

Review

On the Use of Amino Acids to Leach Precious Metals from Primary and Secondary Resources

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Abstract

During hydrometallurgical processing of precious metals, the leaching process is the critical stage mainly contributing to environmental pollution problems. The most important process variables affecting leaching kinetics are temperature, lixiviant concentration, solid-to-liquid ratio, presents of catalysts and synergists, and the type of oxidant. There are significant efforts to replace harmful lixiviants with environmentally friendly solvents in leaching of precious metals during hydrometallurgical processing of precious metals. Of the different lixiviants researched, amino acids demonstrate much potential to compete with traditional lixiviants like cyanide and aqua regia. We have reviewed the chemistry and performance of amino acids in leaching of precious metals from primary and secondary resources and compared them with traditional approaches. The use of different approaches to enhance the leaching kinetics including starved cyanide, addition of strong oxidant, addition of synergists and catalysts, concentration and temperature were reviewed. Commonly used amino acids were reported and the future for commercialization of amino acids for precious metal leaching was discussed. The use of amino acids in absence of cyanide requires the use of strong oxidants and further research is still necessary on green amino acid–oxidant combinations capable of leaching secondary resources and producing high leaching efficiencies at a low cost.

Keywords: leaching; amino acid; lixiviant; hydrometallurgy; E-waste; gold ore

1. Introduction

There is extensive research on green and effective lixiviants aimed at replacing harsh traditional technologies like cyanide and inorganic acids in leaching of precious metals such as gold, silver and platinum group metals. Besides their environmental toxicity, other factors pushing for replacement of these harsh lixiviants includes ineffectiveness in treating low grade ores (which are now abundant) resulting in high reagent consumption, slow kinetics [1–3], and the need for low cost lixiviants. Amino acids possess potential properties required for an effective, green and economical lixiviant for precious metals leaching in comparison with other lixiviants. For example, the current price of industrial glycine is about 1700 USD/ton compared to 2380 USD/ton sodium cyanide. Moreover, glycine is easy to regenerate and reuse. Complexes of amino acids with precious metals have proved to be stable over a wide pH-Eh and temperature ranges [4] with the added advantage that the dissolution of major gangue elements like Fe, Mn, Cr, Si and Al is negligible when operating in an alkaline environment [5,6]. Primary resources for precious metals include



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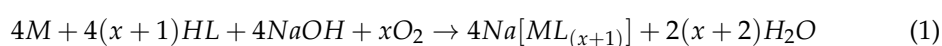
ores, concentrates, oxides, and sulphide minerals, and printed circuit boards (PCBs) are common secondary resources for precious metals.

Presently, there is no specific literature review focusing on amino acid lixiviants for leaching precious metals yet this is a critical stage to control and lower the overall process environmental impact. In this work, a systematic review is made on amino acid leaching of precious metals from different resources like natural ores, tailings and electronic waste focusing on performance, leaching mechanisms, challenges and commercialization potential. We first focused on the leaching chemistry of amino acids before reviewing the performance of different amino acids on different precious metals from both primary and secondary resources.

2. Amino Acid Leaching of Precious Metals

Kinetics and Thermodynamics of Leaching with Amino Acids

Early research demonstrated that amino acids can dissolve gold and the dissolution was favoured by high pH and oxidising conditions [7,8]. High pH enhances the dissociation of glycine to form glycinate required for complexation of gold as shown in Figure 1. Comparisons of the performance of amino acids on gold leaching show that leaching depends on the structure of the amino acid. Korobushkina et al. [8] showed that under the same conditions, gold dissolution in cysteine (close to 14 mg/L) was twice that in alanine and glycine (less than 7 mg/L) and the complexing ability was asparagine > glycine > histidine > cysteine > phenyl alanine > valine > aspartic acid > alanine. Later on, Sarvar et al. [9] also studied gold solubility of different amino acids and confirmed that high pH was necessary for enhanced solubility and the order of leaching efficiency observed was Asparagine > Glycine > Histidine > Cysteine > Phenyl Alanine > Valine > Aspartic acid > Alanine. The same behavior was confirmed by Eksteen and Oraby in 2014 [10]. It was proposed that cysteine should be considered in leaching of gold because it can effectively leach gold at room temperature. However, the challenge with all other amino acids except glycine is polymerization and degradation. The representation of the dissolution of precious metals in amino acids is shown by the equation below [10]:



where M stands for precious metal, L is the amino acid anion e.g., glycine ($NH_2CH_2COO^-$), and x is the valence metal ion. To understand the complexation chemistry of amino acids with gold, Azadi et al. [11] investigated the thermodynamic behaviour of gold-glycine systems and estimated the equilibrium constants of metal-glycinate formation at room temperature. Wang et al. [12] studied the thermodynamics of glycine and thiosulfate systems for gold and copper recovery as an alternative to cyanide. Through Pourbaix and speciation diagrams, the authors determined the predominant complex species under certain conditions and found that glycine has a wide availability zone at alkaline and neutral pH which helps stabilise cupric in thiosulfate solutions. Kanjana Kudpeng et al. [13] investigated the influence of the structure of amino acid on gold leaching from a silicate ore. They found that aspartic and glutamic acids were able to extract gold than other assessed amino acids (glycine, lysine and tryptophan) under neutral pH conditions due to the absence of aromatic rings and long side chains, and the result was confirmed through FTIR studies. Recent studies on amino acid and gold bonding or interaction behaviour of selected amino acids at different pH levels during leaching was investigated by Tapfuma et al. [14]. A FTIR analysis indicated that gold forms complexes with amino acids through N–Au, O–Au, and S–Au bonds. The coordination is achieved by using the α -oxygen from the carboxylate and α -nitrogen from the amino group, as shown in Figure 2.

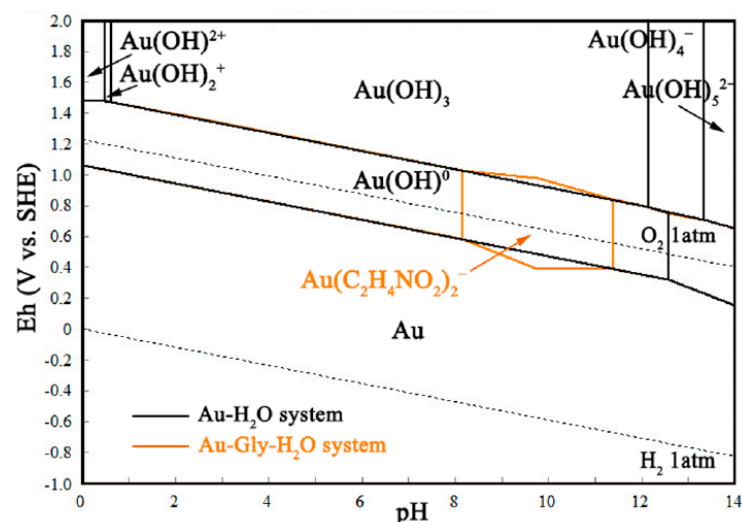


Figure 1. Eh-pH diagram for the Au_glycine system at 25 °C, [Au] = 10^{-4} M, [Gly] = 1 M. Adapted from refs. [12,15].

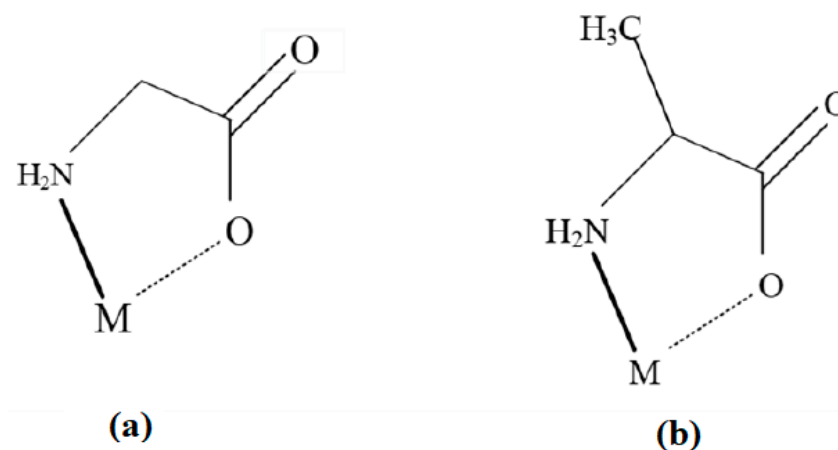


Figure 2. The organometallic coordination of (a) glycine and (b) alanine. Reprinted with permission from ref. [14]. 2026 Elsevier.

Moreover, the dissolution trend for the deprotonated amino acids (at high pH) was found to be cysteine > alanine > glycine > histidine, which corroborated well with FTIR studies and DFT bonding energy trend for the complexes; the finding agrees with the works by early researchers discussed in Section 1. Although amino acids can thermodynamically dissolve gold, the dissolution kinetics observed were far lower than those from the traditional sodium cyanide leaching.

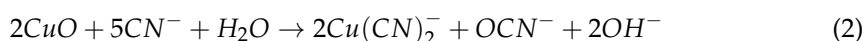
3. Gold Leaching from Primary and Secondary Resources

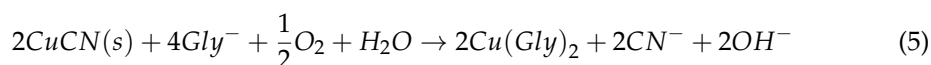
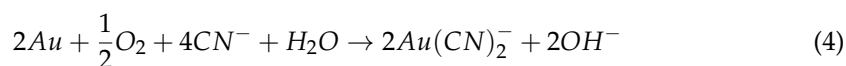
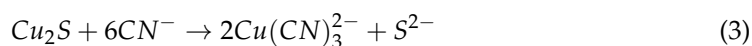
After foundational research on amino acid leaching kinetics from pure gold (foils) [5], subsequent studies focused on extracting gold from primary and secondary sources. Studies show that amino acids can leach gold at high pH in presence of oxygen and that an increase in temperature and concentration of amino acid enhance the leaching rate. In addition, particle size reduction and mechanical activation are beneficial in increasing the leaching rate [16,17]. The leaching behaviour of gold ores is different from that of electronic waste because in e-waste, metals are found in pure form or as alloys whereas ores contain oxides and sulphides [18,19]. Presently, hydrometallurgical processes are directly used in leaching ore concentrates whereas e-waste metal recovery consists of base metal dissolution with a weak lixiviant followed by precious metal dissolution with a different lixiviant under oxidising conditions. The advantages of using amino acids are that the same lixiviant can

be used in both first and second stage leaching to avoid washing between leaching stages and that the agitation tanks in both stages can be of the same construction [10].

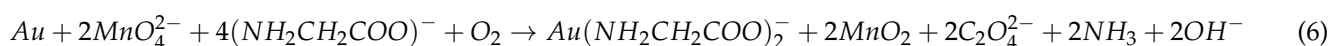
On their own and under mild conditions, amino acids cannot effectively leach gold from both primary and secondary resources and the leaching rates are much slower than those of traditional cyanide leaching. Li et al. [20] investigated leaching of gold from electronic waste solid residue after leaching of base metals using 0.5 M glycine at the initial pH of 10.2, <2 mm particle size, room temperature, 72 h, and ambient O₂ without a strong oxidant and recovered less than 2% of Au and Ag and 12.6% palladium. Slow leaching rates were also observed by Oraby and Eksteen [10,21], and Oraby and Eksteen [21], for a Western Australian paleochannel ore at high operating temperatures although more than 85% of the gold was leached by prolonging leaching time to 336 h. To enhance leaching kinetics, catalytic synergists, elevated temperatures, high amino acids concentrations and strong oxidants are effective methods [22]. Altinkaya et al. [23] used an alkaline glycine only solution at high temperatures of 60 °C, with high oxygen flow rate of 1 L per min, 1.25 M glycine (93.8 g/L), pH of 12, high stirring rate (900 rpm), and 10 wt% solids pulp for 24 h, and recovered more than 85% of gold from a gold ore concentrate. However, the high reagent consumption and use of elevated temperatures poses challenges for commercialization unless the reagent is regenerated and recycled. The use of high concentrations and temperatures was also studied in leaching of gold concentrates achieving a high gold recovery rate of 91% with creatine monohydrate amino acid, which is similar to 90% obtained during cyanide leaching under similar conditions of 300 g/t concentration, temperature of 75 °C, pH of 11.5, time of 24 h, pulp density of 30%, and particle size of 53 microns [22]. P. Altinkaya et al. [24] used pure alkaline glycine with high glycine concentration of 1.25 M, temperature of 60 °C, and pH = 12 to recover 90% of gold from a refractory gold ore which is high when compared to 80% extracted by the traditional cyanidation process showing that amino acids are more effective even in refractory ores. The use of bioleaching from amino_acid-producing bacteria for gold ores has been attempted and it was shown that the leaching rates are slow and low pulp density used makes it less economical for industrial uptake [25–28].

Copper_gold ores pose challenges in the economic recovery of gold using conventional cyanidation, particularly when copper is present at high nuisance levels. The use of amino acids mixed with other lixiviants has demonstrated to be effective in improving the leaching rates of gold [29]. The addition of starved levels of cyanide (zero free cyanide) to glycine was proved by several researchers to be effective in increasing gold leaching rates [5,30–35] from ores and secondary waste. High gold dissolution rates above 90% competing with cyanide leaching were realised at mild operating conditions. Picazo-Rodríguez et al. [36] used pre-treatment in gold ores to minimize the effect of gangue such as jarosite and sulfur and improved the leaching rate of gold from 88% to 94% in glycine_cyanide solutions. The presence of copper in solution catalyses the leaching rate through freeing of cyanide ions from copper_cyanide complexes to form copper_glycine [37], contrary to pure cyanide leaching where copper suppresses gold dissolution by locking cyanide as copper_cyanide [31,38]. Thus, cyanide consumption is significantly reduced by more than 75%. The proposed reactions [38] are shown in Equations (2)–(5) demonstrating the need for strict control of stoichiometric ratios for the system to properly function. Moreover, the benefit of the formation of cupric_glycinate compared to copper_cyanide (in pure cyanide) is the reduction in detoxification costs [5]. The glycine_cyanide starved process is now commercialised as GlyCat [5,23,31] and can recover high gold content from refractory low-grade concentrates containing copper and high levels of sulphides [39].





The use of strong oxidants, i.e., peroxide and potassium permanganate relaxed the use of high reagent concentration and made it possible for gold extraction to be possible at room temperature in absence of toxic cyanide [40]. For example, a study by Oraby et al. [41] for glycine leaching of gold ores showed that 85.1% gold can be leached from an oxide mineral by 1.5 kg/t glycine and 3 kg/t permanganate at 30% solid, pH 10.5 and room temperature for 48 h, compared to 87.4% gold extraction from traditional cyanidation under similar conditions. This was validated by other works where it was shown that a strong oxidant like permanganate can increase gold leaching rate to above 95% under mild conditions of low concentrations and room temperature in alkaline systems of amino acids only [15,42–44]. However, the main challenge is the high oxidant consumption under optimum conditions. Tapfuma et al. [45] used potassium permanganate pre-treatment on Witwatersrand gold tailings before leaching with glycine at a pH of 12, glycine concentration of 1.5 M, solid liquid ratio of 50 g/L and 2 g/L copper ions and dissolved 91.4% of gold in 24 h. The reaction of glycine amino acid with gold in presence of permanganate can be represented in Equation (6) below.



Amino acid_thiosulphate synergistic solutions in presence of copper and a strong oxidant were used to leach gold concentrates [46] and tailings [47,48], and the decomposition and consumption of thiosulphate were significantly reduced and an almost complete gold extraction was observed in 24–48 h. Alex S. Redrovan [47] leached gold using thiosulfate–glycine–copper–permanganate system using the conditions of 0.7 M sodium thiosulfate, 1.75 M glycine, 5 mM copper sulphate, and 0.012 M potassium permanganate, at pH of 9.3, and 60 °C, and achieved a gold recovery of 89.3% within the first 6 h comparable to cyanidation (89.8% in 24 h) and ammoniacal thiosulfate (58% in 6 h). The system's superior performance was attributed to the ability of glycine to prevent thiosulfate degradation through stabilising of copper ions forming a stable complex compared to that of ammonia. The main challenge remaining to be solved is the high reagent consumption.

The addition of ammonia in amino acid_synergist systems has been shown by some researchers to be an effective lixiviant and catalyst for improving gold dissolution rates in ores and electronic waste [49,50] because of the formation of cupric ammine catalyst. However, ammonia poses challenges like high reagent loss, toxicity and corrosivity thus many investigators no longer pursue its usage. The summary on amino acid leaching of gold researches from primary and secondary waste is shown in Table 1.

Table 1. Summary of amino acid leaching studies on gold using amino acids.

Feed Material	Leaching Agent and Amount	Temperature and pH	Oxidant	Duration	Leaching Rate/Au	Reference
Gold foil	0.1 M glycine	60 °C and pH 12.8	1% H ₂ O ₂	96 h	70 mg/L	[5]
Gold foil	0.5 M glycine	60 °C and pH 12.5	4 mL/h continuous H ₂ O ₂	96 h	0.054 mg	[51]

Table 1. Cont.

Feed Material	Leaching Agent and Amount	Temperature and pH	Oxidant	Duration	Leaching Rate/Au	Reference
Gold foil	0.5 M glycine	40 °C and pH 11	0.01 M KMnO ₄	24 h	4%	[15]
50% Au-50% Ag foil	1 M glycine	60 °C and pH 11	1% H ₂ O ₂	167 h	38 mg/L	[52]
Au-Cu concentrate	0.5 M glycine	60 °C and pH 11	O ₂ sparged continuously	96 h	15.4%	[31]
Au-Cu concentrate	10 g/L glycine, 0.8 g/L NaCN	22 °C and pH 11	air	48 h	99.5%	[31]
e-waste	0.5 g/L glycine, 0.5 g/L NaCN	23 °C and pH 11	air	24 h	37.6%	[53]
Copper_gold ore 13.2 g/t grade	0.5 M glycine	60 °C and pH 11.5	4 L/min continuous O ₂	96 h	32%	[54]
Copper_gold ore 1.96 g/t grade	0.5 M glycine	25 °C and pH 10	4 L/min continuous O ₂	168 h	51.44%	[54]
Gold ore 3.74 g/t grade	2.0 g/L glycine	23 °C and pH 10.5	KMnO ₄ (1 g/L)	48 h	85%	[41]
Gold ore 2.5 g/t grade	7.5 g/L glycine	22.1 °C and pH 10.5	1 kg KMnO ₄ per tonne ore	48 h	83.2%	[41]
Gold ore 5.4 g/t grade	93.75 g/L glycine	60 °C and pH 12	1 L/min continuous O ₂	24 h	90%	[24]
e-waste	0.5 M glycine	55 °C and pH 11	0.16 M permanganate	96 h	88.6%	[44]
Gold Concentrate	0.53 M glycine	30 °C and pH 10.5	0.25 M permanganate	48 h	76%	[44]
Gold Ore	1.0 M glycine	55 °C and pH 10.5	2.5% H ₂ O ₂	48 h	91.7%	[33]
e-waste	0.045 M glycine 360 ppm cyanide	Room and pH 12	None	96 h	90.1%	[30]
Gold Ore	1 M glycine cyanide	Room and pH 11	10% H ₂ O ₂	-	89%	[32]
Sphalerite leaching residue	1 M glycine	50 °C and pH 10.5	2% H ₂ O ₂	24 h	88%	[36]
Gold Ore	0.1 M glycine	Room and pH 10.5	KMnO ₄ (2 g/L)	48 h	85%	[36]
Gold Concentrate	2 M glycine	60 °C and pH 12	None	24 h	90%	[16]
e-waste	0.4 M glycine and small amounts of cyanide	23 °C and pH 11	None	24 h	92.1%	[55]
Gold Tailings	0.27 M glycine and thiosulphate	25 °C and pH 9.4	None	48 h	80%	[48]
Gold ore	0.2 M glycine	Room and pH 12.5	None	336 h	85%	[21]
Gold ore	1.5 M glycine	75 °C and pH 12	0.56% H ₂ O ₂	12 h	-	[11]

Table 1. Cont.

Feed Material	Leaching Agent and Amount	Temperature and pH	Oxidant	Duration	Leaching Rate/Au	Reference
Gold concentrate	0.07 M glycine 0.6 M thiocyanate	25 °C and pH 2.0	0.05 M oxidant	3 h	93.2%	[50]
e-waste	0.5 M glycine 0.6 M thiocyanate	25 °C and pH 11	30% H ₂ O ₂ and permanganate	24 h	1.8%	[15]

4. Amino Acid Leaching of Silver and Platinum Group Metals

Most of the research in the literature on amino acid leaching of silver and PGMs was performed on electronic waste and reports on leaching from ores are few. PGMs contains precious and costly metals like platinum and palladium of importance in items like jewellery. Electronic waste consists of base metals and precious metals and the most effective separation process involves two steps: the first includes leaching base metals, which occurs before leaching the residue of precious metals under highly oxidising environments as shown in Figure 3 [56–58]. Different leaching systems including glycine with starved cyanide, glycine-synergistic system and a free glycine system with a strong oxidant have been researched for leaching silver and PGMs. The leaching chemistry and mechanisms of silver and palladium with amino acids is not yet well studied. The summary of amino acid leaching of Ag and PGMs from primary and secondary waste is shown in Table 2.

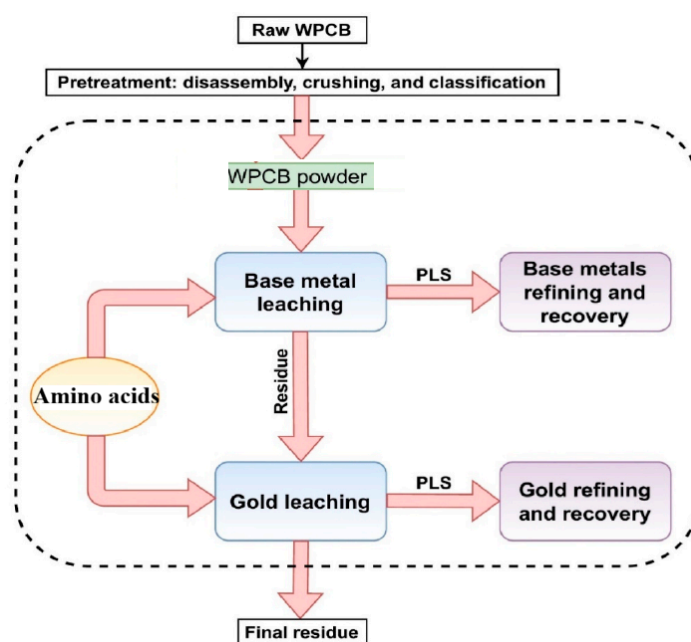


Figure 3. Schematic of two stage leaching of base metals before leaching of gold from the residue. PLS stands for pregnant leach solution. Reprinted with permission from ref. [42]. 2026 Elsevier.

Table 2. Summary of amino acid leaching of silver and gold.

Feed Material	Leaching Agent and Amount	Temperature and pH	Oxidant	Duration	Leaching Rate	Reference
e-waste	0.5 M glycine	55 °C and pH 11	0.16 M per- manganate	96 h	70.2% Ag, 89.3% Pd	[44]
e-waste	0.045 M glycine 360 ppm cyanide	Room and pH 12	None	96 h	89.4% Ag 70.1% Pd	[4]

Table 2. Cont.

Feed Material	Leaching Agent and Amount	Temperature and pH	Oxidant	Duration	Leaching Rate	Reference
Sphalerite leaching residue	1 M glycine	50 °C and pH 10.5	2% H ₂ O ₂	24 h	94.3% Ag	[59]
e-waste	0.4 M glycine and small amounts of cyanide	23 °C and pH 11	None	24 h	85.3% Ag	[60]
Gold tailings	0.27 M glycine and thiosulphate	25 °C and pH 9.4	None	48 h	-	[48]
Sulfide ore	Heterophic bacteria Thiosulfate and copper ions	Heap leaching pH 10	-	30 days	59% Ag	[61]
e-waste	Cyanide_glycine solution	-	-		65–94% Ag	[36,59]
e-waste	1 M glycine-ferricyanide (0.08–0.16 M)	55 °C, pH 11.5	Permanganate	96 h	69% Ag, 68.5% Pd	[56]
Oxide gold ore	3 M glycine	60 °C	Air flow rate of 1 Lmin ^{−1}	60 h	44.5% Ag	[62]
Sulfidic ore	0.5 M cysteine, 0.25 M Na ₂ SO ₃	70 °C, pH 11.5.	-	-	20% Ag	[29]
50% Au-50% Ag foil	1M glycine	60 °C and pH 11	1% H ₂ O ₂	167 h	55 mg/L Ag	[52]
e-waste	0.5 g/L glycine, 0.5 g/L NaCN	23 °C and pH 11	air	24 h	8.8%Ag	[53]

4.1. Silver Leaching

A two-stage leaching of precious metals from electronic waste in glycine at starved levels of cyanide (e.g., NaCN or ferricyanide) can dissolve from around 70–90% silver [30–33] depending on operating conditions like time, temperature and particle size. These dissolution rates are comparable to those obtained from pure NaCN leaching solutions but with a much greater reduction in cyanide consumption 70% [63]. To improve silver recovery rates at mild operating conditions, Picazo-Rodríguez et al. [36] investigated the effect of pre-treatment on gold and silver recovery from a residue obtained after base metal leaching, pure cyanide and cyanide-glycine solutions were compared and it was found that the recovery rates of silver improved from 65% to 94% without prolonging extraction times and using elevated temperatures. A study by Chegeni [22] compared leaching rates of pure cyanide with different amino acids on dissolution rates of gold ore and obtained optimum leaching rates of silver at 55% and 47.18% for pure cyanide and creatine monohydrate amino acid, respectively, which are closer. Low leaching rates experienced from ores compared to those from e-waste occur due to pre-treatment of e-waste performed to remove base metals before leaching whereas ores contain substantial amounts of gangue even after concentration. This agrees well with findings from Oraby et al. [60] who showed that a two-stage leaching recovered about 92.1% gold and 85.3% silver, which values are much higher than those obtained from directly leaching in single stage with cyanide, glycine_cyanide or ammonium.

The use of cyanide-free amino acids with strong oxidants like permanganate can produce high silver extraction rates. For example, Huan Li et al. [44] obtained silver extraction rates of 70.2% in a glycine-permanganate system, which is comparable to 69% extracted from glycine-ferricyanide synergistic system. The main challenge is the use of high oxidant concentration of about 632 kg/t potassium permanganate making the process expensive and showing that further studies are necessary to minimise oxidant consumption.

Synergistic solutions of amino acid with other lixiviants were investigated to improve the leaching kinetics of silver because of low extraction rates in ores. Silver leaching rate of 20% was obtained from a sulphide ore in cysteine-sulphite leaching solutions with 0.5 M cysteine and, 0.25 M Na₂SO₃, at pH of 11.5 and 70 °C. Ahmet Turan et al. [62] used 3 M glycine to extract gold and silver from an oxide gold ore of average particle size 70.7 µm; at 48 h, pH of 11–12, stirring rate of 350 rpm and air flow rate of 1 L·min^{−1}, 81.41% gold extraction and 44.5% silver extraction rates were obtained. Munive et al. [48] used a glycine-thiosulphate synergistic leaching solution to leach gold and silver from mine tailings using CuSO₄ and H₂O₂ as oxidants, and almost complete extraction rates of gold and silver were obtained using 20 g/L thiosulfate and 5 g/L glycine at pH 11 and 30 °C for 48 h, although the reagents concentrations were very high for economic recovery of low metal tailings (0.05 g/t Au, 0.76% Cu). Khezri et al. [64] showed that glycine has a higher affinity for gold compared to silver and this explains lower dissolution rates of silver compared to gold in leaching from both e-waste and ores.

4.2. Palladium Leaching

Almost all research work on amino acid leaching of PGMs is focused on the recovery of palladium from e-waste. This is likely because of harsh conditions required for leaching of PGMs like platinum from virgin ores, thus further research is necessary to investigate the applicability of amino acids in this area [65,66]. Palladium has been successfully recovered from e-waste using two-stage leaching. The extraction efficiencies of solid residue after one step leaching of base metals show that the affinities of amino acids to palladium are comparable to silver although they are lower than those for gold. A free solution of glycine with a strong permanganate oxidant [30,44] proved to be more effective for palladium leaching with dissolution rates above 89% in comparison with glycine-cyanide starved solutions where low leaching rates of around 68–70% [30] were reported. It shows that an oxidant is very important in palladium leaching when compared to synergism; however, the mechanism should be investigated for comprehensive conclusions to be made. The importance of a strong oxidant was shown by Li et al. 2020 [20] through leaching of solid residues with 0.5 M glycine at the initial pH of 10.2, <2 mm particle size, room temperature, 72 h, and ambient O₂ without a strong oxidant, where recoveries under 2% of Au and Ag and palladium of 12.6% were reported. After leaching, the solutions are sent to further processes like cementation, solvent extraction, electrodeposition and adsorption for recovery of pure metals.

5. Major Factors Influencing Precious Metals Recovery

Most work on leaching of precious metals with amino acids was performed on gold in ore concentrates and electronic waste using glycine as the main amino acid. Further research is still necessary for other precious metals like silver and PGMs, and for other amino acids for comprehensive conclusion to be made on the influence of parameters on leaching rate.

5.1. Effect of Glycine Concentration

Many researchers studied the effect of glycine concentration on leaching of pure gold ores [5,21,31,54], mine tailings and electronic waste. Eksteen and Oraby [5] investigated glycine leaching of pure gold and varied the concentration between 0.3 M and 1.0 M with other conditions fixed, i.e., pH 10, temperature 60 °C, 1% hydrogen peroxide and agitation rate of 350 rpm. The rate of gold dissolution increased by approximately four times with changing concentration. This finding agrees well with the research by Tanda 2017 [34] who observed a significant increase in leaching rate from 13.5% to 40.5% by increasing glycine concentration from 0.5 M to 1.0 M at leaching time of 192 h. In their work on leaching of paleochannel ores, Oraby et al. [21] fixed pH at 12.5, temperature at 55 °C and pulp density at 30% and observed the leaching rate, which increased from 50% at a glycine concentration of 3.75 g/L to 85% at a higher glycine concentration of 37.5 g/L. The influence of glycine leaching rate at a low glycine concentration range of 0.025 M to 0.1 M in presence of hydrogen peroxide (concentration 0–2%) and 4 mM cupric ions was also investigated by Eksteen and Oraby [5] while other conditions were systematically varied i.e., temperature (23–60 °C), and pH (10–12.8), as shown in Figure 4. Gold leaching rate increased significantly with an increase in concentration, temperature and pH. The influence of glycine concentration in presence of H₂O₂ on the leaching rate of a gold_silver alloy (50% Au–50% Ag) was performed by Oraby and Eksteen [5]. It was found that at a glycine concentration of (0.3–1 M), pH of (5.8–11) and temperature of (23–60 °C) there is an increase in gold leaching rate. In conclusion, an increase in glycine concentration results in high gold-to-glycine interaction and, resulting in high gold leaching being observed. A high concentration of glycine also helps to stoichiometrically balance the lixiviant used up by the gangue material of the ore, thus facilitating high leaching rates. Although glycine concentration enhances gold dissolution, the use of low reagent concentration is preferable to reduce reagent costs.

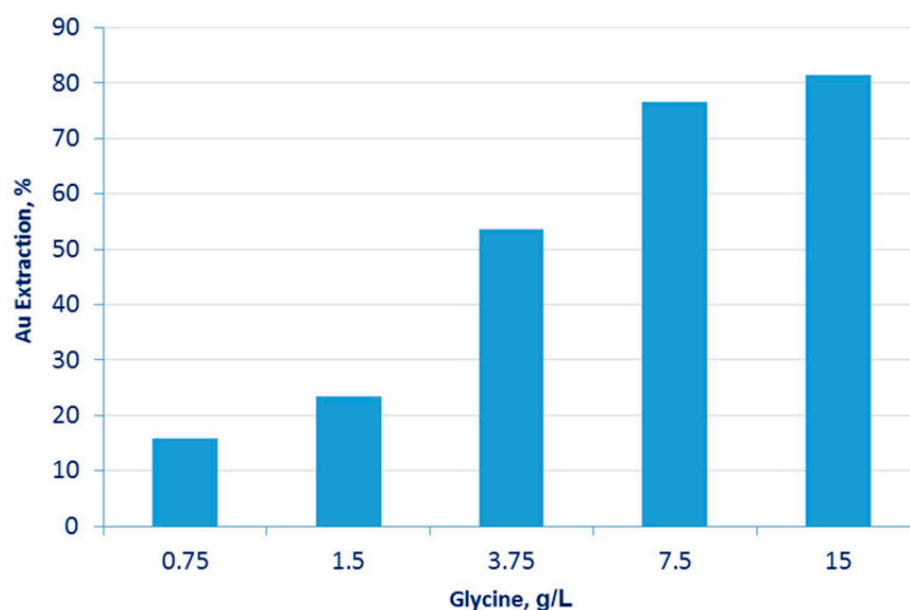


Figure 4. The influence of glycine concentration on gold leaching rate at, 20 ppm Cu²⁺, O₂, pH 10.5–11, 70 °C, after 48 h (redrawn). Reprinted with permission from ref. [41]. 2026 Elsevier.

5.2. Effect of pH

There is an agreement in almost all studies that the leaching of gold is low in acidic and high in alkaline amino acids [5,23,24,54]. This has to do with the change in amino acid structure as the pH is changed; i.e., the structure at high pH is more active for leaching

gold [9]. The influence of pH on leaching of pure gold foils was carried by Oraby and Eksteen [52]. The gold dissolution rate increased from 1 mg/L to 28 mg/L upon an increase in pH from 10 to 11 while glycine concentration was fixed at 0.5 M glycine, temperature at 60 °C and hydrogen peroxide concentration of 1%. Similar behaviour was found by Tanda et al. [54], who observed that gold extraction rate increased by 31% by increasing pH from 10 to 11; the other operation conditions used were temperature of 25 °C and 50% volume of solids. Moreover, a further increase in pH to 12.4 resulted in a further increase of 14% in gold dissolution. Other works confirming the influence of pH on ores include the works by Altinkaya et al. [23] and Oraby et al. [21]. A study by Oraby and Eksteen [5] on glycine leaching of 50% Au—50% Ag alloy also confirmed that gold leaching rate is higher at an alkaline pH of 9 and less at a lower pH of 5.8. The explanation is that at a high pH, glycinate ligand becomes predominant, facilitating the formation of metal complexes. However, specific investigations on the influence of pH on other precious metals (Ag, PGMs) is still scarce.

5.3. Oxidising Agent

Leaching of precious metals operates in the presence of oxygen or other oxidants at high pH because of their inertness compared to leaching of base metals [5,37]. The use of natural oxygen in early research showed that gold leaching rates were kinetically slow for industrial applications demonstrating that strong oxidants were necessary [5]. Strong oxidants in leaching of precious metals have been used to make it possible to leach PGMs (Au, Ag and Pd) at room temperature and atmospheric pressure. Commonly considered strong oxidants for precious metal leaching are hydrogen peroxide (commonly used in gold leaching) and potassium permanganate [5,15,34,41]. Eksteen and Oraby [5] investigated the influence of an oxidant on glycine leaching of pure gold foil with 0.1 M glycine, pH 11.5 and temperature of 60 °C and time of 48 h. It was observed that an increase in hydrogen peroxide concentration from 0.1% to 2% results in an increase in gold leaching rate from 2.5 mg/L to 15 mg/L. Research by Aksu et al. [67] showed that the presence of hydrogen peroxide inhibits copper dissolution because of the formation of an oxide film on copper surface. On the contrary, Tanda et al. [34,54] found that hydrogen peroxide had a negative effect on low-grade gold leaching where gold content decreased from 42.5% in absence of oxidant to 4.7% in presence of 1% hydrogen peroxide. There is a possibility that the amino acid was oxidised demonstrating that proper stoichiometric ratios should be maintained for effective leaching in presence of oxidants.

Oraby, Eksteen and Connor [41] compared the gold leaching performance of different oxidants, including permanganate, hydrogen peroxide, chlorate ions, ferricyanide ions and iodide ions under conditions of pH 10.5, 30% pulp density and 1 g/L glycine concentration. The results proved that permanganate was a stronger oxidant in gold glycine solution as shown in Figure 5. It was found that adding 1.0 g/L permanganate to glycine solution even in absence of cyanide enhances gold leaching rate (85.1%) to the same level as those obtained in cyanide leaching (87.4%) at the same period of 48 h. It was also found that some amino acid was oxidised by permanganate, thus the amino acid concentration should be properly adjusted to cater to oxidation and other side reactions originating from the reactions with ore gangue. Perea and Restrepo, 2018 [15] and Tapfuma et al. [14,45] found that potassium permanganate was the best oxidant for glycine, alanine and cysteine, whereas hydrogen peroxide was the best oxidant for histidine.

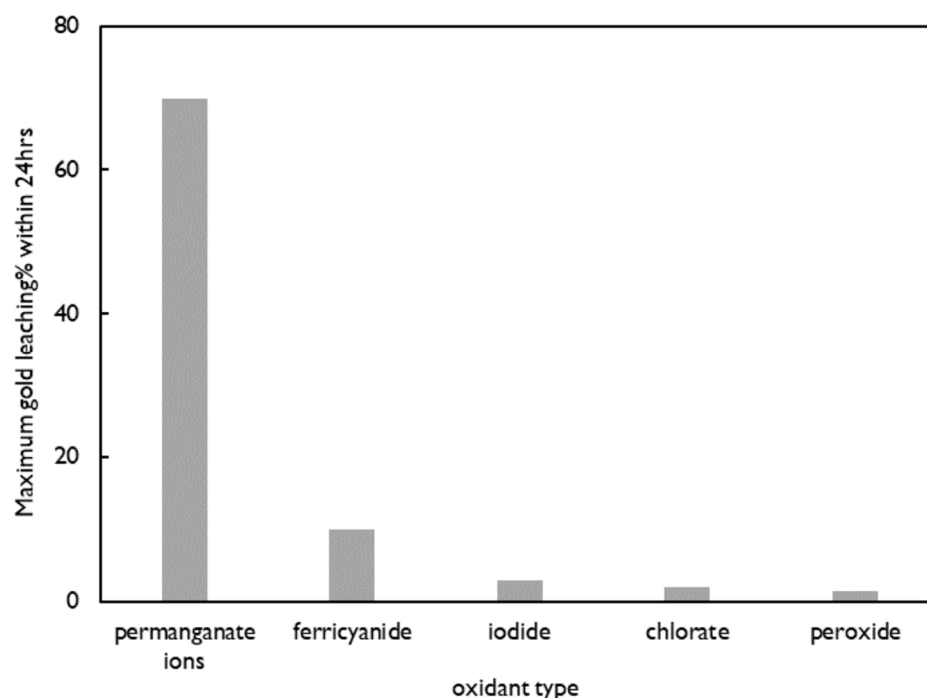


Figure 5. Effects of oxidants on gold extraction from gold oxide ore using glycine (redrawn). Reprinted with permission from ref. [41]. 2026 Elsevier.

5.4. Effect of Catalysis

The presence of other metals in solution during amino acid leaching of precious metals has been shown to be beneficial when it comes to increasing the leaching rate. Tests conducted by Oraby and Eksteen [37] showed that the rate of dissolution of gold from gold_silver alloys (50% Au, 50% Ag) increased by six times compared to the dissolution of pure gold. A similar behaviour was observed for gold_silver alloys during cyanide [68] and thiosulphate leaching [10,69]. Many researchers showed that copper ions act as catalysts for glycine leaching and, in their absence, leaching is difficult [52]. Perea and Restrepo [15] observed double the leaching rate of gold when the solution contains copper ions compared to a solution without copper ions. Catalytic effect has also been observed in presence of small amount of lixivants (synergism) in the solution as discussed in the precious metal leaching section. Thus, the presence of metal ions in amino acid leaching solution has a beneficial effect and should be further investigated for many amino acid systems.

5.5. Effect of Temperature

Favourable leaching conditions for precious metals, enabling faster kinetics, occur at high temperatures and in oxidative environments. However, these conditions should be optimised to lower the plant operating costs. Early research demonstrated that low temperatures achieve low gold leaching rates. Thus, several investigators studied the influence of temperature on gold dissolution from various sources [5,23,24,52]. Low gold dissolution rates were reported by Eksteen and Oraby [5] at temperatures lower than 60 °C and under conditions of 0.1 M glycine, 1% H₂O₂ and pH 11.5. Upon increasing temperature from 60 °C to 75 °C, the concentration of gold in leachate increased from 8 mg/L to 15 mg/L after 48 h of leaching (Figure 6). Altinkaya et al. [23] reported an increase in leachate gold concentration from 0.3 mg/L at room temperature to 0.55 mg/L at 60 °C after 24 h of leaching. Leaching was performed in absence of copper, at pH 10–12, with 0.2 M glycine and 100 g/L solid_liquid ratio and stirring rate of 100 rpm. The work by J.J. Eksteen and E.A. Oraby [37] showed that the presence of oxidants reduces the operation temperatures of gold dissolution. Temperatures of around 40–60 °C in presence of hydrogen peroxide and a high

pH were adequate for high gold dissolution. Thus, high temperatures are favourable for high dissolution; however, implementing high temperatures is economically challenging in commercial plants. The use of a strong oxidant, such as potassium permanganate, can be a better method for enhancing kinetics and reducing operation temperatures [41].

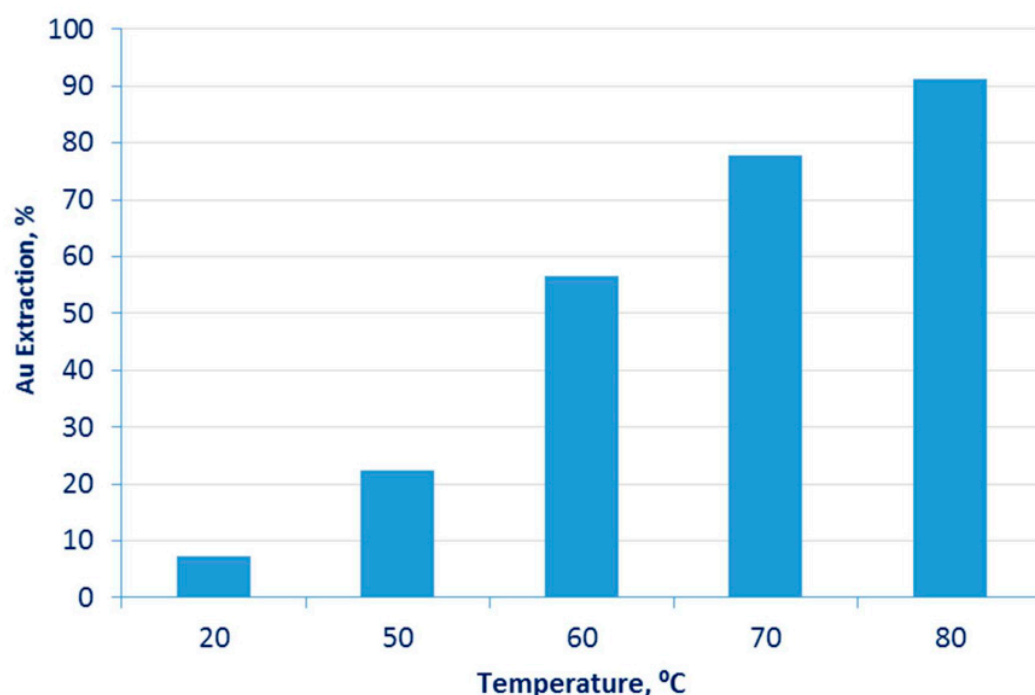


Figure 6. Effect of temperature on gold dissolution with glycine, under 20 ppm Cu^{2+} , O_2 , pH 10.5–11, 70 °C, after 48 h (redrawn). Reprinted with permission from ref. [41]. 2026 Elsevier.

6. Conclusions and Future Perspectives

We have reviewed the use of amino acids for leaching of precious metals from both natural and secondary resources. The review focused on the leaching chemistry and performance of different amino acids in natural and secondary leaching. The use of amino acids proved to be more effective for refractory and high-copper ores than traditional processes. Although preliminary research clearly demonstrated that alkaline amino acids especially glycine can be used for effective leaching of precious metals from ore concentrates, tailings, and electronic waste, much research is required before full commercialization. The leaching performance is influenced by several factors including amino acid type, ore type, pre-treatment, and operating conditions, all affecting reagents consumptions differently. Important operational conditions include temperature, pH, particle sizes, agitation speeds, solid–liquid ratios, concentrations of amino acids and oxidants, and redox potential. Most work is restricted to gold extraction from ore concentrates while work on recovery from secondary resources or recovery of other precious metals like silver and PGMs is still scarce. Aspects that should be addressed include slow leaching kinetics compared to inorganic acids or cyanide, lack proper understanding of extraction mechanisms, incomplete research of most amino acids (only glycine is intensively studied), and leaching performance in different types of ores and secondary materials. To fully commercialise the amino acid agitation leaching process in gold concentrates and secondary resources, the following aspects should be resolved:

(1) The leaching kinetics of precious (gold, silver, PGMs) metals from natural and secondary resources is slow. Amino acids in presence of strong oxidants, catalysts and synergists can compete and surpass traditional leaching approaches. Amino acids are more effective in leaching gold than silver and palladium and the use of strong oxidants

is more important in gold leaching than in palladium leaching. The use of stringent conditions, such as high temperatures and high amino acid concentrations, is unacceptable in the industry because of high costs. Much work should be done to reduce operating temperatures and amino acid concentrations through processes like pre-treatment, uses of green synergists like thiosulfate and low concentrations of powerful oxidising agents like potassium permanganate to improve extraction rates while keeping the operation costs low.

(2) Amino acid leaching of secondary wastes demonstrated higher leaching performance than leaching from natural ores because of the use of a two-step leaching process. The use of amino acids in two-step leaching is beneficial in construction of the same leaching tanks and modifying the conditions for precious metals leaching to include oxidants and synergists.

(3) Researchers are only basing their work on glycine because of its availability. To optimise performance, understanding of coordination chemistry between leaching agents and different metals is necessary and thermodynamic phase stability diagrams should be generated. For now, there are only a couple of studies on interactions between glycine and gold yet work on silver and PGMs is not available. Although glycine is readily available and cheap, priority in research should be given to other better performing amino acids depending on the precious metal to be extracted and conditions need to be optimised for a particular system depending on the appropriate amino acid, e.g., cysteine was shown to be better than gold but is not attractive to researchers because of high cost.

(4) Although many researchers mention that amino acids are easier to regenerate and recycle, this should be validated by using more leaching cycles to confirm the claim. In addition, it is also necessary to perform life cycle evaluations to assess the environmental impacts of different amino acids to understand their potential for replacing traditional technologies.

(5) Research on bioleaching using secreted amino acids is still very scarce and although slow kinetics were observed, they should be researched for economical metallurgical extractions like heap and vat leaching and tested at pilot scale aimed at commercialization.

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