

Review

Industrial Relevance of Oxidants and Leaching Accelerants in Cyanidation of Gold Sulfide Ores

Maria Matar, Bona Lim, Boris Albijanic *, Elsayed Oraby, Emmanuel Baawuah, William Staunton and Kylie Blackwell

Western Australian School of Mines, Curtin University, Perth, WA 6845, Australia; m.matarensuncho@postgrad.curtin.edu.au (M.M.); bona.lim@curtin.edu.au (B.L.); elsayed.oraby@curtin.edu.au (E.O.); emmanuel.baawuah@curtin.edu.au (E.B.); w.staunton@curtin.edu.au (W.S.); kylie.blackwell@curtin.edu.au (K.B.)

* Correspondence: boris.albijanic@curtin.edu.au

Abstract

Gold cyanidation remains one of the most important hydrometallurgical processes in the mining industry. Gold dissolution kinetics and cyanide consumption are governed by coupled anodic–cathodic electrochemical reactions and influenced by pulp pH, particle size, cyanide concentration, mineralogy, and solution chemistry. Despite extensive studies on individual additives in gold cyanide leaching, a coherent synthesis of oxidants and leaching accelerants in modern gold cyanidation remains lacking. The main purpose of this paper is to present a critical review of the literature on leaching accelerants and oxidants used to enhance gold cyanide leaching kinetics and reduce cyanide consumption. The literature highlights that iron sulfide minerals, found in gold ores, can significantly increase cyanide and oxidant consumption through increased oxidant demand, surface passivation, and galvanic interactions that suppress gold dissolution kinetics. This review article summarises the leaching accelerants used, where lead nitrate plays a central role in gold cyanide leaching, and emphasises that its effectiveness is associated with suppression of sulfide-related passivation and favourable modification of surface electrochemistry of gold. The synergistic effects of leaching accelerants with different oxidants on leaching performance are also assessed, with emphasis on their electrochemical roles.

Keywords: gold cyanidation; leaching accelerants; leaching oxidants

1. Introduction

Gold is an important metal with global demand driven by its applications in jewellery, finance, and emerging technologies [1,2]. However, declining ore grades and increasing ore complexity have placed growing pressure on mineral processing operations to develop more efficient and selective extraction technologies. As a result, optimisation of gold hydrometallurgical processes remains a critical research focus for both industry and academia.

One of the most common techniques of gold extraction is cyanidation. This technique was developed to optimise the gold extraction from ores. Oxidants such as oxygen, hydrogen peroxide, ferric, NBS, and permanganate are used in gold cyanidation to improve the dissolution of gold and decrease the consumption of cyanide [3].

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While it is well known that oxygen is critical in cyanidation, the low solubility of oxygen has been a challenge at the processing plants to achieve the desirable concentration of dissolved oxygen (DO) [4]. In most cases, cyanide concentrations are greater than the stoichiometric levels of DO required in leaching slurry, which makes the DO concentration a rate-controlling factor in leaching [4]. Furthermore, gold processing plants in Western Australia utilise hypersaline water in the circuits, which makes maintaining pH and DO even more challenging than other operations with non-saline water [4]. Thus, to overcome this issue and provide a sufficient DO level in the solution, using additional oxidants as well as leaching accelerants has been widely considered in the industry. According to the benchmarking survey conducted by the Amira P420 Gold Technology Group, seven processing plants reported that they are using lead nitrate in the leach circuit. The concentration range of lead nitrate varies from 0.03 kg/t to 4.3 kg/t of feed [5].

Although cyanidation is a mature and widely implemented technology, it continues to be actively optimised, particularly for copper–gold and sulfide-bearing ores where reagent consumption and kinetics are strongly ore-dependent [4–7]. Considerable research has also been directed toward non-cyanide lixiviants (e.g., thiosulfate, thiourea, glycine) driven by toxicity and environmental considerations [8–13]. However, these alternatives still face major barriers to broad industrial adoption, including process complexity, operating cost, and ore-specific performance limitations [2]. Consequently, improving conventional cyanidation through targeted use of oxidants and leaching accelerants remains a practical and high-impact strategy for modern gold plants facing increasingly complex and refractory ores, declining head grades, reduced recoveries, and growing environmental pressures associated with cyanide usage [2]. Alternative lixiviant systems (e.g., thiosulfate, glycine), which could replace cyanide are outside the scope of this review.

While numerous studies have investigated individual additives, there is still a lack of a coherent and critical synthesis focused on the role of oxidants and leaching accelerants in modern gold cyanidation, particularly in terms of their mechanisms, limitations, and practical relevance. This review aims to address this gap by examining the function of oxidants and leaching accelerants in enhancing gold dissolution, with emphasis on their electrochemical roles and interactions with different sulfide minerals. In addition, the potential synergetic effects between oxidants and leaching accelerants are critically assessed, highlighting conditions under which combined reagent strategies may provide improvements in gold leaching performance beyond conventional cyanidation practice.

2. Electrochemistry of Gold Cyanidation

Gold cyanidation is an electrochemical dissolution process in which gold is oxidised in the presence of cyanide [14]. Effective gold leaching requires a suitable ligand (CN[−]), an oxidant, and alkaline conditions that stabilise cyanide and favour gold oxidation [14]. The Elsner equation describes gold cyanidation [15]:



Gold dissolution progresses via coupled anodic and cathodic half-reaction equations (see Figure 1). The anodic process involves oxidation of gold to form the soluble aurocyanide complex, while the cathodic process involves reduction of dissolved oxygen [15,16].

Pulp pH plays a key role in cyanide leaching of gold. Cyanidation is typically conducted above pH 10 to maintain cyanide as CN[−] and prevent the formation of hydrogen cyanide gas (HCN) [14,15]. When pulp pH is higher than 11, gold dissolution decreases due to reduced efficiency of oxygen reduction and passivation by surface metal hydroxide species, and by sulfur species if sulfides are present in the ore [14]. However, when pulp pH is lower than 8, significant conversion of CN[−] to HCN occurs, leading to cyanide loss and serious safety hazards [14].

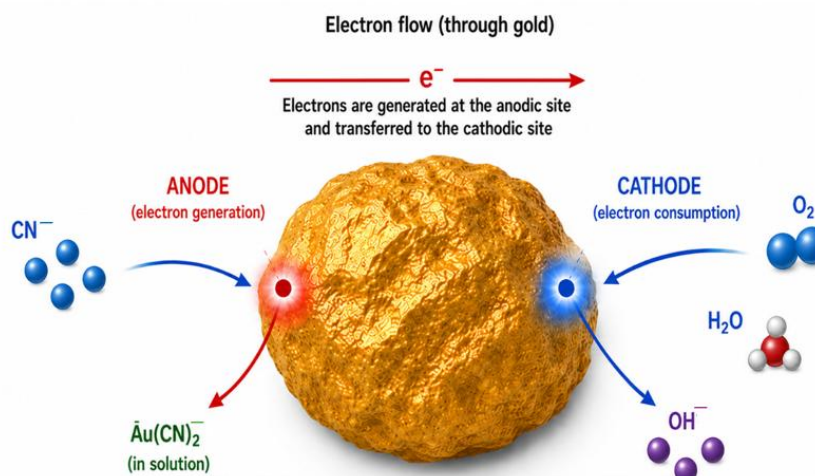


Figure 1. Electrochemical mechanism of gold cyanide leaching.

One of the main challenges in gold cyanidation is the poor selectivity of cyanide, which readily forms stable complexes with other metals such as copper, iron, and silver, leading to increased cyanide consumption [17–20]. Metal–cyanide species may form during cyanidation. These complexes involve dissolved copper, iron, nickel and zinc species and are important because they influence free cyanide availability, reagent consumption, metal speciation, and solution chemistry during gold leaching [17]. Among these species, iron cyanides (ferrocyanide and ferricyanide) are particularly stable under alkaline conditions, whereas copper, nickel, and zinc cyanide complexes contribute to cyanide consumption and may affect downstream cyanide recovery and detoxification processes [17].

In addition to this lack of cyanide selectivity, many gold ores are characterised by coarse gold (often due to inefficiencies in gravity circuits), partially liberated gold, surface passivation of gold, and limited residence times, all of which contribute to reduced gold recovery under conventional cyanidation conditions [14,21]. These limitations support the use of oxidants and leaching accelerants in gold cyanidation, as they modify the surface electrochemistry of gold, thereby enhancing gold dissolution kinetics and reducing surface passivation of gold [17].

3. Gold Cyanidation in the Presence of Sulfide Minerals

Gold may be disseminated in different sulfide minerals such as pyrite, pyrrhotite, arsenopyrite, and chalcopyrite, as well as in non-sulfide minerals such as quartz [19]. The extraction efficiency of gold from sulfide-bearing ores is directly related to the consumption of cyanide and oxidants [18]. One of the main reasons for this behaviour is that gold particles are often finely disseminated and partially encapsulated within sulfide mineral matrices, requiring reagents to penetrate the mineral surface to achieve effective dissolution.

Sulfide minerals influence gold cyanidation through three main mechanisms: (i) gold surface passivation [21], (ii) cyanide and dissolved oxygen consumption [20], and (iii) galvanic interactions [21]. Gold surface passivation is widely regarded as the dominant mechanism responsible for reduced gold dissolution (see Figure 2). Sulfide species or their oxidation products adsorb onto the gold surface and form sulfur-rich or gold sulfide (Au_xS) films that block electrochemically active anodic and cathodic sites, restrict cyanide and oxygen access, and suppress electron transfer, thereby significantly reducing the gold dissolution rate. In addition, sulfide minerals consume cyanide and dissolved oxygen during oxidation, decreasing the availability of these reagents for cyanidation and further reducing leaching efficiency. In contrast, galvanic interactions between gold and conductive

sulfide minerals generally increase gold dissolution by facilitating electron transfer and shifting the cathodic oxygen reduction reaction from the gold surface to the sulfide mineral (see Figure 3). However, the beneficial effect of galvanic interactions may be offset by gold surface passivation and the consumption of cyanide and dissolved oxygen, with the overall leaching performance depending on the mineralogical characteristics of the ore and the prevailing leaching conditions.

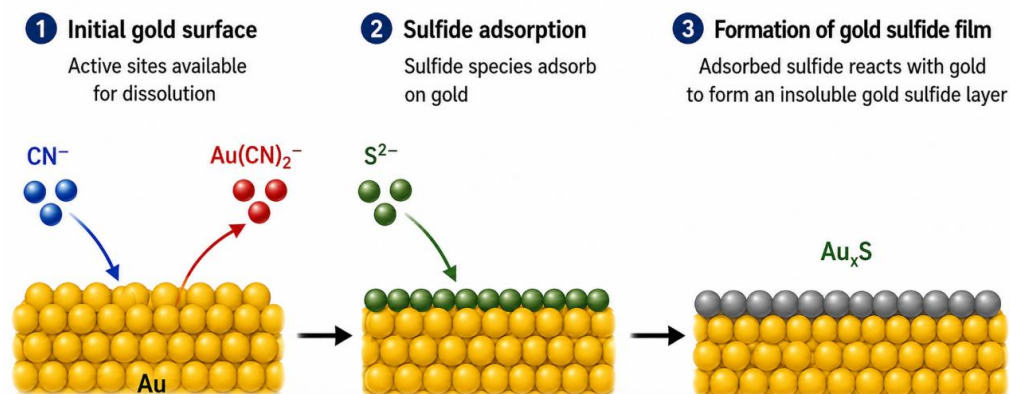


Figure 2. Mechanism of sulfide-induced passivation of gold in cyanide leaching.

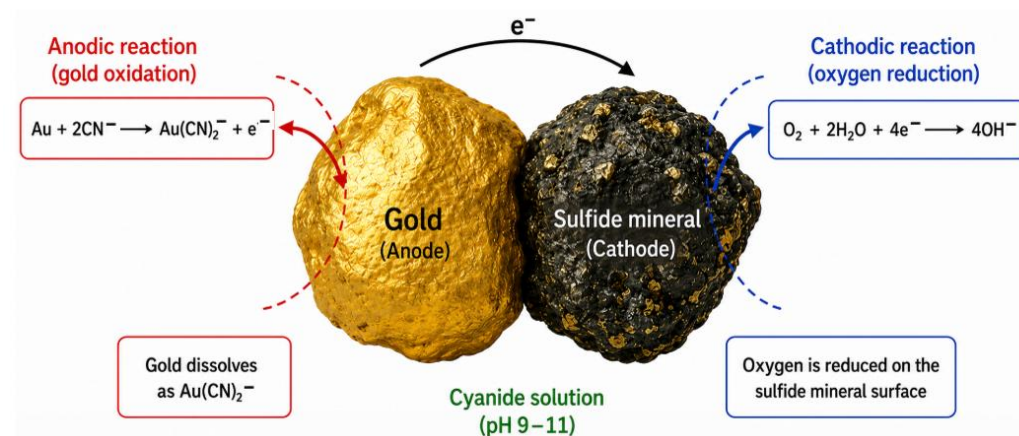


Figure 3. Mechanism of galvanic interactions between gold and sulfide mineral in cyanide solution.

Iron sulfide minerals strongly influence gold leaching through increased oxidant demand, surface passivation, and galvanic interactions [5]. For example, pyrite is generally considered a relatively less reactive sulfide mineral; however, its presence can still significantly influence gold dissolution kinetics [20]. Pyrite oxidation can generate sulfur-rich surface films and iron oxyhydroxide species, which may partially block gold surfaces and suppress electron transfer during cyanidation [20]. However, under certain conditions, pyrite can also enhance gold dissolution through galvanic coupling, where pyrite acts as a cathodic surface promoting oxygen reduction and increasing the mixed potential of the system [21]. For example, studies have shown that just under 1% pyrite in combination with cyanide and oxygen can lead to higher gold extraction compared with pyrite-free ore [21]. For a 5% pyrite ore, a 20% improvement in leaching rate was observed, where complete gold extraction was achieved within 2 h, whereas the pyrite-free ore required 4 h to reach similar recovery [21]. These apparently contradictory effects highlight that the role of pyrite is controlled by competing processes of galvanic enhancement and surface passivation [21].

Pyrrhotite is a highly reactive sulfide mineral and typically exerts a strongly negative effect on gold cyanidation [21]. For example, when the pyrrhotite content increased from 1.2% to 2.4%, gold extraction decreased from approximately 60% to 40% [21]. Pyrrhotite significantly increases cyanide consumption due to the rapid oxidation of sulfur species, which react with cyanide to form thiocyanate [21]. In addition, pyrrhotite promotes gold passivation through the formation of sulfur-rich films, iron oxidation products, and strong galvanic interactions, particularly during grinding with forged steel media, resulting in reduced gold leaching efficiency [22]. Among common sulfides, pyrrhotite typically imposes the highest oxidant demand and therefore represents the most challenging mineral for cyanidation [22].

Arsenopyrite is more reactive than pyrite but less reactive than pyrrhotite [23]. For example, in ores containing 23% arsenopyrite, gold recoveries of approximately 91% were achieved after 24 h with cyanide consumption of around 3 kg/t [23]. However, arsenopyrite can significantly increase processing costs because efficient gold extraction often requires fine grinding (around 60 μm) followed by roasting to achieve recoveries above 80% [24]. By contrast, studies indicate that the presence of ferrous ions can facilitate arsenopyrite oxidation and reduce oxygen consumption during leaching [25]. Chen et al. (2019) showed that hydrogen peroxide exhibits a strong oxidation effect on arsenopyrite and concluded that arsenic sites are more reactive than iron sites during surface oxidation [26].

Chalcopyrite can significantly reduce gold leaching recovery, often by up to 30% compared with chalcopyrite-free ores [21]. During cyanidation, chalcopyrite dissolution releases Cu^{2+} , leading to increased cyanide and oxygen consumption, and enhanced galvanic interactions, which suppress gold dissolution kinetics and reduce overall gold recovery. However, in systems where sulfate and chloride ions are present, fine grinding can enable high copper extraction efficiencies (up to 94%), indicating that copper–gold ores can potentially achieve co-extraction of both metals [27]. In such systems, the selectivity and effectiveness of oxidants and leaching accelerants become critical for controlling gold recovery relative to copper dissolution [27].

Sphalerite generally has little effect on gold leaching performance, whereas galena can improve gold leaching due to the presence of lead species [28]. The interaction between gold and silicate minerals is also important [29].

Although quartz is chemically inert, gold dissolution is often higher in ores dominated by coarse quartz because fewer fine silicate minerals are present to form slimes, resulting in improved solution access and mass transfer to gold surfaces [29]. However, chemically activated quartz (e.g., after roasting at $\sim 650\text{ }^{\circ}\text{C}$) can promote strong gold–silicate associations or encapsulation, resulting in low gold leaching rates [30].

4. Oxidants in Gold Cyanidation: Mechanism, Performance and Comparative Assessment

Oxidants play a fundamental role in gold cyanidation because gold dissolution is controlled by coupled anodic and cathodic electrochemical reactions [31]. While cyanide acts as the complexing ligand for dissolved gold, an oxidant is required to sustain the cathodic reaction and thereby drive anodic gold oxidation. Consequently, the availability, reactivity, and selectivity of the oxidant strongly influence gold recovery, leaching kinetics, and cyanide consumption. Several oxidants have been investigated for gold cyanidation, including dissolved oxygen, hydrogen peroxide, sodium m-nitrobenzene sulfonate, and ferricyanide [3,32,33]. Although each oxidant can enhance gold dissolution under specific conditions, their practical applicability differs significantly depending on ore mineralogy, operating conditions, and economic considerations.

4.1. Oxygen

Dissolved oxygen remains the most widely used and industrially important oxidant in gold cyanidation. Oxygen participates directly in the cathodic reduction reaction and is an essential component of the Elsner reaction, as shown in Equation (1) [15]. Numerous studies have demonstrated that increasing dissolved oxygen (DO) concentration enhances gold dissolution rates, improves cyanide utilisation, and increases overall gold recovery. As a result, oxygen is universally applied in commercial cyanidation circuits [34,35].

Challenges remain when utilising oxygen in gold cyanidation, as oxygen mass transfer rather than chemical reaction kinetics controls gold leaching kinetics [36]. Naturally, oxygen has low solubility in water at ambient temperature. With air, the maximum DO concentration at 25 °C is 8 ppm. If 100% oxygen is used, the DO concentration can reach 40 ppm; however, utilising 100% oxygen is impractical due to the high operating cost [36]. Moreover, increasing the DO in high pulp density slurry requires a substantial volume of high-purity oxygen to achieve the stoichiometric concentrations for cyanidation, for example, 300 ppm of sodium cyanide and 20 ppm of DO [37].

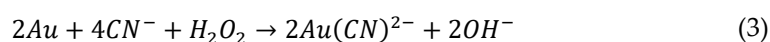
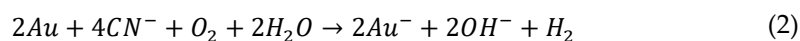
Several methods can be adapted to boost oxidation along with cyanidation, such as roasting and pressure oxidation [38], to overcome the low solubility of DO in the solution. However, these methods require significant infrastructure and capital investment. An effective method to increase dissolved oxygen concentration is to utilise oxygen sparging or oxygen injection [39].

For oxygen injection, one conventional technique is the use of a sintered glass bubbler [40]. However, this approach presents several limitations in gold production, including low oxygen dissolution efficiency (approximately 26%) and ineffective oxidation of slowly oxygen-consuming constituents in the ore [37]. Therefore, for enhanced gas dissolution efficiency, Filblast utilises a patented gas-dispersion technique in which either liquid or slurry serves as the medium for gas atomisation [37]. The Filblast unit was found to be a better option for a lower oxygen flow than the sintered glass bubbler, with the Filblast unit requiring only 5% of the flow required by the bubbler [37].

Another industrial-scale example of oxygen injection in gold cyanide leaching is the Multi Mix Systems (MMS) unit, which delivers high dissolved oxygen concentrations [34]. This enhances leaching kinetics and reagent utilisation, enables high gold extraction, and reduces excessive cyanide and oxygen consumption, thereby eliminating the need for an additional oxygenation stage [34]. These technologies improve oxygen transfer efficiency and increase leaching rates without fundamentally altering the chemistry of the cyanidation process. Consequently, oxygen remains the benchmark oxidant against which all alternative oxidants are compared.

4.2. Hydrogen Peroxide

Hydrogen peroxide has attracted considerable attention as a supplementary oxidant because it can both directly oxidise gold and generate dissolved oxygen through decomposition. Compared with oxygen, hydrogen peroxide possesses a substantially higher oxidation potential, allowing it to accelerate gold dissolution under certain conditions [41]. The presence of hydrogen peroxide increases the concentration of dissolved oxygen in the cyanide leaching solution and helps with the gold dissolution (see Equations (2) and (3)) [41]:



The concentration of hydrogen peroxide can affect the rate of dissolution of gold. Guzman et al. [41] found that small concentrations of hydrogen peroxide, less than 0.0025 M, shift the mixed potential of cyanidation to gold dissolution potentials because of a sig-

nificant decrease in gold dissolution rate. When the concentration of hydrogen peroxide is from 205 to 410 ppm, gold recovery increased from 48.52% to 68.85% [42] as the stronger oxidising conditions enhance anodic dissolution of gold during cyanidation [41].

However, hydrogen peroxide suffers from several limitations that restrict its industrial application. First, hydrogen peroxide is relatively expensive compared with oxygen [41]. Second, excessive peroxide concentrations may result in inefficient reagent utilisation because peroxide decomposes rapidly in the presence of catalytic minerals, dissolved metals, and sulfides [41,43]. Third, uncontrolled peroxide addition may promote undesirable side reactions and increase reagent consumption. Consequently, despite its strong oxidising capability, hydrogen peroxide is generally considered a niche oxidant suitable for specific ores rather than a universal replacement for oxygen.

4.3. Sodium *m*-Nitrobenzene Sulfonate

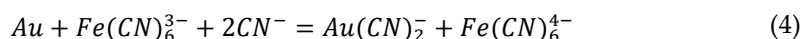
Sodium *m*-nitrobenzene sulfonate (NBS) has been investigated as an electrochemical oxidant capable of enhancing gold dissolution. Studies have shown that the rate of gold dissolution increases approximately linearly with increasing NBS concentration, indicating that NBS can effectively participate in cathodic reactions associated with cyanidation [3,32].

From an electrochemical perspective, NBS offers advantages because its reduction occurs in a similar potential region to oxygen reduction. Nevertheless, its practical application remains limited [3,32]. Unlike oxygen, NBS is ineffective for oxidising sulfide minerals commonly associated with refractory gold ores [3,32]. The reduction potential of NBS is insufficient to effectively promote sulfide oxidation, particularly for reactive sulfides such as pyrrhotite and arsenopyrite. As a result, NBS cannot adequately address sulfide-related oxygen demand and sulfur passivation that frequently limit gold recovery [3,32].

This limitation is significant because many modern gold deposits contain substantial sulfide contents. Therefore, although NBS may accelerate gold dissolution in relatively simple ores, its usefulness decreases considerably in complex sulfide-bearing systems where oxygen remains more effective [3,32].

4.4. Ferricyanide

Ferricyanide has been applied in gold cyanidation as a stable Fe(III)–cyanide complex capable of oxidising gold under alkaline conditions without substantially consuming free cyanide [44]. The dissolution of gold in the presence of ferricyanide can be described by Equation (4) [44].



Xie and Dreisinger [44] reported that gold extraction increased by approximately 25% in the presence of ferricyanide after only 1 h of leaching, and reached 92%–94% after 48 h. However, the effectiveness of ferricyanide is highly ore-specific and strongly dependent on the mineralogical composition of the gold ore [44]. For example, sulfide minerals such as pyrrhotite and chalcopyrite readily consume ferricyanide, reducing its availability for gold oxidation [45,46]. Consequently, ferricyanide performance deteriorates significantly in sulfide-rich ores. Furthermore, the introduction of ferricyanide adds complexity to cyanide solution chemistry and may complicate downstream process management [44–46]. These limitations have restricted its widespread industrial adoption despite promising laboratory-scale results.

4.5. Comparative Assessment of Oxidants

The comparison of these oxidants highlights a clear distinction between laboratory effectiveness and industrial practicality. Hydrogen peroxide and ferricyanide often ex-

hibit stronger oxidising power than oxygen and may produce substantial improvements under controlled laboratory conditions [32]. However, their effectiveness is highly dependent on ore mineralogy, reagent dosage, and solution chemistry. Similarly, NBS can enhance gold dissolution but lacks effectiveness in sulfide-bearing systems, which represent a significant proportion of modern gold resources.

In contrast, oxygen combines several critical advantages. It is inexpensive, environmentally acceptable, readily available, and compatible with existing cyanidation infrastructure. Most importantly, oxygen remains effective across a broad range of ore types and serves as the fundamental cathodic reactant required for gold cyanidation. Although oxygen transfer limitations remain a challenge, modern oxygen-injection technologies have substantially improved oxygen utilisation efficiency and reduced this constraint.

From an industrial perspective, dissolved oxygen is therefore the most effective and practical oxidant for gold cyanidation. Alternative oxidants should be viewed primarily as supplementary reagents capable of enhancing performance under specific mineralogical conditions rather than replacing oxygen. Future developments are likely to focus on synergistic reagent systems, particularly combinations of oxygen with leaching accelerants such as lead nitrate, where oxygen maintains cathodic reduction while the accelerant suppresses sulfide passivation. Such integrated approaches have demonstrated the greatest potential for improving gold recovery, reducing cyanide consumption, and enhancing overall process economics in modern gold operations.

5. Leaching Accelerants in Gold Cyanidation

Leaching accelerants have been widely introduced in gold cyanide leaching to enhance gold recovery and reduce reagent consumption [47]. Among these, lead nitrate has been the most used accelerant for several decades and has been shown to significantly improve gold extraction while reducing cyanide consumption [33]. However, increasing international pressure to minimise environmental impact has motivated the investigation of alternative compounds, such as bismuth nitrate, for use in gold cyanide leaching [48]. This section discusses the influence of lead nitrate and bismuth nitrate on gold cyanide leaching.

5.1. Role of Lead Nitrate

In the absence of lead nitrate, sulfide oxidation during cyanidation produces sulfur species, including aurous sulfide (Au_2S) and polysulfides, which adsorb onto the gold surface, block electrochemically active sites, and reduce gold dissolution [35]. This passivation can be mitigated by lead nitrate, whose beneficial effect is generally attributed to two complementary mechanisms [33,49–51], as illustrated in Figure 4. The primary mechanism is the inhibition of gold surface passivation, whereby sulfur species react preferentially with Pb^{2+} to form lead sulfide (PbS), thereby suppressing the formation of sulfur-rich passivating films and maintaining an electrochemically active gold surface [35,52]. This mechanism is supported by electrochemical studies showing that Pb^{2+} undergoes cementation on the gold surface, as evidenced by characteristic cathodic reduction peaks observed during voltammetric measurements [50]. The secondary mechanism involves the suppression of sulfide oxidation through Pb^{2+} adsorption on sulfide mineral surfaces, resulting in lower cyanide and dissolved oxygen consumption [53] and reduced production of sulfur species responsible for passivation. Experimental observations by Chrysosoulis and Winckers [54] support this mechanism, demonstrating that trace additions of lead nitrate removed sulfur accumulation from gold grain surfaces and accelerated gold dissolution. Although enhanced dissolution of silver and mercury was also observed, these effects are beyond the scope of the present review.

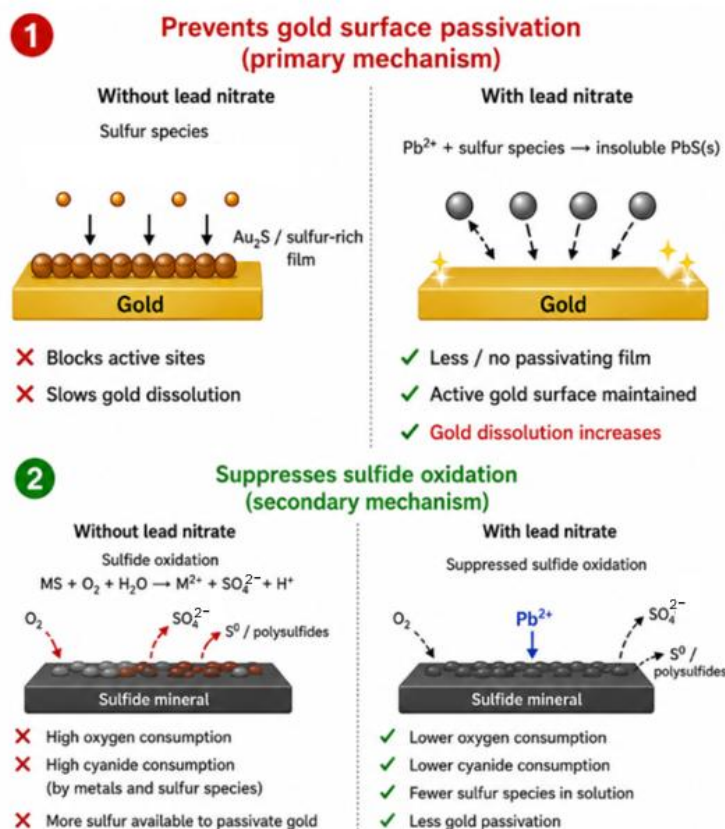


Figure 4. Schematic illustration of the mechanisms by which lead nitrate improves gold dissolution during cyanidation.

Electrochemical studies using cyclic voltammetry demonstrated that the presence of lead ions shifts the mixed potential of the gold system towards more positive values, thereby increasing the anodic current density and enhancing the rate of gold dissolution [49,50,55,56]. Kim et al. (2018) reported that the addition of lead resulted in a low overpotential region of approximately -0.35 V vs. Ag/AgCl, indicating facilitated anodic gold dissolution [56].

Electrochemical investigations also shown that the accelerating effect of lead is sensitive to both lead concentration and solution pH. Bek et al. (2001) reported that at relatively high Pb^{2+} concentrations (~ 0.001 M), a lead-rich surface film formed at potentials around -0.73 V, which slowed gold dissolution due to surface blocking [52]. Additionally, Tshilombo and Sandenbergh (2001) demonstrated that at elevated pH values, the beneficial effect of lead diminished as Pb^{2+} was converted into hydroxide species (e.g., $Pb(OH)^+$, $Pb(OH)_2$), reducing the availability of electrochemically active lead [50]. These results indicate that both excessive lead dosage and highly alkaline conditions can suppress the catalytic role of lead by different mechanisms [50].

The performance of lead nitrate is strongly dependent on ore mineralogy [57]. The greatest improvements are observed in ores with moderate sulfide content, fine particle size distributions, and optimum dissolved oxygen specified by the leach circuit. In low or moderate sulfide ores, direct addition of lead nitrate to cyanidation is sufficient [33,58]. However, in high-sulfide ores (typically more than 3 wt% total sulfides), lead nitrate is most effective when applied during pre-oxidation or pre-leaching stages, where sulfide passivation and oxygen consumption can be partially mitigated before cyanidation [58].

In industrial practice, lead nitrate is typically added at dosages ranging from tens of ppm to several hundred g/t, depending on ore mineralogy and sulfide content [58]. Within this dosage range, plant-scale trials have consistently reported increases in gold recovery

of 4%–6% and reductions in cyanide consumption of 20%–40% across a wide range of ore types [33,57–60]. For example, at the New Britannia Mine (Canada), lead nitrate addition increased plant throughput by approximately 41%, improved gold recovery by around 4%, and reduced cyanide consumption by 37% [33]. At the same metallurgical operation, for an ore containing 2.7% pyrite and 3.0% arsenopyrite, pre-leaching with 20–25 ppm lead nitrate reduced leaching time from 53 h to 30 h while increasing gold recovery from 89% to 91%, resulting in an additional gross revenue of approximately CAN\$ 2.2 million in 2020 [33]. For a third ore at the same metallurgical site, containing 5.0% pyrite, 1.8% pyrrhotite and 0.6% chalcopyrite, lead nitrate addition resulted in a 38% reduction in cyanide consumption and a 4.2% increase in gold extraction, corresponding to an annual additional profit of CAN\$ 375,000 [33].

Similar improvements have been reported at several other industrial operations. At the Sadiola Hill Gold Mine (Mali), the addition of 300 ppm lead nitrate increased gold recovery from 76% to 80%, corresponding to an estimated annual economic benefit of CAN\$ 15.2 million [59]. At the Musselwhite Mine (Canada), lead nitrate addition (50 g/t) increased gold recovery from 88% to 94% and reduced cyanide consumption by 20%, generating cost savings of approximately CAN\$ 3.6 million in 2003 [59]. At the Mouska Mine, processing a copper–gold ore, combined lead nitrate addition (200 ppm) and increased dissolved oxygen improved gold recovery from 95.3% to 96.8% in 36 h and reduced operating costs by 42%, yielding an estimated economic benefit of CAN\$ 2.2 million in 2015 [59].

Lead nitrate remains one of the most effective and economically viable accelerants for gold cyanidation. However, its effectiveness is highly ore-specific and sensitive to operating conditions, necessitating site-specific optimisation rather than universal application strategies [47,50,52,58]. These studies demonstrate that lead nitrate addition consistently enhances gold cyanidation performance across a wide range of sulfide-bearing ores by increasing leaching kinetics, improving gold recovery, reducing cyanide consumption, and delivering substantial economic benefits at the industrial scale [56].

5.2. Synergetic Effects of Oxidants and Lead Nitrate

Laboratory and pilot-scale studies have shown that, in the presence of both dissolved oxygen and lead nitrate, gold leaching equilibrium can be achieved within 12 h, whereas conventional cyanidation requires significantly longer residence times [58]. Dissolved oxygen promotes gold dissolution by acting as the cathodic electron acceptor while simultaneously oxidizing sulfide minerals. Although sulfide oxidation is necessary to sustain the electrochemical dissolution of gold, it also generates sulfur species that contribute to gold surface passivation and increase oxygen consumption. Lead nitrate complements the role of dissolved oxygen through the interaction of Pb^{2+} ions with sulfur species and sulfide mineral surfaces, thereby inhibiting gold surface passivation, suppressing excessive sulfide oxidation, and reducing cyanide and dissolved oxygen consumption. Consequently, the synergistic action of dissolved oxygen and lead nitrate maintains a greater number of electrochemically active gold sites, accelerates leaching kinetics, improves gold recovery, and lowers reagent consumption [33] (Deschenes et al., 2000), as illustrated in Figure 5. This synergy results from complementary electrochemical roles, where dissolved oxygen maintains cathodic reduction and lead species suppress sulfide-related passivation on gold surfaces, leading to improved gold leaching performance [21].

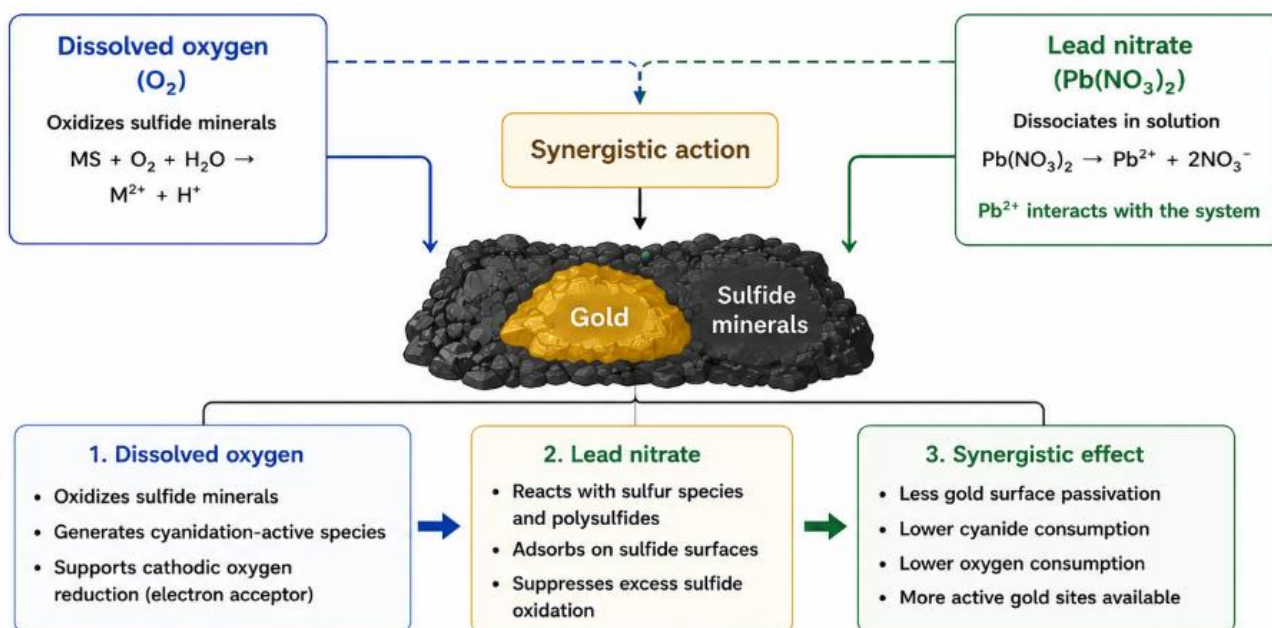


Figure 5. Synergetic action with lead nitrate and oxygen in gold cyanide leaching.

Tables 1–3 provide a concise review of synergies between lead nitrate and oxidants in gold cyanidation. In most cases, enhanced oxidation is achieved using dissolved oxygen, typically supplied as air or pure oxygen, while hydrogen peroxide has been reported in two industrial applications only. As seen in Table 1, the most common synergistic system during gold cyanide leaching is lead nitrate–oxygen. For example, Deschênes and Wallingford [58] demonstrated a strong synergy between lead nitrate and oxygen, reporting that pre-leaching with 200 ppm lead nitrate for 4 h resulted in gold extraction of 96% and approximately 20% improvement in leaching kinetics [58]. The lead nitrate–oxygen synergy is particularly effective in ores containing highly reactive iron sulfide minerals, such as pyrrhotite and arsenopyrite, where oxygen promotes sulfide oxidation while lead prevents sulfur passivation [21].

Table 1 also shows that most studies report improvements in gold recovery of approximately 3–10% and reductions in cyanide consumption of 20%–50% when lead nitrate is combined with enhanced oxidation [61]. These trends are consistently observed across laboratory, pilot-scale, and industrial systems, despite substantial variability in ore mineralogy and operating conditions. In several cases, high gold recoveries (e.g., ~95%–97%) were achieved with substantially lower cyanide consumption when lead nitrate was present, demonstrating that the primary benefit of synergy is not limited to faster kinetics but also includes reduced cyanide consumption [59].

Synergistic effects involving oxidants other than oxygen, such as hydrogen peroxide, remain less well established (see Table 2). For example, the combination of hydrogen peroxide and lead nitrate achieved gold recoveries of 80%–91% in sulfide ores from the Morila deposit [62], while in a Malaysian mesothermal ore, the addition of hydrogen peroxide (410 ppm) and lead nitrate (50 ppm) resulted in approximately 80% gold recovery [42]. Although these results suggest potential benefits, the limited number of studies makes it difficult to distinguish true synergy between hydrogen peroxide and lead nitrate [42].

Table 1. Synergy of lead nitrate and oxygen.

Location of the Sample	Characteristics of Gold Ore	Dissolved Oxygen (ppm)	Lead Nitrate (ppm)	Au (%)	Leaching Conditions	Reference
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Canada, Ottawa	4% pyrite 0.5% pyrrhotite 0.1% chalcopyrite 5.32 Au g/t P ₈₀ = 45 µm	8–12	13–25	93	NaCN consumption: 251–452 g/t pH: 10 NaCN added: 100 ppm	[35]
Canada, Manitoba, New Britannia Mine	0.4% pyrite 3.1% pyrrhotite 4.21 Au g/t P ₇₆ = −74 µm	8	50	95	NaCN consumption: 220 g/t pH: 10 NaCN added: 380 ppm	[33]
Canada, Northwest Quebec	12.3% pyrite 1.4% pyrrhotite 6.75 Au g/t P ₈₀ = −74 µm	8–16	100–200	96	NaCN consumption: 960– 700 g/t pH 10.5 NaCN added: 480 ppm	[58]
Not provided	3.7% pyrrhotite 6.56 Au g/t P ₇₈ = −74 µm	7–15	100–200	97	NaCN consumption: 190–220 g/t pH 11.5 NaCN added: 810 ppm	[51]
Turkey, Izmir, Ovacik Gold CIP Plant	Pyrite, arsenopyrite 9.17 Au g/t P ₈₀ = −59 µm	40	100–200	95–97	NaCN consumption: 230– 270 g/t pH: 10.5–11	[60]
Canada, Quebec, Abitibi	Chalcopyrite, pyrrhotite 9.5 Au g/t P ₁₀₀ = −37 µm	7–15	200	95–97	NaCN consumption: 1640– 1850 g/t pH 10.5 NaCN added: 700 ppm	[47]
Canada, Ontario, Musselwhite Mine Plant	4.2% pyrrhotite 5.38 Au g/t P ₇₄ = −200 mesh	16	200	94	NaCN consumption: 230 g/t	[63]
Canada, Quebec, Yvan Vezina Plant	Chalcopyrite, pyrrhotite 9.55 Au g/t P ₁₀₀ = −37 µm	15	200	97	NaCN consumption: 1850 g/t pH 10.5 NaCN added: 700 ppm	[47]
Mali/Sikasso/Morila Mine Gold Plant sample	0.7% pyrrhotite 0.5% arsenopyrite 0.05% pyrite 3.7 Au g/t P ₇₈ = −75 µm	20	100–200	80–91	NaCN consumption: 200–250 g/t pH: 10.5 350 g/t H ₂ O ₂	[62]
Canada, New Brunswick	2.8% pyrrhotite 1.5% arsenopyrite 0.2% pyrite 8 Au g/t P ₈₀ = 74 µm	9	250	88	pH 10.5 NaCN added: 1001 ppm	[64]
Kiena Mines	0.4% pyrrhotite 3.1% pyrite 4.2 Au g/t Particle size: N.R *	N.R *	50	95	NaCN consumption: 560 g/t	[28]

Mali, Kayes, Sadiola Hill Gold Mine	2.5% pyrite 1.2% arsenopyrite 0.2% pyrrhotite 4.96 Au g/t P ₈₀ = 75 µm	8–16	300–350	80	pH 10.2 NaCN added: 450 ppm	[59]
Alaska, Fox, Fort Knox mill	3.9% arsenopyrite 0.22% galena 0.23% pyrrhotite 5.9 Au g/t Particle size: N.R *	8	75	92	NaCN consumption: 500 g/t pH 10.8 NaCN added: 455 ppm	[65]

N.R *: No data reported.

Table 2. Synergy of lead nitrate and hydrogen peroxide.

Location of the Sample	Characteristics of Gold Ore	Hydrogen Peroxide (ppm)	Lead Nitrate (ppm)	Au (%)	Leaching Conditions	Reference
Malaysia, Peninsular	1.94 Au g/t P ₈₀ = −75 µm	410	50	80	Cyanide consumption: N. R * pH: 11 NaCN added 500 ppm	[42]
Mali/Sikasso/Morila Mine Gold Plant	0.7% pyrrhotite 0.5% arsenopyrite 0.05% pyrite 3.7 Au g/t P ₇₈ = −75 µm	250	100	90	Cyanide consumption: 300 g/t pH: 10.5 NaCN added: 450 ppm	[62]
Turkey/Cerattepe/Artvin	Native gold native silver cuprite 4.6 Au g/t P ₉₀ = −74 µm	N.R *	0 150 300	95– 100	Cyanide consumption: 4400–3910 g/t pH: 10.5 NaCN added 1000 ppm	[43]

N.R *: No data reported.

Table 3. Synergy of lead nitrate and air.

Location of the Sample	Characteristics of Gold Ore	Lead Nitrate (ppm)	Au (%)	Leaching Conditions	Reference
Feed and residue from the Lakefield Research leach	Pyrite P ₁₀₀ = −40 µm 0.8 Au g/t	30	95	4 h pre-aerated 48 h cyanidation pH: 11.2	[54]
Canada, Quebec, Yvan Vezina Plant	Chalcopyrite, pyrrhotite 9.55 Au g/t P ₁₀₀ = −37 µm	200	95	Cyanide consumption: 1640 g/t pH 10.5 NaCN added: 700 ppm	[66]
Iran, West Azerbaijan, Zarshuran gold mine	Low-sulfide gold ore 3.32 Au g/t P ₈₀ = −45 µm	250–750	80–90	Cyanide consumption: 1870 g/t pH 11–11.5 NaCN added: 667 ppm	[67]

5.3. Role of Bismuth Nitrate

Although bismuth does not form stable cyanide complexes [68], bismuth nitrate has been reported to increase gold extraction by approximately three times during cyanida-

tion [69]. However, bismuth nitrate is not used in industrial practice because conventional cyanidation with lead nitrate is well established, cost-effective, and kinetically favourable [70]. As a result, there is limited information available on bismuth nitrate performance during cyanide leaching of gold, with most studies focusing on its electrochemical behaviour [70].

Sandenbergh and Miller (2001) showed that bismuth forms a monolayer on the gold surface, which alters surface electrochemical behaviour and promotes peroxide-related reactions [71]. Moreover, bismuth nitrate promotes the formation of honeycomb-like structures on the gold surface, increasing the effective surface area and facilitating enhanced gold–cyanide interaction [69].

Nicol [72] demonstrated that in the presence of bismuth, passivation of gold is suppressed within the potential region corresponding to the first anodic peak, thereby facilitating anodic gold dissolution [72]. Adzic and Despic [73] investigated the effect of underpotentially deposited bismuth on oxygen reduction at gold electrodes in acidic media and showed that bismuth exhibits a catalytic effect on oxygen reduction kinetics [73]. However, McIntyre and Peck [74] observed that the influence of bismuth on gold cyanidation diminishes with prolonged leaching times, indicating that its accelerating effect may be limited to short-term electrochemical conditions [74].

Bek (2002) investigated the anodic dissolution of gold in cyanide solutions containing bismuth hydroxy compounds and found that trace additions (10^{-5} M) significantly accelerated gold dissolution at potentials below 0 V [75]. Furthermore, the catalytic effect of metal adatoms on gold dissolution follows the trend $Tl < Pb < Bi$, indicating that bismuth exhibits the strongest enhancement among the investigated elements [70].

6. Conclusions

This review critically evaluated the industrial relevance of oxidants and leaching accelerants in gold cyanidation, focusing on their effects on gold dissolution, leaching kinetics, and cyanide consumption. Dissolved oxygen remains the most important and widely applied oxidant because it sustains the cathodic reaction required for gold dissolution, although its effectiveness is limited by low solubility and mass-transfer constraints. Alternative oxidants, including hydrogen peroxide, ferricyanide, and sodium *m*-nitrobenzene sulfonate (NBS), can improve gold leaching under specific conditions but generally exhibit ore-dependent performance and limited industrial application. Among leaching accelerants, lead nitrate remains the most effective reagent due to its ability to inhibit gold surface passivation, enhance dissolution kinetics, and reduce cyanide consumption, whereas bismuth nitrate represents a promising reagent requiring further industrial validation and offering a potential alternative to lead-based reagents.

Reagent selection should be based on ore mineralogy and process conditions, as no single oxidant or accelerant is universally applicable. The combination of dissolved oxygen and lead nitrate remains the most effective and well-established strategy for sulfide-bearing gold ores, providing faster leaching kinetics, higher gold recovery, and lower cyanide consumption. Future research should focus on developing predictive mineralogical and electrochemical models, improving understanding of oxidant–accelerant interactions, identifying environmentally sustainable alternatives to lead-based reagents, and validating emerging reagent systems at pilot and industrial scales.

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