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# Advances in Membrane Technology for Gold Extraction: A Comprehensive Review

Lim Cee Kee[1,2], Noor Fazliani Shoparwe[1,2,*]

[1]Faculty of Bioengineering and Technology, Universiti Malaysia Kelantan, 17600, Jeli, Kelantan, Malaysia
[2]Gold, Rare, Earth & Material Technopreneurship Centre (GREAT), Universiti Malaysia Kelantan, 17600, Jeli, Kelantan, Malaysia

*Corresponding author: fazliani.s@umk.edu.my

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**ABSTRACT**

This comprehensive review investigates recent advancements in separation technologies for gold extraction, focusing on sustainable and efficient methods to address environmental concerns associated with traditional practices. The study explores innovative techniques such as hydrometallurgical methods, biocyanidation, biosorption, and membrane technology, evaluating their mechanisms and environmental implications. Significant trends in gold extraction have emerged over the past five years, as revealed by a comprehensive review of numerous studies. One such trend is the increasing adoption of non-toxic leaching agents like thiocyanate, which show comparable recovery rates to cyanide while posing lower environmental risks. Additionally, advancements in bioleaching through engineered microbial strains have demonstrated improved gold solubilization efficiencies, with reported increases of up to 25% in recovery rates. Membrane technologies, particularly composite and nanostructured membranes, have emerged as promising alternatives for selective gold ion separation, offering enhanced permeability and selectivity. The integration of these advanced technologies into hybrid systems further enhances overall recovery rates, with efficiencies of over 95% when combining biological and physical separation methods. This review concludes that the future of gold extraction lies in the combination of these innovative technologies, which improve recovery efficiencies and address critical environmental concerns. The ongoing research in this field is vital for the development of sustainable gold recovery processes that meet both economic and ecological demands. By examining the mechanisms, efficiencies, and environmental impacts of these methods, this paper highlights the future potential of separation technologies in sustainable gold recovery.

*Keywords: Gold Extraction; gold recovery-electro-driven membrane extraction (EME); polymer inclusion membrane (PIM)*

# 1. Introduction

Gold has held a unique place in human culture and economy for millennia, symbolizing wealth, power, and beauty and finding applications in jewelry, electronics, investment, and industry. However, the traditional methods of gold extraction, primarily cyanidation and amalgamation, often involve energy-intensive and pose severe environmental and health risks. These methods often lead to the contamination of water sources, soil degradation, and the production of toxic waste. As a result, there is a growing need for efficient, innovative, and sustainable approaches to gold extraction.

Separation techniques play a critical role in the gold extraction process, as they allow for the selective recovery of gold from complex ore matrices. Effective separation can significantly improve metal recovery rates, reduce operational costs, and minimize environmental impacts. However, traditional separation methods, such as gravity separation and flotation, often suffer from limitations in terms of efficiency, selectivity, and energy consumption. In recent years, there has been a surge in research and development efforts to explore innovative separation techniques for gold extraction. These emerging technologies, including bio cyanidation, biosorption, and membrane separation, offer promising alternatives to conventional methods. By understanding the principles, advantages, and limitations of these techniques, researchers and industry professionals can identify opportunities to optimize and integrate them for more efficient and sustainable gold extraction.

The earliest methods of gold extraction relied on gravity separation, which exploits the density difference between gold and gangue minerals. This process involved crushing the ore, reducing its size, and adding water to form a slurry. The slurry was then passed through devices like sluice boxes, shaking tables, and spiral concentrators to separate heavier gold particles. While simple and low-cost, gravity separation's efficiency is limited by particle size and fine-grained gold [1]. Another ancient technique, amalgamation, involved using mercury to amalgamate with gold particles. Although efficient, this process posed significant health and environmental risks due to mercury toxicity.

The Industrial Revolution brought about significant advancements in mineral processing, including the development of flotation and cyanidation. Flotation, a surface chemistry-based process, utilizes surfactants to selectively attach to gold particles and float them to the surface. This technique was particularly effective for recovering fine-grained gold particles. Cyanidation, introduced in the late 19th century, revolutionized gold extraction by dissolving gold from low-grade ores using a cyanide solution [2]. While highly efficient, cyanidation has environmental concerns due to the toxicity of cyanide.

As environmental consciousness grew, researchers sought more sustainable alternatives to traditional methods. Membrane separation, ionic liquids, and biosorption emerged as promising technologies. Membrane separation utilizes semi-permeable membranes to selectively separate gold ions from the solution. Different types of membranes, such as nanofiltration and reverse osmosis, offer advantages like high selectivity, low energy consumption, and potential for by-product recovery [3]. Ionic liquids, a class of molten salts with unique properties, have emerged as potential solvents for gold extraction. They offer advantages over traditional organic solvents, such as selective gold extraction from complex solutions and recyclability. Biosorption, a biological process using microorganisms, algae, or fungi, provides a low-cost, eco-friendly alternative [4] to conventional separation techniques. Microorganisms can selectively bind gold ions, and the biomass can be easily recovered and regenerated.

To optimize gold recovery and minimize environmental impact, a combination of these techniques can be employed. For instance, gravity separation can be used as a pre-concentration step to remove coarse gold particles, followed by flotation to recover finer particles [5], thereby enhancing the overall efficiency of the extraction process. This integrated approach not only maximizes gold recovery but also reduces the volume of material subjected to more intensive chemical treatments, ultimately leading to lower reagent usage and decreased environmental footprints. Such a synergistic strategy highlights the potential for innovation in gold extraction methods, setting the stage for more sustainable mining practices in the future.

As research continues to advance, expect to see further innovations in gold extraction, ensuring a sustainable future with synergistic strategy for gold extraction methods. This review aims to provide a comprehensive overview of the latest advancements in technology separation for gold extraction by critically analysing the existing literature's



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advantages and disadvantages of gold extraction method, highlight emerging trends, and discuss the potential for future innovations. This review seeks to explore their potential in revolutionizing the hydrometallurgical process for gold recovery, addressing the urgent requirement for improved efficiency and environmental accountability. Little reviews have addressed the separation technologies employed in gold extraction, and to the best of current knowledge, membrane technology remains an underexplored area in this field. There is a significant need for more comprehensive studies to evaluate the effectiveness and applicability of membrane-based methods for gold recovery. By advancing the understanding of this innovative technology, can potentially unlock new efficiencies and improve sustainability in gold extraction processes.

# 2. Technology Separation for Gold Extraction

Gold extraction methods have evolved significantly over time, each with its unique advantages and drawbacks. Traditional methods like gravity separation and amalgamation, while simple and low-cost, often have limited recovery rates, especially for fine gold particles. Modern techniques such as flotation, cyanidation, biosorption, solvent extraction, and membrane separation offer higher recovery rates and improved efficiency. However, these methods also present challenges related to environmental impact, reagent consumption, and operational costs. As the mining industry strives for sustainable and environmentally friendly practices, ongoing research and development are focused on optimizing existing methods and exploring innovative techniques. This summary, as shown in Table 1, effectively captures the key points from the table, highlighting the diversity of methods, their advantages, disadvantages, and the evolving landscape of gold extraction.

**Table 1**: Various gold recovery methods, including their principles, advantages and disadvantages

| Method | Principle | Advantages | Disadvantages | Reference |
|---|---|---|---|---|
| Gravity Separation | Density difference | Simple, low-cost, environmentally friendly | Low recovery rates for fine gold | [6] |
| Amalgamation | Mercury affinity to gold | High recovery rates, simple process | Environmental Contamination, health risks from mercury exposure | [7-8] |
| Flotation | Surface chemistry differences | Versatile, high recovery rates for various ores | Complex process, reliance on chemicals, limited for fine particles | [9] |
| Cyanidation | Gold dissolution in cyanide solution | High recovery rates, widely used | Environmental concerns due to cyanide toxicity, complex process | [10] |
| Biosorption | Biological adsorption of gold ions | Environmentally friendly, low-cost, high selectivity for gold | Low capacity, complex process, limited industrial applications | [11] |
| Solvent Extraction | Selective transfer of gold to organic phase | High selectivity, rapid kinetics, continuous operation | Generation of organic waste, potential environmental impact | [12] |
| Membrane Separation | Selective transport of gold ions through a membrane | High selectivity, low energy consumption, environmentally friendly | Potential fouling issues, high initial costs | [13-14] |

Gravity separation, an ancient technique, exploits density differences between gold and other minerals. Techniques like panning, sluicing, and shaking tables allow denser particles to settle while lighter materials are washed away [6]. Shaking tables, for instance, have been used to extract 88% of gold from concentrates [15]. For coarse gold particles, gravity separation works well, recovering up to 90% of particles coarser than 40 µm [16]. However, it struggles with fine gold, typically recovering only 20% of 20-40 µm particles. Additionally, the presence of other heavy minerals can complicate the separation process. While gravity separation is low-cost and environmentally friendly, its effectiveness as a standalone technique is limited by its inability to recover fine gold and its sensitivity to ore composition.

Besides, amalgamation involves the use of mercury to extract gold from ores, leveraging the ability of mercury to form an amalgam with gold. This method involves mixing mercury with crushed ore, which binds to the gold and separates it from the other material. This method has been commonly used in artisanal and small-scale mining, particularly in developing countries, due to its several advantages, including simplicity, inexpensiveness, and the fact that it can achieve high recovery rates with minimal equipment. After forming, the amalgam is heated to cause the mercury to evaporate, revealing pure gold [17]. The main obstacle to amalgamation is the substantial risks to human health and the environment that come with using mercury. Water sources may become contaminated by mercury, posing health risks to mining communities and causing extensive ecological harm [18]. Numerous reports on past gold mining sites in developed nations show the significant contribution to Hg contamination and the persistence of Hg as an environmental pollutant [19-21]. For instance, Yoshimura et al. [22] reported average ratios of Hg lost to Au produced of 1.96 in Africa, 4.63 in Latin America, and 1.23 in Asia for artisanal gold mining. There is some mercury that can be recovered and used again in conventional methods. The ineffectiveness of mercury recovery procedures, however, frequently leads to serious environmental contamination.

In contrast, cyanidation offers a more versatile approach to gold extraction, particularly for ores that are less amenable to flotation. The process of cyanidation, patented by MacArthur in 1887 and the Forrest Brothers in 1889, revolutionized the extractive metallurgy of gold [23]. Cyanide is used to leach gold in traditional direct cyanidation, resulting in complex $Au(CN)_2^-$ described by the following equation (1) [24]. A cyanide is an inorganic compound that has a cyano group and is very toxic, especially when heated above 25°C [25]. The use of toxic cyanide solutions to extract gold from ore results in the potential contamination of groundwater and soil [25]. Thus, cyanidation is undesirable due to severe environmental pollution and long process flow. Cyanidation techniques are not economically viable, technically applicable, or easy to operate when processing low-grade gold reserves. Therefore, the mining industry is actively looking for a lixiviant substitute that is not as toxic as cyanide, is recyclable and cost-effective, highly selective for gold leaching, and is environmentally friendly [26]. Wang et al. [27] stated the necessity to control various factors such as the cell population, nutrients, pH, DO concentration, temperature, leach time, and pulp density, which can affect leaching results by affecting bacterial growth and cyanide production. Recent advancements have brought biocyanidation techniques to the market, but the technology is still in its infancy and has only been tested in laboratory settings.

$$4\mathrm{Au} + 8CN^- \rightarrow 4[\mathrm{Au(CN)}_2^-] + 4\mathrm{e} \quad (1)$$

Biosorption, a complementary technique, utilizes biological materials to adsorb and concentrate gold from aqueous solutions. This innovative, sustainable method leverages the inherent ability of biological substances to bind and accumulate metals. With a growing emphasis on environmentally friendly and cost-effective extraction methods, biosorbents offer high recovery ability, even in dilute solutions [28]. These adsorbents, derived from lignin or cellulose, exhibit good performance for gold recovery [29]. However, practical application in industrial sectors is hindered by complexity and high operating costs for low-concentration gold solutions.

Solvent extraction is one of the prevalent methods for selectively separating and concentrating gold in aqueous leach solutions. Also recognized as liquid-liquid extraction, this procedure involves the use of two solvents that are unable to mix in order to move a desired substance from one solvent to another, relying on variations in solubility. Its efficiency and performance are typically assessed by three key measures—distribution coefficient (KD), extraction percentage (%E), and selectivity factor $ß_{A:B}$ [30]. The distribution coefficient is defined as the ratio of the concentration of a solute at equilibrium in two different, immiscible solvents in physical contact. The extraction percentage is a measure of the distribution of a solute between phases given the volumes of the phases, while the selectivity factor is the ratio of distribution coefficients of two solutes, A and B. The equations (2), (3), and (4) representing the aforementioned three measures are shown below [30].

$$\text{Distribution coefficient } K_D = \frac{[solute]organic\ phase}{[solute]aqueous\ phase} = \frac{C_o}{C_a} \quad (2)$$

$$\%E = \frac{C_o V_o}{C_o V_o + C_s V_a} = \frac{\frac{C_o}{C_a}}{\frac{C_o}{C_a} + \frac{V_a}{V_o}} = \frac{K_D}{K_D + \frac{V_a}{V_o}} \times 100(\%) \quad (3)$$

$$ß_{A:B} = \frac{K_{D.A}}{K_{D.B}} \quad (4)$$

Where $C_o$ and $C_a$ are the concentrations of solute in the organic and aqueous phases, respectively, and $V_o$ and $V_a$ are the volumes of the organic and aqueous phases.

Unlike alternative techniques, solvent extraction boasts multiple advantages, such as enhanced selectivity, quicker kinetics and mass transfer, reduced energy consumption, increased production capacity, seamless continuous operation, and effortless automation. These benefits have paved the way for effectively implementing solvent extraction methods in different industries globally. However, to expand its scope of application and solidify its position as a leading metal recovery method, solvent extraction needs to overcome its significant limitations. Some examples of environmental concerns in industrial processes include the significant generation of aqueous and organic waste, the utilization of harmful organic substances, and the elevated expenses associated with chemicals [31-33].

As the demand for more efficient and scalable methods increases, membrane separation technologies have gained attention as a complementary approach for gold extraction. Membrane separation involves the use of semi-permeable membranes to separate components based on size, charge, or chemical potential gradient [34]. Membrane separation offers several advantages, including high selectivity, low energy consumption, reduced environmental impact, and the potential for recovering valuable by-products [35]. Despite challenges such as fouling and initial capital costs, ongoing research and development are paving the way for broader industrial applications. As the gold mining industry increasingly prioritizes sustainability and efficiency, membrane technologies are poised to play an essential role in the future of gold recovery.

# 3. Synergistic Effects and Improved Performance through Integration of Separation Techniques

The gold extraction industry faces numerous challenges, including the need to optimize recovery rates from increasingly complex ore bodies while minimizing environmental impacts. Integrating multiple separation techniques has emerged as a promising strategy to address these challenges. By combining the strengths of various methods, the industry can achieve synergistic effects that enhance overall performance. This integration capitalizes on the unique mechanisms of each method, leading to improved outcomes compared to using a single technique.

Integrating methods can create synergistic effects that improve overall performance. For example, coupling gravity separation with flotation can enhance recovery by removing coarse gold first, making flotation more efficient for finer particles. Gravity separation has proven effective in recovering gold from flotation tailings, with assays of 81% recovery from the ground ore [36]. Yan [37] reported that adding xanthate and dithiophosphate improves flotation recovery by chemisorbing to gold surfaces. Collectors like tertiary dodecyl mercaptan and sodium butyl xanthate enhanced recovery to 90.8 wt% with a grade of 81.1 g/t Au from a 2.9 g/t Au feed at pH 8-8.5 [38]. Yalcin and Kelebek. [38] found that a mixture of potassium amyl xanthate and sodium isopropyl xanthate increased gold recoveries from 91.8 wt% to 95.8%. The combined processes of gravity separation and flotation show relatively high gold recovery values, making the extraction method more economically viable.

Integrating flotation with cyanidation has emerged as an effective strategy for optimizing gold recovery from complex ores. By initially concentrating gold-bearing minerals through flotation, this approach enhances the efficiency of subsequent cyanidation. This synergistic combination not only improves overall gold recovery rates but also minimizes the environmental impact of cyanide use by enabling the treatment of lower-grade ores. Faraz et al. [39] compared selective and bulk flotation for low-grade gold ores, finding that bulk flotation achieved a maximum gold recovery of 90.6%, significantly higher than the 28% recovered through selective flotation. The research also showed



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that selective flotation left 22% of antimony and 31.1% of arsenic in the tailings, making it less suitable for further cyanidation [39].

Additionally, preliminary oxidation of flotation tailings using sodium peroxide increased gold recovery by 2%, while treatment with calcium hypochlorite decreased recovery by 4.64% compared to direct cyanidation [39]. In contrast, biological oxidation using an active bacterial culture increased gold recovery by 2.34% compared to direct cyanidation [39]. These findings illustrate the synergistic effect of integrating biological oxidation with traditional methods. This approach not only improves the accessibility of gold but also significantly boosts overall recovery rates during cyanidation.

Simultaneous leaching and solvent extraction significantly reduces gold ore extraction time. Salimi [40] achieved 94% gold recovery in less than 9 hours, significantly faster than the 35-hour cyanidation leaching process. Sole [41] demonstrated a three-step process involving oxidative leaching, solvent extraction, and gold powder precipitation, achieving high purity ranging from 99.99% to 99.999%. Jiang et al. [42] found that amine extractants extract aurocyanide anions through an ion-association mechanism. Kordosky et al. [43] showed that gold extraction in a cyanide environment involves reagent protonation followed by ion-pair extraction. Kubota et al. [44] explored solvent extraction mechanisms in a chloride medium, suggesting that basic extractants form ion pairs with negatively charged metal complexes like [Au]-.Given the numerous advantages of solvent extraction, there is significant potential for its further expansion in gold extraction, separation, and concentration.

Recently, a membrane separation technique has garnered significant interest as a substitute for solvent extraction, incorporating the application of supported liquid membranes (SLMs). In this technique, an SLM, a microporous polymer thin film impregnated with an extractant (also known as a carrier) dissolved in a suitable diluent, is sandwiched between a feed aqueous solution and a receiving aqueous solution [44]. SLMs allow the simultaneous extraction and back-extraction of the target chemical species and significantly reduce the number of organic diluents needed. The challenge lies in the instability of these membranes caused by the seepage of their diluents and carriers into the surrounding aqueous solutions.

An alternative to SLMs is the concept of polymer inclusion membranes (PIMs). In PIMs, the carrier is immobilized within the entangled chains of a base polymer, creating a membrane with exceptional transport properties and remarkable stability [45]. A variety of metal cations and anions, including Au(III), have been separated successfully by PIMs incorporating appropriate carriers and, in some cases, plasticizers; for instance study carried out by Kubota et al. [44] studied the newly synthesized extractant N-[N,N-di(2ethylhexyl) aminocarbonylmethyl] glycine (D2EHAG). It exhibited high selectivity for the gold(III) ion over the other metal ions present in much higher concentrations in the leachates. The formulations of the feed and receiving solutions for both liquid-liquid and PIM-based extraction, as well as back-extraction of gold(III) ions, were fine-tuned. It was determined that achieving the best extraction efficiency necessitated an HCl concentration of 2 mol/L in the starting solution, achieving equilibrium within 12 h. Au(III) exists as a stable $[AuCl_4]$ - complex, which forms a 1:1 ion pair with the extractant, which incorporates a protonated amine moiety, forms singly negatively charged chloride complexes [46] that are readily extracted into the PIM. These results clearly show that the selectivity for Au(III) in PIM-based extraction is higher than that of the analogous solvent extraction system. Also, it was found that a receiving solution with 0. 1 M thiourea in 1 M HCl was fully capable of quantitatively back-extracting gold(III). During membrane transport experiments using synthetic leachate as the feed solution, it was observed that 96% of the gold(III) ions were selectively transported into the receiving solution of the transport cell. This effectively separated the gold from all other metal ions in the leachate.

Similarly, the simultaneous extraction of gold using PIM with ionic liquid as the carrier was investigated by Wang et al. [29]. The research reported an efficiency of 98.6% of gold(I) extraction from the feed solution into the stripping solution with a concentration of 3.0 mol/L of Potassium Thiocyanate (KSCN). However, the permeability coefficient was relatively low, and it took 24 hours to achieve higher extraction efficiency. Thus, the permeability of gold(I) through the membrane can be improved. Meanwhile, gold can be recovered in situ from a stripping solution via direct electrodeposition. Regardless of the merits of using PIMs for separation, a low diffusion coefficient is often obtained with PIMs [45]. Electro-driven membrane extraction (EME) has recently been developed to improve the permeability of PIMs by applying an electric field on both sides of the liquid membrane [47]. This innovative approach enhances the mass transfer of metal ions, potentially leading to higher recovery rates in gold extraction processes.



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However, the current understanding of EME remains quite shallow. Therefore, further research is essential to harness the capabilities of EME fully, paving the way for its broader application and integration into gold recovery operations in the future. As advancements continue, EME is poised to emerge as a critical component of the evolving landscape of gold extraction technologies.

# 4. Conclusion

The gold extraction landscape is evolving, driven by the need for economic efficiency and environmental sustainability. This review highlights the strengths and limitations of various separation techniques, from traditional to innovative methods. As the industry adapts to changing regulations and consumer demands, integrating these technologies synergistically will optimize gold recovery and minimize environmental impact. Future research should prioritize optimizing membrane separation technologies, particularly through electro-driven polymer inclusion membranes (PIMs). This approach promises to advance sustainable gold extraction methods. By embracing a multifaceted strategy, the gold mining industry can address contemporary challenges and chart a sustainable future, harmonizing economic viability with environmental stewardship.

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