptional electrical and thermal conductivity, catalytic properties, chemical stability, and resistance to corrosion. For instance, gold and silver are widely used in microelectronics for components like bonding wires and connectors, while platinum group metals such as Pt and Pd are integral in catalytic converters and medical devices [42]. Gold, in particular, is also applied in medical treatments, such as managing rheumatoid arthritis, due to its anti-inflammatory properties [43], and silver's well-established antimicrobial activity continues to be exploited in wound care and infection control [41].

5.2 Removal of toxic metals in gold mining wastewater

Gold mining activities are known to release substantial quantities of toxic metals into surrounding environments through processes such as ore extraction, cyanidation, tailings discharge, and wastewater disposal. These activities result in the mobilization of heavy metals such as lead (Pb), mercury (Hg), arsenic (As), copper (Cu), nickel (Ni), and cadmium (Cd), many of which are persistent, non-biodegradable, and highly toxic to both aquatic and terrestrial ecosystems. In gold mining regions, these contaminants often originate from effluents and tailings ponds, particularly in artisanal and small-scale gold mining (ASGM) where the use of mercury for gold amalgamation remains widespread [36].

Table 1 provide an overview of the environmental impacts associated with toxic metal release from gold mining operations. While several industrial- and pilot-scale technologies discussed in Sections 3 and 4 effectively address major contaminants like sulphates, copper, antimony, and arsenic, other pollutants such as chromium (Cr), nickel (Ni), iron (Fe), and nitrate remain underrepresented in current large-scale treatment applications.

At the laboratory scale, the adsorption method continues to be the most extensively studied approach for removing toxic metals from gold mining wastewater. This is largely due to its simplicity, operational flexibility, broad range of adsorbents, low energy requirement, and cost-effectiveness [35]. However, like chemical and biological precipitation, adsorption also produces toxic sludge, and the regeneration of exhausted adsorbents often demands substantial energy input, making it economically and technically challenging. Despite these drawbacks, the versatility and efficiency of adsorption techniques have sustained growing interest among researchers, especially for the removal of As, Hg, and Sb, which are frequently reported in gold mining wastewater due to the ore's geochemical composition and the reagents used during gold extraction.

Notably, arsenic removal has attracted particular attention due to its extreme toxicity and carcinogenic potential. Several advanced and eco-friendly materials have been explored for this purpose, including bio-adsorbents such as palm oil fuel ash (POFA) and chitosan; submerged aquatic plants like *Egeria densa*, *Hydrilla verticillata*, and *Cabomba piauhyensis*; and metal–organic frameworks (MOFs) enhanced with iron nanoparticles (Fe NPs). Among these, Fe NPs have gained significant interest due to their large surface area, strong magnetic properties, abundant active sites, and high affinity for arsenic binding. Modified sorbents, such as Fe-NP-loaded chitosan beads and ZIF-8 MOF composites, have demonstrated exceptional performance in removing as from simulated gold mine effluents.

In conclusion, while adsorption-based technologies are promising for gold mining wastewater remediation, particularly in the removal of high-risk toxic metals, further optimization is required to improve their economic feasibility, regeneration efficiency, and scalability for field deployment [36, 37].

5.3 Overview and critical analysis of laboratory-scale technologies

Laboratory-scale studies have explored a wide range of bio-based adsorbents for the removal of toxic and heavy metals from gold mining wastewater. These materials are popular due to their low cost, availability, reusability, eco-friendliness, and potential for valorizing agricultural and industrial waste. Their surface functional groups play a vital role in facilitating the adsorption of toxic metals such as arsenic (As), mercury (Hg), cadmium (Cd), and lead (Pb), which are commonly found in gold mine effluents.

For example, palm oil fuel ash (POFA), an abundant agro-industrial byproduct, contains polar siloxane (Si–O–Si) and silanol (Si–OH) groups that react with metal ions to form stable metal hydroxide complexes [40]. Moringa oleifera seeds, traditionally known for their natural coagulation properties, contain amino and carboxylate functional groups that facilitate metal removal through charge neutralization and ion adsorption. These natural coagulants are especially valuable in regions engaged in artisanal and small-scale gold mining (ASGM), where low-cost and accessible treatment options are critical.

Chitosan, derived from crustacean shells, is another widely studied biopolymer with exceptional adsorption capabilities for gold mining contaminants. Its hydroxyl and amine groups allow for effective metal ion removal through mechanisms such as chelation, hydrogen bonding, and electrostatic attraction [39]. Moreover, carbon-rich materials—including biochar, activated carbon, and graphene oxide—have shown strong performance in capturing a broad spectrum of metals and cyanide compounds present in gold mine tailings and effluents [41, 42, 43].

While these bio-based technologies show promising results at both laboratory and pilot scales, scaling up their application to industrial gold mining operations presents notable challenges. These include issues related to insufficient material availability, variability in adsorbent performance, and process integration at larger volumes. Furthermore, the potential saturation and regeneration limitations of these materials must be addressed for real-world implementation.

Despite these challenges, the use of natural sorbents offers a sustainable and cost-effective approach to mitigating the environmental impacts of gold mining wastewater—particularly in low-resource and high-impact zones where toxicity, community health risks, and ecosystem disruption remain pressing concerns [44].

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6.0 Overview and Future Perspectives

This review has highlighted the significant environmental and ecological risks posed by gold mining wastewater, emphasizing its detrimental effects on aquatic ecosystems, soil health, agricultural productivity, and public health. Gold mining effluents—especially from artisanal, small-scale, and industrial operations—contain a complex mixture of toxic and precious metals (e.g., Hg, As, Pb, Sb, Cu, Cd), cyanide compounds, sulphates, and acidic discharges, all of which contribute to long-term environmental degradation if not properly treated prior to discharge.

The current treatment technologies applied at industrial gold mining sites, such as SAVMIN, SPARRO, biogenic sulphide technology, and DESALX, have demonstrated success in large-scale applications, particularly in the removal and recovery of gold, copper, arsenic, sulphate, and antimony. These systems have shown potential in improving water quality and promoting resource recovery, especially when integrated into circular economy frameworks. However, operational data related to energy consumption, cost-effectiveness, sludge handling, and long-term sustainability remain limited, with only the MF/UF–RO membrane system providing partial insights into recovery efficiency and cost [44].

Pilot-scale treatment systems for gold mining wastewater—such as constructed wetlands, microfiltration-reverse osmosis, and Cocopeat adsorption columns—have also been explored. While promising, these require further optimization, upscaling, and field validation, particularly in ASGM regions, where environmental compliance and access to advanced technologies are minimal [45].

Laboratory-scale investigations have largely focused on adsorption technologies using bio-based and industrial waste-derived sorbents for the removal of toxic metals like Hg, As, and Cd, and for the recovery of trace amounts of gold and other precious metals. However, there is a noticeable research gap in developing integrated membrane systems, advanced ion exchange processes, and green chemical precipitation technologies that can be scaled economically and sustainably. In particular, the treatment and recovery of Rh, Pd, Ir, Ni, Cr, and residual cyanide (CN^-) remain underexplored at both pilot and industrial scales.

To support environmental sustainability and water reuse in gold mining operations, there is an urgent need for the development of affordable, energy-efficient, and zero-liquid-discharge (ZLD) treatment systems. These systems must be designed with a focus on resource recovery, minimising secondary pollution, and adapting to diverse wastewater composition.

7.0 Conclusion

Gold mining wastewater poses serious environmental and health risks due to its toxic composition. Industrial-scale treatment systems like SAVMIN, SPARRO, biogenic sulphide, and DESALX are effective in removing pollutants and enabling water reuse but face challenges such as high costs and sludge generation. Pilot-scale and lab-scale methods, including membrane systems, wetlands, and adsorption using bio-based sorbents, show promise—particularly for artisanal mining. However, gaps remain in scalability, cost-effectiveness, and treatment of lesser-studied contaminants like rhodium and residual cyanide. Future solutions should focus on integrated, zero-liquid-discharge systems that enable efficient contaminant removal, water recovery, and metal reclamation while supporting sustainability and circular economy goals.

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