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Review

Advances in Hydrometallurgical Gold Recovery through Cementation, Adsorption, Ion Exchange and Solvent Extraction

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Abstract: Hydrometallurgical gold recovery processes play a pivotal role in the gold mining industry, contributing to more than 90% of global gold production. Among the array of techniques available, the Merrill–Crowe process, adsorption, ion exchange, and solvent extraction are central in extracting gold from leach solutions. While the Merrill–Crowe process and gold complex adsorption onto activated carbon represent historical cornerstones, their inherent limitations have prompted the emergence of more recent innovations in ion exchange and solvent extraction, offering enhanced selectivity, control, and sustainability. The evolution of modern organic chemistry has significantly influenced the progress of ion exchange technology, mainly through the introduction of advanced polymer matrix synthetic resins. At the same time, novel solvents tailored to gold complex interactions have revitalized ion exchange and solvent extraction. Introducing ionic liquids and deep eutectic solvents has also added a new dimension to efforts to improve gold extraction metallurgy. This paper reviews these cutting-edge developments and their potential to revolutionize the hydrometallurgical gold recovery process, addressing the pressing need for improved efficiency and environmental responsibility.

Keywords: gold recovery; adsorption; Merrill–Crowe; ion exchange; solvent extraction; ionic liquids

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1. Introduction

Gold, with an annual production of 3100 tons and current reserves of 52,000 tons worldwide [1], has played a central role in human culture, economics, and technology throughout the history of mankind. Due to its high reduction potential (e.g., $Au^+ + e^- \rightarrow Au$, $E^\circ_{298K} = +1.69$ V), gold is one of the few elements in a native state in nature. Gold has been historically considered a rare and precious metal; the current price of gold ranges from USD 1800 to USD 2000 per ounce [2]. Ever since the California Gold Rush in 1848, large-scale gold production has been ongoing, and it experienced significant growth during the 1980s, driven by high gold prices and the use of heap leaching, which facilitates the recovery of gold from low-grade deposits. In the USA alone, approximately 170 tons of gold are estimated to have been produced in 2022 from gold mines, with a total value of USD 10 billion [1]. Among the 11 gold-producing states, Nevada accounts for the largest share, contributing 72% of the total domestic production. Gold is also produced as a by-product of other base metal mines, mainly copper mines, or through scrap recycling. The recent increasing consumption of gold as an industrial metal and its limited supply makes it imperative to recover this highly desired metal from secondary sources, including E-waste and wastewater.

Gold has unique physicochemical properties, such as high thermal and electrical conductivities, exceptional ductility, chemical inertness, and high corrosion resistance [3].

These attributes enable gold to have a wide range of applications across various fields, including investment, jewelry, electronics, aerospace, medicine, dentistry, and construction, to name just a few. In particular, the electronics sector has notably witnessed a surge in gold consumption, accelerated by the recent transition to a digitized and sustainable future. Semiconductor chips require the use of this metal for coating and thin bonding wires, while gold nanoparticles are irreplaceable to improve the efficiency of solar cells. Currently, more than 1000 kg of gold ore is required to manufacture 40 mobile phones [4].

The development of gold metallurgy, from basic ornaments to complex extraction and refining techniques, reflects the progress of human civilization and our pursuit of this valuable and noble metal. In ancient times, gold was obtained from natural sources through a process known as mercury amalgamation. With the introduction of cyanide, a more economically viable method for gold recovery emerged and, currently, around 90% of gold ore is treated using cyanide worldwide [5]. Around 1903, the Merrill–Crowe process was introduced, enabling the retrieval of dissolved gold cyanide that had adhered to zinc or aluminum particles. Incorporating activated carbon (AC) further improved the efficiency and technology of this process [6].

While the Merrill–Crowe process and AC adsorption are still widely employed in the industry due to their effectiveness and operational simplicity, the increasing complexity of low-grade ores and the recycling of end-of-life materials, which often contain multiple components, necessitate the introduction of more advanced technologies. These include methods like ion exchange (IX) and solvent extraction (SX), which were first implemented in the mid-20th century for recovering gold and other noble metal complexes from leach liquor. Modern advancements in organic chemistry have had a significant impact on the development of innovative organic solvents, which have rejuvenated IX and SX technologies, such as through the introduction of advanced synthetic resin matrices [7]. Furthermore, recent developments in emerging chemicals such as ionic liquids and deep eutectic solvents have opened new pathways for environmentally sustainable and robust gold extraction from various sources.

This paper presents a comprehensive literature review on both historical and recent advances in hydrometallurgical gold recovery. It includes a detailed and critical assessment of research articles covering conventional and newly emerging techniques such as the Merrill–Crowe process, activated carbon adsorption, ion exchange, solvent extraction, and the use of ionic liquids and deep eutectic solvents. This review aims to understand their potential to revolutionize the hydrometallurgical process for gold recovery, addressing the urgent need for enhanced efficiency and environmental responsibility. Specific challenges related to each process are discussed, along with outlooks. The thorough review of the current status of existing processes provided in this paper will help advance these techniques in a more effective and sustainable manner, paving the way for better and forward-looking gold processing in the future.

2. Adsorption of Gold on Activated Carbon—Merrill–Crowe Process

The Merrill–Crowe process and the adsorption of gold onto AC are the most frequently used industrial processes, accounting for more than 70% of treatments in removing noble metals from the leach liquor. The Merrill–Crowe process, a process often referred to as "Precipitation", which is equivalent to the metallurgical term "Cementation" in the Spanish language, was utilized in 1500 BC as a process carried out in the gold industry to recover noble metals from solution by adding active metals such as zinc or aluminum powders [8,9]. This section details the salient physical structure and pertinent chemistry associated with these processes.

2.1. The Merrill–Crowe Process

The Merrill–Crowe process relies on a redox reaction, wherein noble metal ions, such as gold cyanide, undergo deposition onto a highly reactive metal such as zinc or aluminum

powder. In the case of gold cyanide deposition onto zinc powder, the cathodic reaction is given in Equation (1), while the anodic reaction is expressed in Equation (2) [10].

$$Au(CN)_2^- + e^- \leftrightarrow Au + 2CN^- \quad E^o = -0.62V \tag{1}$$

$$Zn + 4CN^- \leftrightarrow Zn(CN)_4^{2-} + 2e^- \quad E^o = +1.35V \tag{2}$$

The overall reaction becomes Equation (3).

$$Zn + 2Au(CN)_2^- \leftrightarrow 2Au + Zn(CN)_4^{2-} \quad E^o = +0.73V \tag{3}$$

As emphasized by many researchers [9,11], it is crucial to degas the liquid phase to maintain a level of oxygen concentration less than 0.5 ppm to facilitate an efficient deposition reaction. Reactive metals such as zinc and aluminum are susceptible to oxidation, even with trace amounts of oxygen in the liquid. Additionally, for the effective precipitation of gold cyanide, the solution must be clarified to eliminate solid particles of less than 1 ppm for effective gold cyanide precipitation. Figure 1 illustrates a schematic depiction of this process.

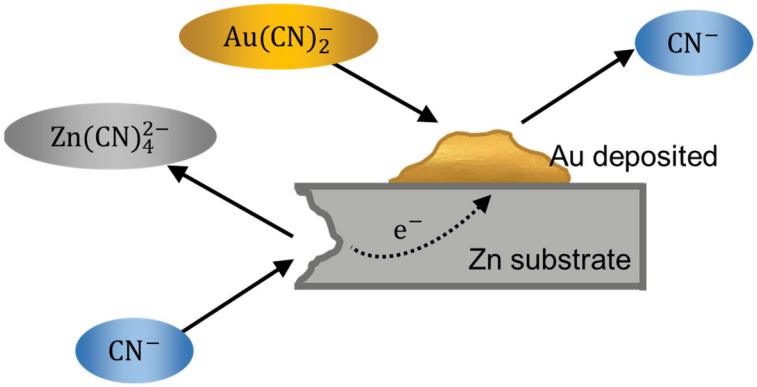

Figure 1. Schematic presentation of the Merrill–Crowe process.

Cyanide remains the primary lixiviant used in gold leaching. However, due to its toxic nature, significant research efforts have focused on finding alternatives. Similar reactions as those given in Equations (1)–(3) would occur for other lixiviants. For example, gold thiosulfate $(AuH_2O_6S_4)^{2-}$ would react with zinc particles to produce elemental gold and zinc thiosulfate (ZnS_2O_3), and gold thiourea with zinc would produce zinc thiosulfate $(Zn(CS(NH_2)_2)^{2+}$ and elemental gold [12–15]. Other metals, such as aluminum and copper, are also used to recover gold complexes from the solution, as gold is the most noble metal [16–18].

In the gold industry, dissolved gold is efficiently removed using the Merrill–Crowe process through a series of tanks, either by carbon-in-pulp (CIP) or carbon-in-leach (CIL) operations. The main difference between these two operational modes is that in CIP, gold extraction usually takes place in a series of three leaching tanks containing ground gold ore and a lixiviant, such as sodium cyanide, before the adsorption of dissolved gold complexes onto activated carbon in the leaching tanks. Once the dissolved gold complexes are adsorbed onto the activated carbon, the carbon particles are usually separated from the pulp by screening. The gold-loaded activated carbon is subjected to elution followed by either electrowinning or cementation using zinc powder. CIP is preferred for its higher recovery rates and cost-effectiveness compared to CIL, as the separate leaching and adsorption phases in CIP offer better control and optimization. However, it is important to note that CIL, with its simplicity and efficiency, remains a favored operational mode in our industry [19].

For effective cementation, several precursor operations play a crucial role. These include the removal of oxygen, which can interfere with cementation, and the filtration of solid particles to ensure a clean and efficient reaction environment. It is important to note that since many gold-bearing ore deposits contain copper, a significant impurity, copper removal is essential before the cementation operation. These precursor operations are key to ensuring the success and efficiency of the cementation process [15,20]. Certain impurities in the solution notably impact the precipitation of gold cyanide onto zinc. For example, when sulfide levels reach 14 ppm or higher, the cementation of gold cyanide onto zinc stops. A similar phenomenon occurs when the concentration of copper cyanide exceeds 850 ppm, antimony is at 20 ppm, or arsenic is at 17 ppm.

The formation of zinc hydroxide, $Zn(OH)_2$, is a major concern in this process. The formation of such hydroxides causes retardation of the noble metal precipitation [21]. The industry has also noted that many impurities, including sodium sulfide–cyanide complexes of copper, arsenic, and antimony, are frequently present in the gold cyanide solution, significantly deteriorating noble metals' cementation recovery. On the other hand, adding lead nitrate ($Pb(NO_3)_2$) into the solution improves the cementation of gold onto zinc [22]. It should be noted that there is still no consensus on the mechanisms by which this salt has a positive effect, but only some speculations have been put forward. Some speculate it is due to a catalytic effect or morphology change/depolarization effects [21].

2.2. Adsorption of Gold Cyanide on Activated Carbon

Activated charcoal, also known as AC, has a long history of use since ancient civilizations for various human applications in medicinal and purification purposes. In 1880, Davis patented a process for gold recovery from chlorination leach liquors using wood charcoal. In 1894, Johnson invented wood charcoal about a decade later to recover gold cyanide from cyanide solutions [23].

AC can be manufactured from various sources, such as coconut shells, peach pits, bituminous coals, and peat. These raw materials are first carbonized at around 700 °C, then activated at temperatures between 800 and 1100 °C in the presence of various oxidizing gases, such as steam, air, or carbon dioxide. This process is responsible for creating pore structures [24]. As shown in Figure 2, three types of pores are present in the carbon matrix: macropores, mesopores, and micropores. Post-activation, the raw materials transform into a non-graphitic carbon with a highly disordered microstructure, resulting in high surface area and porosity [24,25]. The basic structure of pure graphite is given in Figure 3. Carbon can be chemically activated with or without heat treatment, as discussed in the following section.

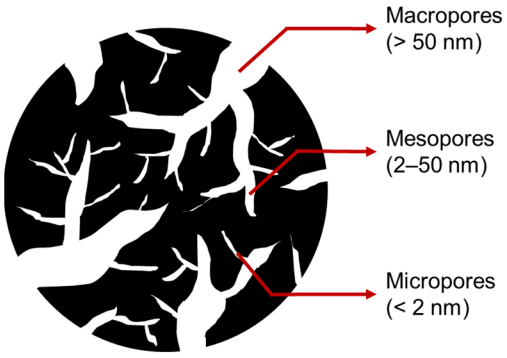

Figure 2. Schematic presentation of various pores in activated carbon [26].

During the activation process, it is believed that various organic substances emerge from carbon atoms, including carboxyl, phenolic hydroxyl, quinone-type carbonyl, normal lactone, fluorescein-type lactone, carboxylic acid anhydride, and cyclic peroxide groups [27,28]. These organic components might play a role in selectively adsorbing metal ion complexes in a solution. For example, the oxygen functional groups on the carbon edges have shown increased adsorption energy for $Cu(CN)^{2-}$ in the presence of

OH and COOH while exhibiting decreased adsorption energy for $Au(CN)^{2-}$ with OH and increased adsorption energy for $Au(CN)^{2-}$ with COOH [29].

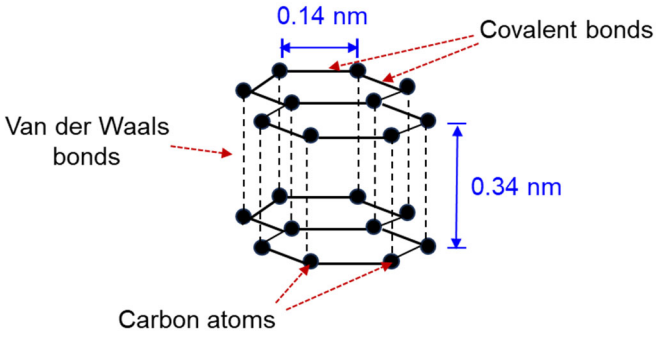

Figure 3. Schematic presentation of graphite structure [25].

Gold and other metal complexes are adsorbed onto the surface of AC by complexing with these organic functional groups. The standard criteria for selecting AC in noble metals recovery encompass key parameters such as adsorption rate, capacity, iodine number, carbon tetrachloride number, particle size, attrition, and desorption characteristics [30].

A number of potential adsorption mechanisms have been put forward in the literature. Most theories are semi-speculative, and further studies are needed to elucidate the exact chemistry and accurate mechanisms underlying the adsorption behavior of gold-cyanide onto AC. Davidson suggested that the effect of cations in the system plays a significant role in the adsorption behavior of gold onto carbon. The ion pair $M^{n+}[Au(CN)_2^-]_n$ is responsible for adsorption, in which M stands for metal. The calcium ion exhibits the most strongly adsorbed complex, followed by other cations in the order of $Ca^{2+} > Mg^{2+} > H^+ > Na^+ > K^+$ [30,31].

Research indicates highly favorable adsorption of platinum group–cyanide complexes onto AC, including platinum, palladium, and rhodium [31,32]. Notably, Snyders et al. [33] observed efficient recovery of platinum group metals, gold, and nickel using coconut–AC, while recoveries of Cu and Fe were comparatively less effective. The pH of the solution emerged as a critical factor, with results at pH 9.5 surpassing those at pH 12. Although $Au(CN)_2^-$ exhibits a higher interaction potential than $Cu(CN)_2^-$, the favorable influence of functional groups such as OH^- and $COOH^-$ on copper cyanide led to a reversal in interaction potential on the AC's surface [29]. A recent study involving carbon nanofibers treated with ammonia plasma followed by N-amino rhodamine assembly has shown a recovery rate of over 96% for Au(III) from a mixture containing Cu(II), Ni(II), Zn(II), and Pb(II) at 50 mg/L [34].

Other researchers have demonstrated that the adsorption mechanism is determined by a specific diffusion-controlled process. [35,36]. On the other hand, it has been reported that hydration energy plays an important role in the adsorption of gold complexes onto carbon [37,38]. For example, aurocyanide $Au(CN)_2^-$ often competes with water molecules for adsorption sites on carbon. When strongly solved, ions pose a high hydration energy and are less likely to leave the aqueous phase to adsorb onto the solid surface. Aurocyanide exhibits relatively low hydration energy compared to other metal ions, making it more likely to adsorb onto activated carbon. Conversely, small anions, such as CN^-, which have many tightly bound water molecules, do not undergo adsorption. The adsorption behavior of metal cyanides shares similarities with IX, as illustrated in Table 1, which compares the adsorption modes of activation carbon and IX.

One of the drawbacks of the AC-based process is the time required for the elution process, where the loaded AC is subjected to a hot NaOH solution, usually consisting of 1% NaOH and 0.1%–0.2% NaCN, at a nearly boiling temperature for 36 to 72 h [39]. The elution process can be sped up by subjecting the elution process to 120 to 130 °C at 5.83 bars for 36–72 h of operation. The eluted gold-bearing solution is then subjected to the Merrill–Crowe process [39].

Table 1. A comparative summary between activated carbon and ion exchange processes.

	Activated Carbon	**Ion Exchange**
Adsorption Mechanism	Ion-pair adsorption; Coulombic attraction; Van der Waals force attraction	Ionic exchange (cation; anion; chelation)
Selectivity	Not so good (Pt-group metals; Cu)	Good; versatile
Cost	Good and convenient	Expensive
Mode of Operation	Granular; CIP, CIL	Column; RIP, RIL
Elution	Easy but regeneration with high-temperature treatment may be required	Easy and regeneration is simple and cost-effective

As the need to recover gold from secondary sources has expanded and the search for eco-friendly lixiviants has also increased, many attempts have been made to modify the surface of AC to accommodate other extractant media such as halogen salts, thiosulfate, thiourea, and ethylenediamine. As a result, many researchers have been looking for a surface modification suitable for various gold-bearing ligands to improve the adsorption of these chemical moieties on AC [40–42]. For example, to improve the adsorption of $Au(S_2O_3)_2^{3-}$, AC was altered using a calcination process with double-layered metal hydroxides such as Mg-Al or Cu-Fe. It was found that the calcination with the Cu-Fe double-layered hydroxide improved the adsorption efficiency by 7-fold over that of the Mg-Al double-layered hydroxide [40].

The gold industry's two most widely used technologies are the Merrill-Crowe and AC processes. However, drawbacks and challenges have been encountered in recovering gold from leach liquor. Both processes suffer from a lack of selectivity, especially when the solution contains other noble metals, as in the case of treating secondary sources. The Merrill–Crowe process suffers from high cyanide consumption and substantial cost involved in the treatment after the gold precipitation process. The AC process also suffers from a lack of selectivity due to carbon fouling, as well as high AC-regeneration costs.

Advancement of the AC process of gold complexes along with other metals is an emerging technology, and a profound understanding of the adsorption behavior of various gold complexes on AC, coupled with insights into IX systems, will pave the way for an advanced process of separation of gold from diverse metal complexes. The evolution of adsorption mechanisms within this process appears to be aligned with the development of IX and the continuous refinement of lixiviant compositions utilized in gold leaching to meet the needs of better recovery and selectivity as the sources of gold are expanded to meet the escalating industrial demand for gold and other noble metals.

3. Ion Exchange of Gold

In gold extraction, IX is a comparatively newer technology than carbon adsorption. The investigation of IX for gold recovery from cyanide solutions began in the late 1940s in the United States, South Africa, and the former USSR. This technology was then more actively implemented in USSR countries, with the commissioning of the first resin-in-pulp (RIP) plant at the Muruntau Mine in Uzbekistan. Meanwhile, carbon adsorption was more popular in other countries, and the first RIP facility was commissioned at the Golden Jubilee Mine in South Africa in 1988 [9]. More recently, the Barrick Gold Corporation launched a thiosulfate leaching process paired with a resin-in-leach (RIL) plant in Goldstrike, Nevada, USA, in 2014 [43]. As discussed earlier, the thiosulfate medium is not amenable to an AC-based process, necessitating the adoption of IX resins.

As previously noted, IX is often compared to the AC adsorption process, as they have similar process flows: the adsorption of metal complex ions onto IX resin or AC, followed by elution and gold recovery. However, the gold extraction mechanisms between these two methods differ significantly, as summarized in Table 1. In the AC adsorption process, gold

attaches to the AC surface via ion-pair adsorption, Coulombic forces, or Van der Waals attractions. On the contrary, in IX, an exchange occurs between ionic species on the resin and metallic ions in the leach liquor. IX is known for its high selectivity, leveraging specific functional groups on the resin surface that are optimal for gold extraction. On the other hand, AC typically shows a higher gold recovery capacity than IX resins [44]. The elution process in IX is generally simpler, although the overall costs associated with IX are higher. A comparative summary of AC and IX is tabulated in Table 1.

IX resins are available in gel or macroporous forms, and their beads are utilized for the IX process. The backbone of these resins is typically made of styrene or acrylic, cross-linked with divinyl benzene (DVB). Various functional groups are attached to the resin surface, and the specific type of resin is determined based on these functional groups; cationic, anionic, and chelating groups are the most common types. Among these, anionic resins are most commonly used for gold extraction, as gold is predominantly present as an anionic species in leach liquors, such as gold cyanide ($Au(CN)_2^-$) and gold thiosulfate ($Au(S_2O_3)_2^{3-}$).

Anionic resins are divided into two groups: strong-base and weak-base resins. Strong-base resins typically have quaternary amines as their functional group, initially paired with sulfate or bisulfate ions. Because strong-base resins are stable in solution across various pH levels, they can be used in target solutions regardless of the solution pH. When a solution containing gold complex ions is loaded, an exchange occurs between the gold ions and the anion species on the resin surface, as shown in Equation (4) [9,45]:

$$]-{}^{+}NR_3X^- + Au(CN)_2^- \leftrightarrow \Big] -{}^{+} NR_3Au(CN)_2^- + X^- \quad (4)$$

where $]-$ represents the inert polymer matrix, R is the CH_3 group, and X is an anion (e.g., sulfate or bisulfate).

Weak-base resins have functional groups that are primary, secondary, or tertiary amines. Before these resins can be used, they must first undergo protonation, as outlined in Equation (5). This protonation makes them stable within a pH range of 9–11. Subsequently, the anionic gold complex ion can be adsorbed onto the protonated IX resin (Equation (6)).

$$\text{Protonation}:]-NR_2 + HX \leftrightarrow] -{}^{+} NR_2HX^- \quad (5)$$

$$\text{Adsorption}:]-{}^{+}NR_2HX^- + Au(CN)_2^- \leftrightarrow \Big] -{}^{+} NR_2HAu(CN)_2^- + X^- \quad (6)$$

In Table 2, the results of several IX research studies are summarized. The IX of gold cyanide and thiosulfate was commonly reported, as cyanide and thiosulfate are the most effective lixiviants for gold. It is indicated that strong-base resins were predominantly used for gold extraction. Msumange et al. (2022) compared IX resins and AC from leach liquor derived from copper-rich refractory gold ore [44]. For this study, Purogold A194 and S992 were utilized as IX resins, representing strong-base and weak-base resins, respectively. Both resins resulted in the same gold recovery of 89%, but S992, the weak-base resin, exhibited higher selectivity, extracting only 9% of Cu. Moreover, apart from traditional resin forms, a fibrous polymer also showed gold extraction ability. The sulfochlorinated polyethylene (PESCI) fiber was employed as the raw resin material, and it was aminated and quaternized to function like a strong-base resin. It demonstrated the ability to extract 100% of gold from a synthetic gold cyanide solution, although 57% of Cu was also extracted [46]. Using a thiocyanate solution, most of the gold was successfully eluted after three stages of the elution process.

For gold thiosulfate extraction, IX is known to be a better technology than AC, as AC lacks an affinity for gold thiosulfate [45]. Utilizing a strong-base resin, namely DOWEX 21K, several studies have demonstrated the successful extraction of 80%–100% gold from synthetic gold thiosulfate solutions [47–49]. According to Zhang and Dreisinger (2004), DOWEX 21K and G51 showed comparable gold extraction abilities, but 21K showed better selectivity in separating gold from copper [48]. In terms of elution, a mixture of Na_2SO_3 (2 M) and NH_3 (1 M) was effective, achieving the elution of 99.9% of gold. Gámez et al.

(2019) applied IX to recover gold thiosulfate from waste printed circuit board (WPCB) leach liquor [50]. The strong-base resin Purogold MTA 5011 was utilized, and 87% of the gold was extracted along with 29% of the copper. For the elution process, using a thiocyanate solution enabled the elution of 98% of the gold. In addition to the aforementioned saleable resins, a newly fabricated resin was used for gold recovery. Zhao et al. (2022) synthesized aminated microspheres called 'PS-TETA,' using chloromethylated polystyrene (PS-Cl) and triethylenetetramine (TETA) [51]. The polymer-based PS-TETA had similar characteristics to strong-base resins, as its gold extraction mechanism was based on anion exchange, with consistent gold extraction affinity regardless of pH. PS-TETA demonstrated the capability to extract 95% of gold, and the extracted gold was effectively eluted in a Na_2SO_3 solution, achieving a 90% recovery.

In addition to gold cyanide and thiosulfate, the extraction of gold thiocyanate has also been studied. Azizitorghabeh et al. (2023) selectively extracted gold thiocyanate from pyrite concentrate leach liquor using a strong-base resin, Purogold MTA 5011 [52]. They achieved a 99% extraction for Au with only a 5% co-extraction of Cu. In the elution process, 99.2% of gold was eluted using a mixed solution thiourea (0.01 M) and sulfuric acid (0.1 M).

Deng et al. (2020) investigated gold extraction from a cyanide-starved glycine solution [53]. In this study, they used a novel type of resin, IXOS-AuC, known as 'imprinted resin'. Unlike conventional IX resins, IXOS resin is synthesized using a combination of polystyrene and other monomers, which are bound together by a functionalized ligand that imprints the shape of the $Au(CN)_2^-$ molecule during the polymerization stage [53,54]. Thus, it can have high selectivity for gold, particularly in the presence of copper species. The extraction results demonstrated that 97.2% of gold could be extracted, while only 7.4% of copper was extracted. During the elution step, gold was effectively eluted through a 2-stage elution process involving a mixed solution of thiocyanate and acidic thiourea. Xiong et al. (2018) utilized a synthesized polymer-based microsphere, 2-aminothiazole-functionalized poly(glycidyl methacrylate) (A-PGMA), to extract $AuCl_4^-$ from a solution containing impurity metal ions such as Zn(II), Mg(II), Cu(II), Ge(IV), and B(III) [55]. The gold extraction mechanism involved both ion exchange and chelation between the S and N groups on the A-PGMA surface and $AuCl_4^-$, resulting in a 96%–98% gold extraction while leaving behind the co-existing metal ions. Moreover, the microsphere showed good recyclability with effective gold extraction observed even after five repetitive experiments.

Conventional IX resins often encounter several unsolved drawbacks, such as swelling and ineffective accessibility to adsorption sites, which hinder efficient kinetics. Despite these challenges, it is still evident that significant advancements in the IX process for recovering dissolved gold ions from leach liquors are anticipated in the near future. IX has numerous advantages over the Merrill–Crowe process, AC adsorption, and SX. Its exceptional selectivity, versatility, flexibility, efficiency, chemical stability, superior performance, renewability, environmental friendliness, and ease of process control and automation make it an optimal choice for gold extraction. In particular, there is great potential for the development of a variety of resins tailored for specific applications by manipulating their functional groups (e.g., newly developed IXOS resins and aminated microspheres). With the growing importance of low-carbon emission processes in future industries, there is an urgent need for further development in robust resin materials, allowing good selectivity and high elution capabilities to facilitate easier regeneration of the resin.

Table 2. An overview table summarizing selected previous ion exchange research results.

Gold Ion Type	Feed	Resin (Type)	IX Method	Recovery	Elution Method	Leaching Method	Reference
$Au(CN)_2^-$	Copper-rich refractory gold ore	Purogold A194 (strong base)	Shaking flask (pH 10.5–11, 5 g/L adsorbent, 170 rpm, 25 °C, 4 h)	89% Au (37% Cu)	–	Acid leaching (1 M H_2SO_4, 2 h)–Roasting (650 °C, 8 h)–Cyanide leaching (1.5 g/L NaCN, 25% *w*/*w* solids ratio, 1.5 L/min air flow rate, pH 10.5–11, 24 h)	[44]
	Copper-rich refractory gold ore	Purogold S992 (weak base)	Shaking flask (pH 10–10.5, 5 g/L adsorbent, 170 rpm, 25 °C, 4 h)	89% Au (9% Cu)	–	Acid leaching (1 M H_2SO_4, 2 h)–Roasting (650 °C, 8 h)–Cyanide leaching (1.5 g/L NaCN, 25% *w*/*w* solids ratio, 1.5 L/min air flow rate, pH 10.5–11, 24 h)	[44]
	Synthetic solution, 1000 mg/L Au, 14 mg/L Ag, 300 mg/L Ni, pH ≥ 11, 25 °C	NOTREN (strong base)	Column IX (0.025 g resin, 200 mL/h solution flow)	>90% Au (~100% Ag, ~20% Ni)	–	–	[56]
	Synthetic solution, 1000 mg/L Au, 1000 mg/L Cu, no pH control	Purolite D2780 (prepared as trimethylamine resin)	Overhead stirring (22 °C, pH > 9.8, 200 rpm, 72 h)	100% Au (98% Cu)	–	–	[57]
	Synthetic solution, ~1.5 mg/L Au, 200 mg/L CN^-, pH 11	Aminated sulfochlorinated polyethylene (PESCI) fiber (strong base)	Shaking flask	100% Au (57% Cu)	Shaking flask (5 N NaSCN)	–	[46]

Table 2. *Cont.*

Gold Ion Type	Feed	Resin (Type)	IX Method	Recovery	Elution Method	Leaching Method	Reference
$Au(S_2O_3)_2^{3-}$	Synthetic solution, 100 mg/L Au, 0.0005–0.005 mol/L Cu^{2+} and Ni^{2+}, 0.5–3 mol/L NH_4OH, 0.05–0.3 mol/L $S_2O_3^{2-}$	DOWEX 21K (strong base)	Shaking flask (200 rpm)	100% Au (at 5–20 g/L resin concentration)	Column IX (sodium or potassium salts, 2.5 mL bed, 12 BV/H * flow rate)	–	[49]
	Synthetic solution, 20 mg/L Au	DOWEX 21K (strong base)	Column IX (1.5 mL/g resin, 13 BV/h)	~80% Au	Column IX (2 M Na_2SO_3 + 1 M NH_3)	–	[48]
	Waste printed circuit board (WPCB) leaching solution	Purogold MTA 5011 (strong base)	Magnetic stirring (200 rpm, 24 h, pH 10)	87% Au (29% Cu)	Magnetic stirring (KSCN, 50 g/L resin, 500 rpm, 24 h)	Nitric acid leaching–Ammonia + thiosulfate leaching	[50]
	Synthetic solution, 2.5 kg Au/t-resin for desorption test	Amberlite IRA-400 (strong base)	Mechanical stirring (250 rpm, ambient temperature)	99.8% Au (desorption)	Column IX (1 M NaCl + 0.2 M Na_2SO_3, 10 BV desorbent, 6 BV/H)	–	[58]
	Synthetic solution, 25 mg/L $Au(S_2O_3)_2^{3-}$	PS-TETA (aminated microsphere)	Mechanical stirring (200 rpm, 298 K)	95% Au	Mechanical stirring (0.1 M Na_2SO_3, 24 h)	–	[51]
$Au(SCN)_2^-$	Pyrite concentrate	Purogold MTA 5011 (strong base)	Shaking flask (200 rpm, 25 °C)	99% Au (5% Cu)	Shaking flask (0.01 M Thiourea + 0.1 M H_2SO_4, 50g/L resin, 200 rpm, 25 °C, 24 h)	Bio-oxidation and thiocyanate leaching (0.2 M NaSCN + 0.01 M Fe^{3+}, pH 2, ambient temperature, 24 h)	[52]
Other	Synthetic solution, cyanide-starved gold glycine solution, 6.33 mg/L Au	IXOS-AuC	Shaking flask (1.5 g resin, 250 rpm, 24 hr, room temperature)	97.2% Au (7.4% Cu)	Shaking flask (1st: DI water, 2nd: sodium thiocyanate and acidic thiourea, 55 °C, 6 h)	–	[53]
	Synthetic solution, 100 mg/L $AuCl_4^-$	A-PGMA	Shaking flask (10 mg resin in 20 mL solution, 300 rpm, 5 h, pH 4, room temperature)	96%–98% Au	–	–	[55]

* BV/H: bed volume per hour.

4. Solvent Extraction of Gold

While not as widely practiced as adsorption, SX is one of the prevalent methods for selectively separating and concentrating gold in aqueous leach solutions. Also known as liquid–liquid extraction, this process employs two immiscible solvents to transfer a target substance from one solvent to another based on solubility differences. Its efficiency and performance are typically assessed by three key measures—distribution coefficient (K_D), extraction percentage ($\%E$), and selectivity factor ($\beta_{A:B}$). 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 representing the aforementioned three measures are shown below:

$$\text{Distribution coefficient } K_D = \frac{[\text{solute}]_{\text{organic phase}}}{[\text{solute}]_{\text{aqueous phase}}} = \frac{C_o}{C_a} \quad (7)$$

$$\%E = \frac{C_o V_o}{C_o V_o + C_a V_a} = \frac{C_o/C_a}{C_o/C_a + V_a/V_o} = \frac{K_D}{K_D + \frac{V_a}{V_o}} \times 100(\%) \quad (8)$$

$$\beta_{A:B} = \frac{K_{D,A}}{K_{D,B}} \quad (9)$$

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.

Compared to alternative techniques, SX offers several advantages including higher selectivity, faster kinetics and mass transfer, lower energy consumption, higher production capacity, continuous operation, and ease of automation. These advantages have led to the successful commercialization of SX processes across various industries worldwide [59,60]. Nonetheless, in order to broaden its application range and establish itself as a more prominent metal recovery technique, SX must address its critical drawbacks. Examples include the substantial generation of aqueous and organic waste, the use of harmful organic substances, and the high cost of chemicals.

Historically, SX in precious metal recovery dates back to its initial introduction by the International Nickel Company (INCO) in the UK. The process involved the use of dibutyl carbitol as an extractant for gold recovery from chloride solutions [61,62]. Later, in the 1990s, another industrial process for gold refining was developed, known as the Minataur^{TM} process [63]. This process, largely practiced in South Africa, Algeria, and Dubai [62], enables processing of raw materials with a high gold content of over 50%. It starts with the oxidative leaching of gold-containing solid feed, followed by SX of gold, and finally precipitation of gold powder, with remarkably high purity ranging between 99.99% and 99.999%. Additionally, the Anglo Platinum Refinery in South Africa recovers gold via SX using methyl-isobutyl-ketone.

Significant effort has been made to elucidate the mechanisms of gold extraction during SX. Jiang et al. (2003) [64] revealed that regardless of the type of modifiers or diluents used, aurocyanide anions are extracted by an amine following an ion-association mechanism. Kordosky et al. (1992) [65] demonstrated that in a cyanide environment, the gold extraction mechanism involves reagent protonation followed by ion-pair extraction. Another study by Kubota et al. (2019) [66] discussed SX mechanisms in a chloride medium and proposed similar mechanisms wherein, when a basic extractant is used, negatively charged metal complexes such as $[AuCl_4]^-$ form ion-pairs with the protonated extractant. This proposed mechanism is in line with findings from other studies [67,68].

Moreover, the impact of other ionic species on gold extraction has been investigated. Increased extraction and an increase in the salt content of the aqueous phase have been consistently observed. This is attributed to the "salting-out" effect in the gold extraction system, which was first observed in the work conducted by Mooiman and Miller (1991) [69].

To date, numerous SX processes have been developed for gold recovery from various feedstocks, an overview of which is provided in Table 3. Broadly, these processes can be classified into two groups based on the medium of feedstock: cyanide- or chloride-based aqueous feed. Regardless of the solution medium (cyanide or chloride), the impurities commonly observed include platinum group metals, Ag, Cu, Ni, Zn, Pb, and Fe.

For gold recovery from cyanide media, extractants such as dibutyl carbitol, Aliquat 336, N,N′-bis (2-ethylhexyl) guanidine, tributyl phosphate, and dibutylbutyl phosphonate have been utilized, all resulting in >95% gold extraction. Furthermore, a superior purity of >99.99% was achieved using TBP despite the high content of impurities in the feed aqueous solution (195 mg/L Au, 136 mg/L Cu, and 1.8 mg/L Ag) [70].

To extract gold from chloride media, Cyanex extractants and TBP are predominantly used. Except for one instance where ethylenodiamino-bis-acetylacetone was used as an extractant that resulted in 65% gold extraction, previous studies have consistently achieved >95% gold extraction, similar to cyanide media. Commonly co-extracted impurities were found to be Sn, Pd, and Pt. Although a synergistic effect of extractants was observed in some studies [71], limited research has been dedicated to investigating the synergistic effects of extractants in SX processes for gold recovery.

To transfer the gold ions loaded in the organic phase back to the aqueous phase, a variety of stripping agents have been employed. These agents are designed to stabilize gold ions in the aqueous phase to facilitate effective recovery of Au, simultaneously to demonstrate selectivity towards gold over other metals that may have been co-extracted, such as Pd(II) and Pt(IV). Among the most commonly used stripping agents for gold recovery are thiosulfate, thiourea, sulfite, sulfide, and hydrazine. A previous study has demonstrated that gold stripping by inorganic salts follows the perchlorate effect, wherein the effectiveness of stripping agents is in the following order: $ClO_4^- > SCN^- > I^- > NO_3^- > Br^- > HSO_4^- > SO_4^{2-} > OH^-$ [72].

Given the numerous advantages of SX over other comparable technologies, there is significant potential for this technique to further expand, particularly in the areas of gold extraction, separation, and concentration. To advance its commercialization and industrialization, greater efforts should be made towards deepening our understanding of the mechanisms involved in SX, optimizing existing processes, developing innovative and robust processes, performing large-scale validation tests, and conducting technoeconomic and life cycle analyses.

Table 3. An overview table summarizing the details of previous research work undertaken for solvent extraction of gold.

Feed	Extractant(s)	Diluent(s)	Other Element(s) in Solution	Best Performance	Ref.	Comments
Alkaline cyanide solution, 2000 mg/L Au	Tetradecyldimethyl benzylammonium chloride + TBP	n-Heptane	–	99.9% extraction	[64]	Au is stripped with 2,2′-thiodiethanol, glycol, or ammonium thiocyanate aqueous solutions.
Cyanide leach solution, 1000 mg/L Au	N,N′-bis (2-ethylhexyl) guanidine	Exxon aromatic 150	Ag, Zn, Cu	95% extraction	[65]	The used extractant extracts Au with a high extraction percentage at pH < 10.5 and shows good selectivity over Cu and Fe.
Alkaline cyanide solution, 1000 mg/L Au	TBP, DBBP, Di(2-ethylhexyl)2-ethyl hexyl phosphonate, tributyl phosphine oxide	Xylene	–	100% extraction	[69]	Au extraction efficiency of 100% is achieved when using TBP as an extractant at pH 1.
Synthetic cyanide solution, 602 mg/L Au	TBP	Escaid 110, Shellsol 2046	Ag, Cu, Ni, Zn, Fe	99.99% purity	[70]	Loadings as high as 5000 mg/L Au are obtained in the organic. Phosphine oxides may have some merit as synergists.
Alkaline cyanide solution, 500 mg/L Au	Dibutyl carbitol	n-Octanol + kerosene	–	96.2% extraction	[73]	The extraction equilibrium is reached within 2 min.
Cyanide leach solution, 10 mg/L Au	Aliquat 336	Solvesso 150	Cu, Fe, Ni, Zn, Ag, Co, As, Sb, Ca	99.9% extraction	[74]	An aromatic diluent, such as Solvesso 150, needs to be used to prevent emulsion formation.
Synthetic cyanide leach solution, 10 mg/L Au	Quarternary ammonium cetylpyridinium bromide + TBP	n-Dodecane	–	>98% extraction	[75]	About 90% of Au is stripped using a 3 mol/L KSCN solution.
Thiocyanate solution, 20 mg/L Au	Alamine 336	Hexane	Fe	97.6% recovery	[76]	Sodium hydroxide/thiocyanate, ammonium hydroxide, and acidic thiourea are used for Au stripping.
Chloride leach solution, 197 mg/L Au	Vacuum pump oil	Toluene	Cu, Fe, Pd, Ni, Zn	>95% extraction	[77]	The maximum loading capacity of Au in 10% VPO in toluene is found to be 1.08 g/L.
Chloride–hypochlorite leach solution of waste PCBs, 152 mg/L Au	TBP	Exxol D80	Cu, Ni	99% extraction and recovery	[78]	The extraction process is determined to be spontaneous and exothermic.

Table 3. *Cont.*

Feed	Extractant(s)	Diluent(s)	Other Element(s) in Solution	Best Performance	Ref.	Comments
Chloride leach solution, 100 mg/L Au	Cyanex 272, LIX 63	Kerosene	Pt, Pd	99% extraction and recovery	[79]	Only Au is extracted by Cyanex 272, whereas both Pd and Au are extracted by LIX 63.
Chloride leach solution, 100 mg/L Au	Cyanex 272	Kerosene	Ag, Cu, Ni, Sn, Zn	100% extraction	[80]	Au and Sn are co-extracted into the organic phase.
Synthetic chloride solution, 100 mg/L Au	Diethyl carbonate	Diethyl carbonate, D70, or a mixture thereof	Cu	98.7% extraction	[68]	The highest Au extraction is obtained at O/A = 1.1 and with the addition of 5 vol% ethanol.
Synthetic chloride solution, 75 mg/L Au	Cyanex 302	Toluene	Cu, Ni, Pd, Pt, Fe	>99% extraction and recovery	[81]	Au loaded in the organic phase is stripped with $Na_2S_2O_3$.
Acidic chloride-based solution, 16 g/t Au in PCB	Ethylenodiamino-bis-acetylacetone	Toluene, chloroform, methylene chloride, 2-ethylhexanol	Pt, Pd	65% extraction	[67]	A 3-step stripping process is proposed for the recovery of Au, Pt, and Pd in the EDAB-acac-methylene chloride system.
Polysulfide solution, 32.5 mg/L Au	TBP, amine alkyl extractants	n-Octane, kerosene	Cu	95.5% extraction	[71]	A mixture of N1923-TBP shows a synergistic effect.
Discarded mobile phone leachate, 160 mg/L Au	D2EHAG	n-Dodecane	Pt, Pd, Pb, Zn, Al, Fe, Ni, Cu	>90% extraction	[66]	D2EHAG exhibits a high affinity for Au(III) ($[AuCl_4]^-$) compared with other metal ions.
Printed substrate leachate, 150 mg/L Au	Polyoxyethylene nonyl phenyl ethers	Chloroform, dichloromethane, dichloroethane	Pd, Pt, Zn, Cu, Fe	98% extraction, 88% recovery	[82]	The Au extraction increases with an increase in the ethylene oxide number of the extractant.
Waste PCBs leachate, 120 mg/L Au	Acidified N1923	Sulfonated kerosene	Co, Ag, Pb	95.6% recovery	[83]	N1923 extracts Au through an anion exchange mechanism.
Waste PCBs leachate, 110 mg/L Au	Trioctylamine	Kerosene	Cu, Sn, Ni, Cr, Ba, Sb, Pb, Ti, Zn	99.6% extraction	[84]	After SX, selective back-extraction is performed using 0.1M NaOH solution which allows selective precipitation of Cu.
Waste PCBs leachate, 13 g/t Au in PCB powder	Tertiary amide	Toluene	Cu	>99% extraction	[85]	Prior to SX, 95% gold is leached from the residue arising from stage-one leaching by using 3 mol/L H_2SO_4 with 3 mol/L NaBr.

TBP: tributyl phosphate; DBBP: dibutylbutyl phosphonate; D2EHAG: N-[N,N-di(2-ethylhexyl)aminocarbonylmethyl]glycine.

5. Ionic Liquids and Deep Eutectic Solvents—Needs and Future Trends

The recovery of valuable metals from various sources has heavily relied upon using water-based solvents. The recent rapid expansion of industrial sectors necessitates broadening the spectrum of metal sources, including recycling from end-of-life sources, as well as exploring more versatile and environmentally friendly solvents. Non-aqueous solvents such as ionic liquids (ILs) and deep eutectic solvents (DESs) have the potential to improve and advance many metal recovery processes. ILs, in particular, are a family of molten salts consisting of organic cations and organic or inorganic anions. They typically exist as a liquid phase at low temperatures and are considered metal recovery solvents for their robustness and environmental friendliness, along with their chemical, electrochemical, and thermal stability. Furthermore, they offer versatility and can be tailored to specific metals, making them particularly apt for complicated systems commonly encountered in treating secondary sources. ILs are typically classified into six subgroups: neutral, protic and aprotic, chiral, polymeric, metallic, and bio-ionic liquids [86]. The recent literature extensively covers the advancements and physicochemical characteristics of these solvents [87–89].

The most commonly used IL cations include imidazolium, pyridinium, ammonium, and phosphonium, which are associated with anions such as halides, tetrafluoroborate $[BF_4]^-$, hexafluorophosphate $[PF_6]^-$, bis(trifluoromethyl sulfonyl)-imide $[Tf_2N]^-$, carboxylates $[RCO_2]^-$, alkyl sulfates $[CnSO_4]^-$, and alkyl sulfonates $[CnSO_3]^-$ [90,91]. The gold (III) extraction from secondary sources relies upon non-cyanide-based lixiviants and, hence, typically produces gold in the form of anionic tetrachloroaurate $[AuCl_4]^-$ or tetrabromoaurate $[AuBr_4]^-$, which are frequently extracted by cationic protonated amines [92–94]. Recent studies have indicated that ILs can easily replace these solvents. Most prior studies have utilized ILs to extract gold-bearing ions from water-based solutions after leaching. For example, AuX_4^-, where X represents either Cl^- or Br^-, has been successfully extracted from solutions using water-soluble ILs such as 1-octyl-3-methylimidazolium chloride ($[OMIM]^+$), 1-octylpyridinium ($[OPYR]^+$), or MO1-methyl-1-octylpyrrolidinium ($[MOPYRRO]^+$), wherein the extraction of an anionic gold complex in the IL phase involves an anion exchange between one gold complex and one NTf_2 anion [95].

There have been attempts to recover gold (I) from cyanide solution using ILs such as 1-hexyl-3-methylimidazolium hexafluorophosphate ([HMIM][PF6]), 1-butyl-3-methylimidazolium hexafluorophosphate ([C4MIM][PF6]), and 1-hexyl-3- methylimidazolium hexafluorophosphate ([C6MIM][PF6]) [96]. A recovery and separation study of a gold and platinum halogen complex using tetra alkyl ammonium cations demonstrated an excellent extractability of gold with various anions, confirming that the more hydrophobic ions resulted in a higher yield. The extraction yield increases in the order $Tf_2N^- < DCA^- < SCN^-$, with all systems progressing via an anion exchange mechanism. The study indicated that Tf_2N^- was suitable for efficiently separating gold and platinum from mixed Au/Pt solutions [91].

On the other hand, DESs are a class of liquids that are mixtures of hydrogen bond donors and acceptors. The melting point of DESs is far less than those of two individual components, and their characteristics are very similar to those of ILs [87]. DESs often have high ionic strengths, and they are less expensive and relatively harmless compared to ILs. For example, choline chloride (Figure 4) and a hydrogen bond donor such as glycerol have been used in SX to separate and purify metals including Au, Pd, In, Re, etc. [97,98]. A study on the recovery of Au(III) from a hydrochloric medium using three DESs based on quaternary ammonium salts, [N3333]Br, [N4444]Br, and [N8881]Br, and N-hexanoic acid was carried out. An excellent extraction and a complete stripping with $NaBH_4$ were reported in this study [98].

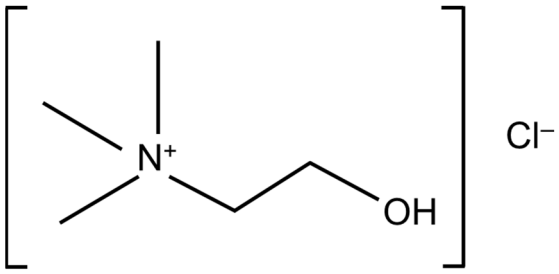

Figure 4. Chemical structure of choline chloride.

Some of the problems associated with adopting solvents such as ILs and DESs in gold recovery processes are inherent drawbacks such as high viscosity, difficulties recycling, high costs for large-scale operations, and slow kinetics due to two distinctive phases involved in the extraction reaction. A study attempted to ease such problems by introducing an upper critical solution temperature (UCST)-type IL. This thermoregulated IL had increased solubility at high temperatures and was entirely miscible, introducing a homogeneous system and enabling the metal recovery reaction to proceed at an enhanced rate [99]. Many investigations have been conducted regarding ILs and DESs, and relevant research activities have had limited success. The research and development of these systems are still emerging, and more appropriate and versatile fundamental approaches are needed to popularize and substantiate the process in the field of extractive metallurgy.

6. Concluding Remarks

A thorough literature review was conducted to summarize both historical and recent advancements in hydrometallurgical gold recovery methods. This review paper covers various gold recovery techniques, including the Merrill–Crowe process, adsorption, ion exchange, solvent extraction, and emerging novel approaches that utilize ionic liquids and deep eutectic solvents. Over 95 journal articles were meticulously examined to critically evaluate each technology's current status and evolving trends.

The Merrill–Crowe and AC processes have significantly advanced in industrial applications, with over 70% of treatments currently employing the processes in the recovery of noble metals, including gold, from leach liquor. The Merrill–Crowe process effectively removes gold complexes due to its high recovery rate, simplicity, and cost efficiency. However, it requires extensive pre-treatment to clear the solution and poses a high zinc consumption. The electrochemistry of the gold recovery mechanisms is well established, but the process is unsuitable for low-grade ores and lacks good selectivity, especially against silver.

On the other hand, the AC process shines with its high efficiency, flexibility, and the high purity of gold it yields. However, it grapples with challenges such as carbon fouling, the cost of carbon, relatively complex processes, and cyanide management. Despite these hurdles, significant strides have been made in understanding the adsorption process of gold onto activated carbon. While the full intricacies remain elusive due to the complex nature of the activated carbon surface, various mechanisms reported in the literature have been reviewed. This ongoing research instills hope that a complete understanding of the adsorption process is within our reach. We firmly believe that the AC process holds great promise for the future recovery of gold from primary ores and secondary resources.

The ion exchange process has shown remarkable effectiveness in removing and recovering gold from leach liquor. It shows exceptional selectivity, adaptability, and efficiency. Moreover, it maintains chemical stability, offers excellent renewability, and poses minimal environmental impact. There is significant potential to develop customized resins for different applications by tailoring functional groups and even backbones, suggesting that promising advances in gold selectivity and resin recyclability are likely, particularly in the treatment of gold from more complicated sources (e.g., refractory ores, secondary resources) where flexibility and adaptability could be industrial issues.

Considerable research in solvent extraction has focused on extracting gold from cyanide or chloride media. However, a major challenge lies in the co-extraction of common impurities, such as platinum group metals, due to the lack of selectivity of the investigated extractants. Moreover, most studies have been confined to lab-scale batch experiments, with limited efforts towards scaling up and commercializing the process. Overcoming the intrinsic limitations of solvent extraction, including the use of harmful and costly organic substances, is crucial for its industrialization.

Meanwhile, emerging techniques for gold recovery through hydrometallurgical routes show promise. The utilization of new chemical classes, such as ionic liquids and deep eutectic solvents, holds great potential for developing more sustainable and efficient gold recovery processes. Despite the challenges they face, including high viscosity, limited recyclability, high costs, and slow kinetics, these chemicals demonstrate the potential to enhance various gold recovery processes beyond the scope of this review, including leaching, ion exchange, solvent extraction, and electrolysis. More efforts are needed to advance our understanding of their properties and applicability for gold extraction from diverse resources.

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