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Evaluating the performance of operational variables in the sodium cyanide gold leaching process: A review article

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ABSTRACT

The application of sodium cyanide for gold leaching remains the predominant method for gold extraction. However, the efficiency of the gold leaching process depends on several interacting performance variables, including cyanide concentration, pH, pulp density, particle size, leaching time, dissolved oxygen, agitation rate, and temperature. The combined influence of performance variables on gold recovery has not been fully optimized. Therefore, a quantitative assessment is required to understand their relational strength effects. A literature review identified eight key performance variables commonly monitored in gold leaching operations, both with and without pretreatment methods. The effects of performance variables on gold recovery were evaluated using grey relational analysis and the coefficient of variation. Artificial intelligence, particularly artificial neural networks integrated with statistical methods, was also explored to predict the effects of variables on strength and gold recovery efficiency. The analysis produced mean relational degrees of 0.59 and 0.54, with coefficients of variation of 9.0% and 10.8% for processes without and with pretreatment methods, respectively. The relational degree indicated moderate variability across the datasets. The findings confirm that input performance variables strongly influence gold leaching efficiency. The dosage ranges identified in this study can serve as valuable benchmarks for optimizing gold recovery in industrial leaching operations.

KEYWORDS

Gold, NaCN leaching, performance variables, strength effect, grey relational analysis

I. INTRODUCTION

Gold extraction from gold-bearing ores has evolved through a range of methods over time. For highly refractory ores, the extraction techniques primarily rely on pyrometallurgical pre-treatment processes, including roasting, smelting, or calcining, followed by electrorefining. For non-refractory, mildly refractory, and moderately refractory ores, hydrometallurgical processes are commonly employed, typically involving leaching, adsorption, and electrowinning (Surimbayev et al., 2024; Chetty et al., 2023).

Sodium cyanide (NaCN) has long been the prominent leaching lixiviant in the industry. NaCN provides a reliable, relatively low-cost process with higher gold recoveries (Hilson & Monhemius, 2006). Nevertheless, extensive research has focused on the development and application of non-cyanide gold leaching lixiviants, including polysulfides, thiosulfate, thiourea, glycerine, aqueous chlorine, and biogenic lixiviants (Aylmore 2016; Konyratbekova et al., 2015; Barbouchi et al., 2024). Although these lixiviants have been employed, their adoption remains at the early stage for economically viable commercialization (Konyratbekova et al., 2015; Zhang & Senanayake 2016; Zhang et al., 2022; Kang et al., 2023; Ji et al., 2023). NaCN remains the preferred lixiviant in the gold-processing industry because of its simplicity, effectiveness, and ease of process control (Sparrow & Woodcock, 1995; Manzila, 2022). However, the use of NaCN solutions presents several drawbacks, including longer process duration, relatively high reagent cost, and limited selectivity, as other metals and minerals may also dissolve under cyanide leaching conditions (Dai et al., 2012; Konyratbekova et al., 2015).In addition, cyanide is highly toxic to humans, the environment, and aquatic organisms, raising significant concerns regarding its safe handling, environmental management, and disposal (Johnson, 2015). Furthermore, cyanide solutions are incapable of effectively treating certain refractory ores (Altinkaya et al., 2020).

Leaching techniques are classified into percolation and agitation processes. In percolation leaching, the ore remains stationary, while the leaching solution percolates through the ore, promoting the dissolution of

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the target mineral. In-situ leaching, vat leaching, heap leaching, and dump leaching are all based on a percolation process (Gupta, 2003). Among other percolation leaching techniques, vat leaching has gained popularity in most small-scale mines for gold extraction due to its short retention time, simplicity, and efficiency (Walsh et al., 2009; Marsden & House, 2006).

On the other hand, agitation leaching keeps the finely ground particles in suspension by agitating the slurry mechanically or pneumatically. Compared with percolation leaching, whose extraction efficiency is below 75%, agitation leaching provides more aggressive leaching conditions, resulting in higher recoveries (>90%) within a shorter leaching time. However, agitation leaching requires high capital investment (Han et al., 2024; Manzila, 2022; Ilyas & Lee, 2018; Kondos et al., 1995).

The gold cyanidation method has been widely used in industry for its high selectivity in gold dissolution. However, several variables affect the process and must be controlled during operation. These variables include: slurry pH, particle size, cyanide concentration, oxygen concentration, residence time, temperature, slurry density, and agitation. Different types of gold ores require different dosage levels of leaching parameters (Brittan & Plenge, 2015). Several parameters indicate that optimal conditions vary with gold ore type, composition, and operating conditions (Kondos et al., 1995). Therefore, optimization of these parameters is required to achieve higher gold recoveries and thereby develop more efficient, economical, and environmentally sustainable processes.

The implementation of this necessitates a synergistic approach that blends innovative metallurgical principles and automation with digital technologies. Artificial intelligence (AI) techniques have gradually been used in gold leaching operations to improve effectiveness, precision, and control. The significance of using AI in gold extraction processes lies in their ability to examine complex interactions among operating constraints, thereby improving estimation accuracy for gold recovery (Costa et al., 2024; Osei et al., 2024; Xu et al., 2020). This increases efficiency, enhances safety, and improves environmental sustainability. By leveraging AI technologies, the gold extraction industry can overcome traditional challenges and make operations smarter, safer, and more profitable. There is a huge volume of literature that involves the application of AI in gold metallurgy (Gbolagade et al., 2023; Nighojkar et al., 2023; Costa et al., 2024; Osei et al., 2024; Zulu et al., 2023). The AI models improve the prediction of leaching rates, kinetics, and control of process variables, leading to more efficient and cost-effective operations (Dong et al., 2022; Dong et al., 2023). However, the complexity of the leaching process, together with potential mismatches in model parameters in terms of compatibility and scalability, can lead to prediction errors (Dong et al., 2022).

The use of Relative Strength Effect (RSE) or sensitivity indices / variable importance metrics to adjust one specific variable such as leaching time, cyanide concentration, temperature, particle size and pH while keeping all other variables constant helps to understand the effect of gold recovery changes over a specific variable. The RSE depends on the dominance of each input variable in terms of its contribution to the output. Common RSE methods have been used in gold leaching processes, including Grey Relational Analysis (GRA), Standardized Regression Coefficients (SRC), and Neighborhood Component Analysis (NCA).

RSE methods have normalized coefficients ranging from 0 to 1. Values closer to 1 indicate strong influence, while values near 0 imply negligible effect under the studied specific conditions (Pianosi et al., 2016). Khoshjavan et al. (2011) reported Normalized Strength Effect (NSE) values indicating that leaching time dominates the process (0.44), followed by temperature (0.163), particle size (0.14), NaCN concentration (0.10), solids content (0.091%), and pH level (0.08). Application of GRA with Artificial Neural Networks (ANN) for gold leaching process identified leaching time, pH, and temperature to be the dominant variables (Xu et al., 2020). The use of SRC with ANN indicated that the leaching time had the most dominant effect on gold recovery (Azizi & Ghaedrahmati, 2015). Osei et al. (2024) used NCA with random forest, gradient boosting, and ANN, indicating that cyanide concentration and leaching time had the greatest dominance on gold recovery.

The RSE method normalizes the effects of input variables, enabling their comparison on a common scale. It is therefore widely used to evaluate the model outputs and apportion them to different sources of input variables (Saltelli et al., 2004). Unlike RSE, sensitivity analysis provides information on the changes of output with respect to model input variables (Saltelli et al., 2019). However, the economic optimization problem of the leaching process, which includes improving the intractability and anti-disturbance performance, can be improved by using Integrated Dynamic Model Predictive Control (IDE-MPC) with an improved Particle Swarm Optimization (PSO) algorithm (Niu et al., 2022).

Thus, the main objective of this research was to conduct a comprehensive literature review on gold leaching using NaCN lixiviant at different concentration levels. The review also sought to identify the key performance variables that currently influence gold recovery from different gold ores. Furthermore, this study reviews AI methods applied in gold leaching with NaCN solutions. The conclusion offers specific recommendations for researchers, paving the way for future advancements in the field.

II. MATERIALS AND METHODS

A. *Data Collection Strategies*

This study collected, screened, reviewed, and analyzed relevant scholarly articles on the gold leaching process from various databases such as Google Scholar, Web of Science, ScienceDirect, ResearchGate, Springer Nature, and other related sources. The search included peer-reviewed journal articles, conference papers, and relevant reviews published between 2000 and 2026.

Literature data were collected using keyword combinations and Boolean keywords such as "gold leaching," "gold leaching AND Cyanide", "factors affecting gold leaching AND Cyanide", "gold recovery prediction AND Cyanide", "gold recovery prediction AND AI methods", or "gold prediction AND neural methods". The search aimed to capture a wide range of factors affecting gold recovery both with and without the use of AI methods. It also included the application of AI methods to gold cyanidation, and different performance metrics, including RSE. After retrieval, the literature data were screened manually, quantitatively tabulated, and analyzed.

The flow diagram (Fig. 1) summarizes the methodology adopted in this work, beginning with data collection on the input variables in the gold leaching process for ores treated either with or without pretreatment methods. Only the gold leaching process that used NaCN as the dissolution lixiviant was selected for this study. In addition, AI-based methods used to predict the gold recovery percentages were reviewed. For the leaching process, performance analysis was conducted for vat leaching input variables. The data obtained were evaluated using descriptive statistics to determine gold recovery outcomes. Finally, the input variables for gold leaching process were ranked using GRA method.

B. *Statistical Metrics Evaluation*

The mean ($\underline{\gamma}$), standard deviation (σ), and the coefficient of variation (CV) were used to calculate the variation of n repetitions of each performance variable during the gold leaching process. The formulas for $\underline{\gamma}$, σ, and CV are presented in equations 1, 2, and 3, respectively.

$$\bar{\gamma}= \frac{\sum_{k=1}^{n} \gamma_k}{n} \tag{1}$$

$$\sigma_i = \sqrt{\frac{1}{n-1}\sum_{k=1}^{n}\left(\gamma_{i,k} - \bar{\gamma}_i\right)^2} \tag{2}$$

$$CV_i = \frac{\sigma_i}{\underline{\gamma_i}} \times 100\% \tag{3}$$

Where, $\gamma_{i,k}$ denotes the variable i in run k, $\underline{\gamma_i}$ denotes the mean of variable i and σ_i denotes the standard deviation of variable i.

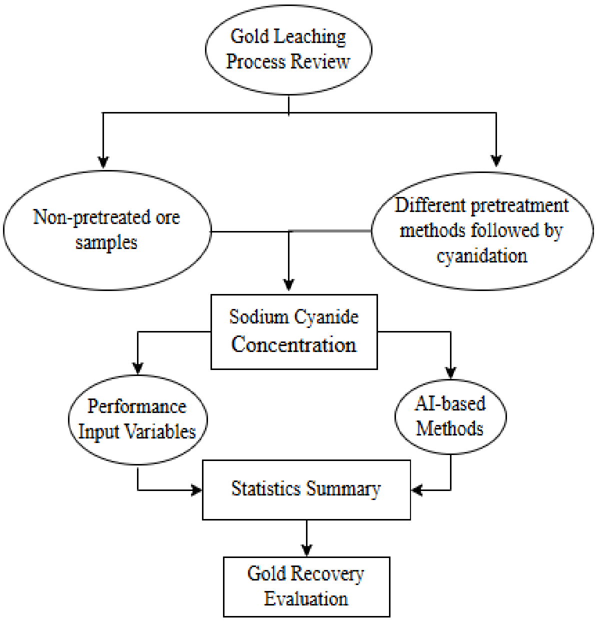

Fig. 1. Flow diagram of the methodology

In this study, the GRA was used to analyze the strength of the effect of input variables on the one output. GRA enabled the transformation of the multi-variable optimization design into a single-response (Aral & Beşe, 2024; Prakash et al., 2020). The method identified which input variables (e.g., leaching time, pH, sodium cyanide concentration, etc.,) are most influential to the gold recovery efficiency with the larger-the-better criteria as described by Xu et al. (2020). Because, different influencing variables have different units, GRA was used to normalize them to positive scales ranging from 0 to 1. A distinguishing coefficient of 0.5 was assumed to determine the relational coefficients (Mahmoudi et al., 2020). The average of the grey relational coefficients for each variable was then used to define the relational degrees.

III. RESULTS

A. *Performance Variable Analysis*

Cyanide concentration is one of the most significant factors directly influencing the electrochemical dissolution of gold. Gold dissolution depends on the ability of cyanide ions to form soluble complexes with gold, allowing it to be separated from the ore matrix. Table 1 shows the optimum conditions for a smooth cyanidation reaction for various leaching data collected from the literature. Higher cyanide concentration leads to a faster dissolution rate of gold (Kim & Ghahreman, 2019; Abdollahi et al., 2015). Concentrations higher than the stoichiometric value normally drive the chemical reaction forward. However, excessive cyanide concentration can lead to several issues: (i) the formation of unwanted side reactions in which metals present in the ore, such as Cu, Zn, and Fe, may react with cyanide, consuming cyanide and reducing its availability for gold extraction (Abdollahi et al., 2015); (ii) environmental risks, as excess cyanide increases, its concentration in the tailings stream, requiring stringent safety and environmental management measures (Kuyucak & Akcil, 2013).

The cyanidation reaction is a redox reaction, and the presence of oxygen serves as an oxidizing agent in half-reactions. The reaction often proceeds through a two-electron transfer involving a hydrogen peroxide intermediate. Hydrogen peroxide greatly enhances gold dissolution kinetics (Marsden & House, 2006). However, excessively high concentration of oxygen can promote side reactions, particularly sulphuric acid production, which will interfere with the alkaline conditionsrequiredfor the cyanidation reaction (Kuyucak & Akcil, 2013; Ilyas & Lee, 2018).

The optimum recommended pH range of 9.5 to 11 plays a vital role in the cyanide leaching process because cyanide exists in its free form, which can easily react. Acidic solution can form hydrogen cyanide gas (HCN), which is volatile and highly toxic and not reactive for gold extraction (Eugene & Mujumdar, 2009). In addition, higher pH can reduce the solubility of gold in cyanide by producing more precipitates (such as iron hydroxide) that prevent gold extraction (Hiji & Maganga, 2015).

A moderate temperature between 20-30 °C is required. Higher temperatures will require higher energy input and more operational costs (Chen et al., 2021). Cyanide dissolution does not require high temperatures. Moreover, at higher temperatures, volatility of cyanide increases, leading to a greater loss of reactant through evaporation (Ng et al., 2023). In addition, side reactions occur at higher temperatures, such as oxidation of sulphide, which not only consume oxygen and cyanide but also generate sulphuric acid, affecting the alkalinity condition required for the cyanidation process (Ghorbani et al., 2016).

Leaching reactions generally follow the shrinking core model mechanism. Sufficient time is required to complete the reaction, with the recommended time ranging from 24 to 48 hours (Table 1). At the beginning of the process, the chemical reaction mechanism controls; the reaction and the reaction rate are faster. After some time, due to depletion of cyanide and formation of product, the control mechanism changes to ash layer control, and the reaction is slower. Therefore, excessively long leaching time is not useful. On the other hand, if the leaching time is too short, the reaction will be premature, leading to incomplete gold recovery (Brittan & Plenge, 2015).

Particle size is another factor affecting the cyanidation reaction. The finer grinding increases the reaction surface area and particle liberation and hence increases the rate of reaction (Birloaga et al., 2013), but overly fine grinding can lead to excessive cyanide consumption and higher operational costs (Egan et al., 2016). Typical particle sizes of 80% passing 75 μm indicate that the majority of the gold is liberated from the gangue minerals and exposed to the solution; the actual value depends on liberation size studies for the particular ore.

Agitation and slurry density further impact leaching efficiency by affecting the diffusion layer thickness and mixing intensity. Effective agitation improves mass transfer of cyanide and oxygen, while optimal slurry densities (typically 35–50% solids) strike a balance between reaction efficiency and reagent usage (Hlabangana et al., 2018). Generally, ore mineralogy and composition play another role in the cyanidation reaction without pretreatment, as shown in Table 1. Some of the sulphide minerals, such as pyrite and arsenopyrite, can compete with gold for cyanide and hence reducethe overall efficiency of gold recovery (Eugene & Mujumdar, 2009; Ben, 2022). In summary, achieving optimal gold recovery requires a careful balance and integration of these parameters for efficient, economical, and environmentally sustainable leaching operations.

B. Leaching Additives

Recent developments emphasize the important functions of lead nitrate ($Pb(NO_3)_2$), hydrogen peroxide (H_2O_2), and ethylenediaminetetraacetic-acid (EDTA) as additives that improve the efficiency of gold extraction in cyanide solutions (Dai et al., 2018).

The Effect of Lead Nitrate: Lead nitrate is mainly used in cyanidation processes to reduce the harmful effects of sulfide minerals. Sulphides frequently create protective layers on gold surfaces, which impede the leaching process (Baharun et al., 2020). Lead ions promote an electrochemical reaction that increases gold dissolution. The process includes the deposition of lead at a lower potential on surfaces, which lowers the overpotential needed for the oxidation of gold [1]. This significantly increases gold leaching rates, especially in systems with high sulfide content (Marsden & House, 2006). Research indicates that in settings with adequate lead ions, gold-silver alloys exhibit higher leaching rates. These rates tend to be influenced more by the diffusion of oxidants than by chemical reactions, leading to improved recovery rates (Soltani et al., 2020).

The Effect of Hydrogen Peroxide: Hydrogen peroxide plays two roles in the cyanidation process: it acts as an oxidizing agent and may enhance gold dissolution. Increasing the concentration of dissolved oxygen enhances gold leaching by facilitating better electrochemical reactions with hydrogen peroxide (Dai & Breuer, 2013). The effectiveness of hydrogen peroxide depends on its concentration. Low concentrations, such as 2.5 mM, have shown limited benefit because oxygen reduction typically occurs before the peroxide reduction in cyanide solutions. Higher concentrations may increase oxidative stress on cyanide complexes, which could negatively affect gold recovery. The appropriate concentration must be carefully controlled to ensure it is effective without causing harm (Nunan et al., 2017).

Effect of EDTA: Gold ores and concentrates that are complex and resistant frequently show low effectiveness in cyanidation, even after significant oxidation of sulfides. This behavior is often linked to the significant use of cyanide by cyanicides, the passivation of gold surfaces caused by sulfur ions, and the trapping of small gold particles within cemented gangue mineral aggregates. These factors restrict cyanide access and slow gold dissolution (Marsden & House, 2006; Ilyas & Lee, 2018; Asamoah, 2020). Asamoah (2020) showed that EDTA can effectively reduce this type of resistance and significantly improve gold recovery during alkaline cyanide leaching. EDTA is an effective chelating agent that can bind to various divalent and trivalent metal ions, such as Ca^{2+}, Fe^{3+}, and Cu^{2+}. These metal ions are important components of secondary sulfate minerals and cyanide compounds (Zhang et al., 2019; Kuzu et al., 2025). The EDTA improves the process gold dissolution by eliminating thin layers of various unwanted minerals. The Jarosite, gypsum, silicates, and other substances can restrict access to cyanide, bind with cyanide-consuming agents (especially copper minerals) that increase cyanide usage, and stabilize the electrochemistry of the slurry (Zhang et al., 2010). This stabilization helps maintain more favorable redox potentials for gold oxidation by reducing competing redox reactions that involve iron compounds. The addition of 0.08–0.4 M EDTA in cyanide leaching improved gold extraction to 83–86%, even when cyanide concentrations were low (Zhang et al., 2010; Kuzu et al., 2025). The use of EDTA in cyanidation effectively reduces the amount of reagents needed. The use of sodium cyanide decreased by approximately 50-60% in EDTA-activated systems compared with traditional cyanidation. Additionally, the need for sodium hydroxide is lowered because alkaline-consuming sulfate minerals are eliminated (Zhang et al., 2019; Asamoah, 2020; Kuzu et al., 2025).

Table 1. Gold leaching input variables and gold recovery with direct cyanidation of different ore samples.

S/N	Sample Composition	Input parameters	Dosage range/ size	Gold recovery	Sources
1	Representative ore sample with grade of 3 g/t	NaCNConc (ppm)	1000	92.87%	Azizi et al. (2012)
		O_2Conc (ppm)	16		
		Solid Content (%)	30		
		Temperature (ºC)	20		
		pH	11.5		
		Size (μm) P_{80}	25		
		Agitation (rpm)	NR		
		Leaching time (h)	12		
2	Sulfide-associated gold ore originating from an artisanal mining area in Zimbabwe.	NaCN Conc.. (ppm)	5000	71.6%	Manzila et al. (2022)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	30		
		Temperature (ºC)	Ambient		
		pH	10 -11		
		Size (μm) P_{80}	150		
		Agitation (rpm)	300		
		Leaching time (h)	24		
3	Complex polymetallic gold ore from the Gandi gold mine, located in Semnan Province, Iran	NaCN Conc. (ppm)	4500	62.21%	Barani et al. (2022)
		O_2Conc. (ppm)	Ambient		
		Solid Content (%)	30		
		Temperature (ºC)	Ambient		
		pH	10.5		
		Size (μm) P_{80}	74		
		Agitation (rpm)	150		
		Leaching time (h)	48		
4		NaCN Conc. (ppm)	750	77%	

Table 1. (*cont.*)

	Sulfidic gold ore, dominated by pyrite, pyrrhotite and chalcopyrite.	O_2 Conc. (ppm)	Ambient		Altinkayaet al. (2020)
		Solid Content (%)	30		
		Temperature (ºC)	22		
		pH	11		
		Size (μm) P_{80}	86		
		Agitation (rpm)	NR		
		Leaching time (h)	48		
5	Low-sulfidation gold ore	NaCN Conc. (ppm)	600	96.5%	Putri et al. (2023)
		O_2 Conc. (ppm)	20		
		Solid Content (%)	40		
		Temperature (ºC)	Ambient		
		pH	10.5		
		Size (μm) P_{80}	75		
		Agitation (rpm)	NR		
		Leaching time (h)	48		
6	Gold-bearing ore with average Au and Ag contents of 1.32 & 3.27 g/t, respectively.	NaCN Conc.. (ppm)	500	83.08%	Surimbayev et al. (2024)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	33		
		Temperature (ºC)	Ambient		
		pH	11		
		Size (μm) P_{80}	<71		
		Agitation (rpm)	NR		
		Leaching time (h)	24		
7	Free-milling gold ore from the Mouteh gold mine, in Iran	NaCN Conc. (ppm)	3000	94%	Shafiei et al. (2025)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	30		
		Temperature (ºC)	Ambient		
		pH	10.5		
		Size (μm) P_{80}	70		
		Agitation (rpm)	450		
		Leaching time (h)	24		
8	Gold ore from Colombia with over 80% quartz as well as pyrite and chalcopyrite	NaCN Conc. (ppm)	2000	92%	Torkaman & Veiga (2023)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	10		
		Temperature (ºC)	Ambient		
		pH	11		
		Size (μm) P_{80}	120		
		Agitation (rpm)	NR		
		Leaching time (h)	24		
9	Sulphidic gold ore with grade of 1.70g/t	NaCN Conc. (ppm)	400	91.3%	Nunan et al. (2017)
		O_2 Conc. (ppm)	7.2		
		Solid Content (%)	60		
		Temperature (ºC)	Ambient		
		pH	10.5		
		Size (μm) P_{80}	NR		
		Agitation (rpm)	NR		
		Leaching time (h)	24		
10	Refractory Au-Ag ore from Beiya (Yunnan, China	NaCN Conc. (ppm)	1700	85.44%	Zhang et al. (2020)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	25		
		Temperature (ºC)	28		
		pH	10.5		
		Size (μm) P_{80}	75		
		Agitation (rpm)	NR		
		Leaching time (h)	36		
11		NaCN Conc. (ppm)	1000	87.11%.	

Table 1. (*cont.*)

	Samples of gold ores from the Sarigoni gold mine in Iran	O_2 Conc. (ppm)	Ambient		Khosravi et al. (2017)
		Solid Content (%)	33		
		Temperature (ºC)	Ambient		
		pH	11		
		Size (μm) P_{80}	74		
		Agitation (rpm)	40		
		Leaching time (h)	24		
12	Refractory gold ore from the Mouteh gold mine, in Iran	NaCN Conc. (ppm)	5000	58%	Shafiei et al. (2025)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	30		
		Temperature (ºC)	Ambient		
		pH	10.5		
		Size (μm) P_{80}	70		
		Agitation (rpm)	450		
		Leaching time (h)	24		
13	Sedimentary Rock-Hosted Disseminated Agh-Darreh Gold Deposit	NaCN Conc. (ppm)	400	86.4%	Asadi et al. (2024)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	50		
		Temperature (ºC)	Ambient		
		pH	11		
		Size (μm) P_{80}	75		
		Agitation (rpm)	350		
		Leaching time (h)	36		
14	Gold tailings from flotation	NaCN Conc. (ppm)	5000	59.2%	Mbayo et al. (2022)
		O_2 Conc. (ppm)	9		
		Solid Content (%)	40		
		Temperature (ºC)	Ambient		
		pH	11		
		Size (μm) P_{80}	74.3		
		Agitation (rpm)	500		
		Leaching time (h)	24		
15	Oxide gold ore containing free and exposed gold <150 µm	NaCN Conc. (ppm)	3000	95.03%	Roostaei et al. (2025)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	25		
		Temperature (ºC)	80		
		pH	10.5		
		Size (μm) P_{80}	53		
		Agitation (rpm)	800		
		Leaching time (h)	24		
16	Gold tailings from Sluice box	NaCN Conc. (ppm)	1000	7.8%	Wahyuningsih et al. (2024)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	40		
		Temperature (ºC)	Ambient		
		pH	10.5		
		Size (μm) P_{80}	53		
		Agitation (rpm)	65		
		Leaching time (h)	72		
17	Copper-rich gold ore (69 g/t Au, 9.4 g/t Ag, 1.63% Cu)	NaCN Conc. (ppm)	1500	12.5%	Kuzu et al. (2025)
		O_2 Conc. (ppm)	9		
		Solids content (%)	25		
		Temperature (ºC)	20		
		pH	11		
		Size (μm) P_{80}	60		
		Agitation (rpm)	600		
		Leaching time (h)	24		
18		NaCN Conc. (ppm)	1500	90%	

Table 1. (*cont.*)

	Amalgam waste containing an average of 5.5 g/ton of gold	O_2 Conc. (ppm)	Ambient		Youpoungam et al. (2024)
		Solid Content (%)	30		
		Temperature (ºC)	Ambient		
		pH	11		
		Size (μm) P_{80}	106		
		Agitation (rpm)	450		
		Leaching time (h)	24		
19	Low grade (2.5 ppm Au) with high Ag(160 ppm)	NaCN Conc. (ppm)	2500	92.5%	Karimi et al. (2010)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	25		
		Temperature (ºC)	Ambient		
		pH	10.5		
		Size (μm) P_{80}	75		
		Agitation (rpm)	NR		
		Leaching time (h)	24		
20	Refractory Gold ore sample with 2.8 g/t of Au, 4.37 g/t Ag	NaCN Conc. (ppm)	10,000	15%	Quijada-Noriega et al. (2025)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	20		
		Temperature (ºC)	Ambient		
		pH	10.5		
		Size (μm) P_{80}	37		
		Agitation (rpm)	300		
		Leaching time (h)	48		
21	Sample containing 1.17 ppm Au from Aghdareh gold mine	NaCN Conc. (ppm)	730	91.5%	Azizi&Ghaedrahmat al. (2015)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	36		
		Temperature (ºC)	Ambient		
		pH	10.11		
		Size (μm) P_{80}	37.52		
		Agitation (rpm)	NR		
		Leaching time (h)	23.2		
22	Gold–silver ore sample containing 9.85 g/t Au and 217.10 g/t Ag	NaCN Conc. (ppm)	500	91.92%	Birol&Uçurum (2015)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	25		
		Temperature (°C)	85		
		pH	20		
		Size (μm) P_{80}	90		
		Agitation (rpm)	1000		
		Leaching time (h)	90		
23	Polymetallic sulfide ore containing 0.7 g/t Au and 5.7 g/t Ag	NaCN Conc. (ppm)	1000	81.2%	Navas Jaramillo & Gonzalez Zuñiga (2025)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	33		
		Temperature (°C)	Ambient		
		pH	10		
		Size (μm) P_{80}	90		
		Agitation (rpm)	400		
		Leaching time (h)	24		
24	Gold ore sample with1.09 g/t Au from Central Kazakhstan	NaCN Conc. (ppm)	500	77%	Dosmukhamedov et al. (2024)
		O_2 Conc. (ppm)	11.5		
		Solid Content (%)	40		
		Temperature (°C)	Ambient		
		pH	11.5		
		Size (μm) P_{80}	75		
		Agitation (rpm)	NR		
		Leaching time (h)	12		
25		NaCN Conc. (ppm)	467.3	62.02%	

Table 1. (*cont.*)

	Gold ore with 1.94 g/t Au from a local gold mine in Peninsular Malaysia	O_2 Conc. (ppm)	Ambient		Baharun et al. (2020)
		Solid Content (%)	25		
		Temperature (°C).	26.5		
		pH	11.0		
		Size (μm) P_{80}	75		
		Agitation (rpm)	500		
		Leaching time (h)	24		
26	Low-grade gold ore	NaCN Conc. (ppm)	210	93%	Hlabangana et al. (2018)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	50		
		Temperature (°C).	85		
		pH	12		
		Size (μm) P_{80}	75		
		Agitation (rpm)	90		
		Leaching time (h)	24		
27	Concentrate, containing 10.6 g/t Au, 42 g/t Ag, 0.21% Cu, 3.57% Zn, and 31% Fe	NaCN Conc.. (ppm)	7000	73%	Celep et al. (2025)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	40		
		Temperature (ºC)	Ambient		
		pH	11		
		Size (μm) P_{80}	55		
		Agitation (rpm)	600		
		Leaching time (h)	24		
28	Pyritic gold flotation concentrate, which assayed 11 g/t Au, 42 g/t Ag, 0.21% Cu, 3.57% Zn, and 31% Fe	NaCN Conc. (ppm)	1500	37%	Deveci et al. (2023)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	60		
		Temperature (ºC)	Ambient		
		pH	10.5		
		Size (μm) P_{80}	28		
		Agitation (rpm)	600		
		Leaching time (h)	24		
29	Leach feed material obtained at the CIL plant	NaCN Conc. (ppm)	250	97%	Beyuo et al. (2016)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	55		
		Temperature (ºC)	Ambient		
		pH	11		
		Size (μm) P_{80}	106		
		Agitation (rpm)	NR		
		Leaching time (h)	24		
30	Copper Flotation tailings	NaCN Conc. (ppm)	0.5	81.79%	Medina & Anderson (2020)
		O_2 Conc. (ppm)	4.6		
		Solid Content (%)	45		
		Temperature (ºC)	Ambient		
		pH	11.66		
		Size (μm) P_{80}	NR		
		Agitation (rpm)	NR		
		Leaching time (h)	32		
31	Sample containing 0.8 g/t Au, 1.8 g/t Ag, 0.2 g/t Hg, and 38 g/t As	NaCN Conc (ppm)	1500	95.21%	Olyaei et al. (2017)
		O_2 Conc (ppm)	Ambient		
		Solid Content (%)	40		
		Temperature (ºC)	Ambient		
		pH	10.5		
		Size (μm) P_{80}	63		
		Agitation (rpm)	750		
		Leaching time (h)	12		
32		NaCN Conc. (ppm)	1000		

Table 1. (*cont.*)

	Refractory sulfide concentrates pre-leached with biogenic ferric	O_2 Conc. (ppm)	Ambient	57% by direct cyanidation 93% after two-step Bio-oxidation	Fomchenko et al. (2016)
		Solid Content (%)	30		
		Temperature (ºC)	20		
		pH	10.5		
		Size (μm) P_{80}	44		
		Agitation (rpm)	NR		
		Leaching time (h)	48		
		Pretreatment	Bio-oxidation		
33	Gold clay ore containing arsenic and manganese	NaCN Conc. (ppm)	6400	78.23%	Li et al. (2010)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	28.6		
		Temperature (ºC)	25		
		pH	11		
		Size (μm) P_{80}	43		
		Agitation (rpm)	NR		
		Leaching time (h)	48		
34	Carbonaceous gold-bearing ores in Ethiopia	NaCN Conc. (ppm)	500	61.7%	Chaka & Rupprecht (2024)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	50		
		Temperature (ºC)	25		
		pH	10		
		Size (μm) P_{80}	75		
		Agitation (rpm)	200		
		Leaching time (h)	48		
35	Micro-fine refractory gold concentrate with high levels of arsenic and sulfur	NaCN Conc. (ppm)	1500	10.7% by direct cyanidation 83.37% after pretreatment	Lin et al. (2022)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	20		
		Temperature (ºC)	Ambient		
		pH	11		
		Size (μm) P_{80}	74		
		Agitation (rpm)	NR		
		Leaching time (h)	24		
		Pretreatment:	Roasting at 500 ∘C for 2h followed by roasting at 650 ∘C for 3h		
36	Refractory gold concentrate	O_2 Conc. (ppm)	10,000	57% Direct cyanidation 24–27% after Roasting	De Michelis et al. (2013)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	33		
		Temperature (ºC)	Ambient		
		pH	11.5		
		Size (micron) (P_{80})	74		
		Agitation (rpm)	240		
		Leaching time (h)	24		
		Pretreatment: Roasting	Roasting at 450-650∘C for 4 -6 h		
37	Copper-bearing pyritic gold concentrate	NaCN Conc. (ppm)	1500	46% @80 μm 60% @22 μm 82% @4.2 μm	Celep et al. (2016)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	20		
		Temperature (ºC)	Ambient		
		pH	10.5		
		Size (micron) (P_{80})	Based on recovery		
		Agitation (rpm)	600		
		Leaching time (h)	24		

NR = Not reported

C. Pretreatment for Refractory Gold Ores

Gold ores are typically categorized into three primary classes based on their metallurgical response: free-milling, mildly to moderately refractory, and complex or highly refractory ores. Free-milling ores give a gold recovery >95% with direct cyanidation (Ilyas & Lee, 2018; Vaughan, 2004). On the other hand, refractory ores do not provide economic gold recovery with conventional cyanidation due to fine-grained gold inclusions in sulphides, the presence of leach-robbing ores such as copper sulfides, pyrrhotite, etc., and preg-robbing materials such as carbonaceous materials

(Sceresini & Breuer, 2016; Dai et al., 2012). Complex gold ores contain copper with other gangue minerals that interfere with cyanidation by either consuming cyanide solution, oxygen, or re-adsorbing gold from the solution (Miller et al., 2016; Mabwe 2020; Marsden & House, 2006). The mildly refractory ores give gold recovery ranging between 80 and 95%, moderately refractory ores give gold recovery ranging between 50 and 80%, and highly refractory ores givegold recovery of less than 50% (Barbinta-Patrascu et al., 2024; Asamoah et al., 2014).

Refractory gold ores, particularly those in which gold is hosted within sulfide minerals such as pyrrhotite and arsenopyrite, as well as ores containing carbonaceous matter, present major challenges during direct cyanidation due to encapsulation of gold particles, surface passivation, high cyanide and oxygen consumption, and preg-robbing effects (Yang et al., 2013; Suratman, 2017; Manzila et al., 2022). The untreated refractory ores commonly yield gold recoveries below 70%, even under aggressive cyanidation conditions. To overcome these limitations, a range of physical, chemical, thermal, and biological pretreatment technologies have been developed to liberate gold prior to cyanidation, enabling post-treatment recoveries exceeding 80% (Mutimutema et al., 2022). Gold recoveries greater than 80% observed in Table 2 for refractory ores are attributable to the presence of effective pretreatment prior to cyanidation. Studies employing roasting, pressure oxidation, or bio-oxidation consistently report post-treatment gold recoveries exceeding 80%, whereas untreated ores typically yield below 80%. This highlights that pretreatment is not merely an auxiliary step but a dominant factor governing the success of cyanide leaching for refractory systems. Common pretreatment methods are stipulated below:

Ultra-Fine Grinding: Ultra-fine grinding (UFG) is a physical pretreatment method that reduces particle size to below 20 µm, thereby increasing surface area and enhancing gold exposure to cyanidation (Barriga, 2022). UFG is particularly effective for ores where gold is locked within fine-grained sulfide matrices. While UFG alone may not completely overcome chemical refractoriness, it significantly improves cyanidation kinetics. It is often combined with oxidative pretreatments such as Pressure oxidation (POX) or bioleaching (Andrianandraina et al., 2022). Gold recovery with UFG can exceed 20% compared to conventional grinding (Celep et al., 2010; González-Anaya et al., 2011; Gómez Santiago et al., 2025). The main drawback of UFG is its high energy demand.

Flotation Pre-Concentration: Flotation pre-concentration is frequently employed as an upstream process to selectively concentrate sulfide minerals prior to pretreatment. Flotation reduces the mass of material requiring oxidation and improves the economic viability of roasting, POX, or bioleaching (Faraz et al., 2014). The typical processing route for refractory ores involves flotation followed by an appropriate pretreatment and subsequent cyanidation of the treated concentrate. This integrated approach can achieve high overall gold recoveries while reducing reagent consumption and processing costs.

Roasting Pretreatment: Roasting is a thermal pretreatment process typically conducted at temperatures between 500 and 700 °C in the presence of oxygen (Ma et al., 2023). During roasting, sulfide minerals such as pyrite and arsenopyrite are oxidized to porous iron oxides, liberating encapsulated gold particles and eliminating sulfur and arsenic species that hinder cyanidation. Numerous studies have shown that roasting can increase gold recovery from less than 30% in untreated ores to over 85% following cyanidation (Yoğurtcuoğlu, 2023; HosseiniBohluli et al., 2025; Espinoza-Martínez et al., 2025). However, roasting can also hamper the leaching kinetics by locking gold within newly formed oxide/sulfate matrices (e.g., bianchite, franklinite, hematite) or by partially converting sulphides to sulphates, which consume reagents and form a passivating layer (De Michelis et al., 2013). Therefore, roasting of refractory ores is effective only when conducted under well-controlled conditions; otherwise, it may adversely affect gold recovery. Despite its effectiveness, roasting is associated with high energy consumption and environmental concerns related to sulfur emissions, necessitating advanced gas-handling and mitigation systems. Therefore, optimum roasting conditions have to be established (Hapid et al., 2024).

Bioleaching: This is also referred to as bio-oxidation, and it employs acidophilic microorganisms to oxidize sulfide minerals under controlled conditions. Some of the current laboratory and industrial microorganisms applied include Acidithiobacillus ferrooxidans, Acidithiobacillus thiooxidans, Acidithiobacillus ferrivorans, Leptospirillum ferrooxidans, Sulfolobus species, and white-rot fungi (Wang et al., 2025). This process operates at relatively low temperatures and pressures, making it an environmentally favorable alternative to roasting. Bioleaching achieves sulfide oxidation levels up to over 60%, depending on ore mineralogy and operating conditions. Subsequent cyanidation of bio-oxidized materials commonly results in gold recoveries greater than 80% (Huang & Yang, 2021; Takimoto et al., 2025). However, bioleaching has slower kinetics and requires careful control of microbial activity, residence time, and solution chemistry.

Pressure Oxidation (POX): This is a highly effective pretreatment technology widely adopted in industrial operations for treating refractory sulfide gold concentrates. The process is carried out in autoclaves at elevated temperatures (180–225°C) and oxygen pressures (350–700 kPa), enabling rapid and extensive oxidation of sulphide minerals (Wang et al., 2025). POX routinely achieves sulfide destruction levels exceeding 90%, resulting in significant gold liberation. Post-POX cyanidation recoveries greater than 90% are commonly reported, making this method a benchmark pretreatment for highly refractory ores (Fleming, 2010; Thomas & Pearson, 2016). The main limitations of POX include high capital and operating costs, as well as the need for specialized materials and process control.

Table 2. Gold leaching input variables and gold recovery with different pretreatment methods followed by cyanidation of different ore samples.

S/N	Sample Composition	Input parameters	Dosage range/ size	Gold recovery	Sources
1	Carbonaceous gold ore concentrate	NaCNConc (ppm)	2940	67% By Direct cyanidation	Wang et al. (2019)
		O_2Conc (ppm)	Ambient		
		Solid Content (%)	20		
		Temperature(ºC)	50		
		pH	11		
		Size (μm) P_{80}	38		
		Agitation (rpm)	300	95.2% after roasting	
		Leaching time (h)	48		
		Pretreatment:	Roasting at 500°C for		
2	Refractory gold ore from Tri-K gold mine –Guinea	NaCNConc (ppm)	1000	62.6 % by Direct Cyanidation	Barbouchi et al. (2025)
		O_2Conc (ppm)	Ambient		
		Solid Content (%)	33		
		Temperature(ºC)	25		
		pH	11		
		Size (μm) P_{80}	100		
		Agitation (rpm)	NR	93.6% after Pretreatment	
		Leaching time (h)	15		
		Pretreatment	Persulfate oxidation		
3	BolkardağGossan-containing refractory ores	NaCNconc (ppm	1500	52.0% by direct cyanidation	Yoğurtcuoğlu and Alp (2023)
		O_2Conc (ppm)	Ambient		
		Solid Content (%)	10		
		Temperature(ºC)	Ambient		
		pH	11		
		Size (μm) P_{80}	29.6		
		Agitation (rpm)	magnetic		
		Leaching time (h)	24	94.4% After roasting	
		Pretreatment	Roasting @800°C		
4	Gold-bearing depositsample from Kazakhstan	NaCN Conc. (ppm)	2000	97.51%	Kenzhaliyev et al. (2023)
		O_2Conc (ppm)	Ambient		
		Solid Content (%)	30		
		Temperature (ºC)	Ambient		
		pH	10.5		
		Size (μm) P_{80}	71		
		Agitation (rpm)	Stirred		
		Leaching time (h)	24		
		Pretreatment	Floatation		
5	Low-grade gold refractory sulfide ore	NaCNConc (ppm)	4000	63.59% by direct cyanidation	Sedighi and Ahmadi (2025)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	25		
		Temperature (ºC)	Ambient		
		pH	10.5		
		Size (μm) P_{80}	75	80.21% after bio-oxidation using mesophilmicroorganisms	
		Agitation (rpm)	mechanical		
		Leaching time (h)	48		
		Pretreatment	Bio-oxidation		
6		NaCN Conc. (ppm)	1600		

Table 2. (*cont.*)

	Gold ore containing 31.1 g/t Au and 6.15 %S . Other contents were C, As and Sb at 3.61%, 1.70% and 0.94%, respectively.	O_2 Conc. (ppm)	Ambient	Without treatment 8.1% With treatment 87.8%	Xu et al. (2016)
		Solid Content (%)	25		
		Temperature(ºC)	25		
		pH	10.5		
		Size (μm) P_{80}	48		
		Agitation (rpm)	300		
		Leaching time (h)	48		
		Pretreatment	Heating (60-80 °C) followed by treatment with $KMnO_4$ and H_2SO_4 for 3-5 h		
7	Silicified sulfide ore sample containing gold and silver	NaCN Conc. (ppm)	800	37.96% by direct cyanidation 81–86% after Pressure oxidation	Salazar-Campoy et al. (2020)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	20		
		Temperature(ºC)	Ambient		
		pH	11.0		
		Size (μm) P_{80}	55		
		Agitation (rpm)	600		
		Leaching time (h)	72		
		Pretreatment	O_2 pressure: 87.5 psi and 80ºC		
8	The ore sample contained 56 g/ton Au, 10 g/ton Ag, 85% SiO2, 1.1% Cu and 3.1% S.	NaCN Conc. (ppm)	1500	12.3% by direct cyanidation 98.2% after pretreatment	Bas et al. (2012)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	25%		
		Temperature(ºC)	Ambient		
		pH	11		
		Size (μm) P_{80}	75		
		Agitation (rpm)	600		
		Leaching time (h)	24		
		Pretreatment	(0-1 M NH3), (0-1000 g/ton Pb(NO3)2)		
9	HighSulfur and Arsenic refractory gold ore with 1.5 g/t Au	NaCN Conc. (ppm)	1500	22% by direct cyanidation 92.5% after roasting	Ibrahim et al. (2025)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	25		
		Temperature(ºC)	Ambient		
		pH	11.6		
		Size (μm) P_{80}	300		
		Agitation (rpm)	400		
		Leaching time (h)	16		
		Pretreatment	Roasting at 650 °C for 4.5 h		
10	Floatation concentrate with 5.3 g/t Au	NaCN Conc. (ppm)	6000	81.4% by direct cyanidation 86.5% after Roasting	Malyshev et al. (2025)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	25		
		Temperature(ºC)	20		
		pH	11		
		Size (μm) P_{80}	45		
		Agitation (rpm)	NR		
		Leaching time (h)	4		
		Pretreatment	Roasting at 550–600 ∘ C		
11	Pre-oxidized gold concentrate	NaCN Conc. (ppm)	1500	48% by direct cyanidation 62% after fungal deg	Liu et al. (2016)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	20		
		Temperature(ºC)	30		
		pH	11		
		Size (μm) P_{80}	38		
		Agitation (rpm)	1050		
		Leaching time (h)	24		
		Pretreatment	Fungal Biodegradation		
12		NaCN Conc. (ppm)	10,000		

Table 2. (*cont.*)

	Double refractory gold flotation concentrate subjected to sulfide biooxidation	O_2 Conc. (ppm)	Ambient	81.1% after sulfide oxidation 94.7% after sulfide bio-oxidation + CM degradation	Amankwah et al. (2005)
		Solid Content (%)	40		
		Temperature(ºC)	Ambient		
		pH	11		
		Size (μm) P_{80}	75		
		Agitation (rpm)	NR		
		Leaching time (h)	24		
		Pretreatment	Bio-oxidation		
13	Flotation concentrate of double refractory gold ores containing sulfides and carbonaceous matter	NaCN Conc. (ppm)	10,000	41%% without pretreatment 81% after bacterial oxidation 94% after bacterial +Fungal treated	Ofori-Sarpong et al. (2013)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	45		
		Temperature (ºC)	25		
		pH	11.5		
		Size (μm) P_{80}	75		
		Agitation (rpm)	150		
		Leaching time (h)	24		
		Pretreatment	Bio-oxidation		
14	Oxide gold ore obtained from Gold Fields Damang	NaCN Conc. (ppm)	250	87.1%	Gbedemah et al. (2022)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	50		
		Temperature (ºC)	Ambient		
		pH	11.5		
		Size (μm) P_{80}	106		
		Agitation (rpm)	NR		
		Leaching time (h)	24		
15	Micro-fine refractory gold concentrate with high levels of arsenic and sulfur	NaCN Conc. (ppm)	1500	10.7% by direct cyanidation 83.37% after pretreatment	Lin et al. (2022)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	20		
		Temperature (ºC)	Ambient		
		pH	11		
		Size (μm) P_{80}	74		
		Agitation (rpm)	NR		
		Leaching time (h)	24		
		Pretreatment:	Roasting at 500 ∘C for 2h followed by roasting at 650 ∘C for 3 h		
16	Refractory gold concentrate	O_2 Conc. (ppm)	10,000	57% direct cyanidation 24–27% after Roasting	De Michelis et al. (2013)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	33		
		Temperature(ºC)	Ambient		
		pH	11.5		
		Size (micron) (P_{80})	74		
		Agitation (rpm)	240		
		Leaching time (h)	24		
		Pretreatment: Roasting	Roasting at 450-650 ∘C for 4-6 h		
17	Knelson Concentrator's Tailing dominated by silicate, sulfide, and carbonate minerals.	NaCN Conc. (ppm)	5000	30.18% without pretreatment 51.48% after Flotation 51.44% After floatation + Ultrafine grinding to 6 µm	Ardian et al. (2025)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	20		
		Temperature(ºC)	Ambient		
		pH	11		
		Size (micron) (P_{80})	75		
		Agitation (rpm)	NR		
		Leaching time (h)	48		
		Pretreatment:	Flotation and ultrafine grinding		
18		NaCN Conc. (ppm)	700		

Table 2. (*cont.*)

	Refractory gold concentrates from lower zone Salave Project located in northern Spain	O_2 Conc. (ppm) Solid Content (%) Temperature (ºC) pH Size (micron) (P_{80}) Agitation (rpm) Leaching time (h) Pretreatment:	Ambient 30 Ambient 11 60 600 30 Atmospheric Oxidation and ultrafine grinding	7.3% without pretreatment 29.1% after Ultrafine grinding only to 10 µm 86.3% After atmospheric Oxidation + Ultrafine grinding to at 30 kWh/t	Barriga (2022)
19	Pyritic gold concentrate from the Bacis Mine (Durango, Mexico)	NaCN Conc. (ppm) O_2 Conc. (ppm) Solid Content (%) Temperature (ºC) pH Size (micron) (P_{80}) Agitation (rpm) Leaching time (h) Pretreatment:	5000 Ambient 20 Ambient 11 61 350 24 Roasting @550°C and Alkaline Pressure Oxidation at 150 °C and 1MPa	32% without pretreatment 80% after Roasting @74 µm 92% After alkaline Pressure oxidation	Espinoza-Martínez et al. (2025)
20	Pyritic gold concentrate from the Bacis Mine (Durango, Mexico)	NaCN Conc. (ppm) O_2 Conc. (ppm) Solid Content (%) Temperature (ºC) pH Size (micron) (P_{80}) Agitation (rpm) Leaching time (h) Pretreatment:	1500 Ambient 25 20 10 50 750 24 ultrafine grinding to 3.7 µm	40% without pretreatment 66% after ultrafine grinding to 3.7 µm	Celep et al. (2010)
21	Flotation gold concentrate derived from a sulfide-rich gold ore	NaCN Conc. (ppm) O_2 Conc. (ppm) Solid Content (%) Temperature (ºC) pH Size (micron) (P_{80}) Agitation (rpm) Leaching time (h) Pretreatment:	3300 Ambient 25 Ambient 10 44 NR 36 Biooxidation with Thiobacillus ferrooxidans	27.17% by direct cyanidation 94.47% after Biooxidation with Thiobacillus ferrooxidans	Zhu et al. (2012)
22	Carbonaceous gold ore in Shaanxi province, China	NaCN Conc. (ppm) O_2 Conc. (ppm) Solid Content (%) Temperature (ºC) pH Size (micron) (P_{80}) Agitation (rpm) Leaching time (h) Pretreatment:	3000 Ambient 28.6 Ambient 11 74 NR 24 Roasting at 650 °C | 2.0 h | 0.6 m^3/h air	12.5% without Roasting 66% after roasting	Li et al. (2022)
23	Refractory floatation gold concentrate from Agnes Mine, South Africa dominated by pyrite and arsenopyrite	NaCN Conc. (ppm) O_2 Conc. (ppm) Solid Content (%) Temperature (ºC) pH Size (micron) (P_{80}) Agitation (rpm) Leaching time (h) Pretreatment:	13000 Ambient 40 25 10.5 - 11 75 175 24 Bio-oxidation residues using *extremophile*	Below 35% without bio-oxidation 92.4% after bio-oxidation	Ciftci and Akcil (2010)
24		NaCN Conc. (ppm)	2000		

Table 2. (*cont.*)

	Sulfidic refractory gold ore in which gold occurs mainly in pyrite and partly in copper-arsenic sulfosalts	O_2 Conc. (ppm)	Ambient	30.6% without pretreatment 43.3% after Ultrafine grinding 70.2% after Roasting at 800°C 90.7% after POX 93% after bio-oxidation	Ahn et al. (2019)
		Solid Content (%)	10		
		Temperature (ºC)	Ambient		
		pH	11		
		Size (micron) (P_{80})	75		
		Agitation (rpm)	NR		
		Leaching time (h)	24		
		Pretreatment:	Ultrafine grinding, Roasting, POX, bio-oxidation		
25	Sulfidic refractory gold ore in which gold occurs mainly in pyrite and partly in copper-arsenic sulfosalts	NaCN Conc. (ppm)	450	Below 30% without pretreatment 98.6% after Pressure oxidation	Lemos et al. (2025)
		O_2 Conc. (ppm)	9		
		Solid Content (%)	20		
		Temperature (ºC)	Ambient		
		pH	10.5		
		Size (micron) (P_{80})	75		
		Agitation (rpm)	600		
		Leaching time (h)	40		
		Pretreatment:	Pressure oxidation		
26	Sulfidic refractory gold ore in which gold occurs mainly in pyrite and partly in copper-arsenic sulfosalts	NaCN Conc. (ppm)	3000	0% Totalpreg-robbing. 98% after Roasting	Nanthakumar et al. (2007)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	14		
		Temperature (ºC)	Ambient		
		pH	10.5		
		Size (micron) (P_{80})	42		
		Agitation (rpm)	180		
		Leaching time (h)	24		
		Pretreatment:	Roasting at 750 °C		
27	Zarshuran refractory gold ore containing 3.32 ppm Au, 1.09% As, and 0.5% sulfur	NaCN Conc. (ppm)	667	79.4% without pretreatment 89.4% after pretreatment	Soltani et al. (2020)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	37		
		Temperature (ºC)	Ambient		
		pH	11.5		
		Size (micron) (P_{80})	45		
		Agitation (rpm)	500		
		Leaching time (h)	40		
		Pretreatment:	Oxidative Ammonia		
28	The sulfide ore obtained from Sardasht area in Northwestern of Iran	NaCN Conc. (ppm)	5000	54.7% without pretreatment 82% after pretreatment	Saba et al. (2011)
		O_2 Conc. (ppm)	Ambient		
		Solid Content (%)	50		
		Temperature (ºC)	25		
		pH	10.5		
		Size (micron) (P_{80})	37		
		Agitation (rpm)	1000		
		Leaching time (h)	24		
		Pretreatment:	Chemical		

NR= Not reported

D. Application of Artificial Intelligence in the Gold Cyanidation Process

Artificial intelligence (AI) methods have been applied to the gold leaching process to enhance efficiency, accuracy, and control conditions. The AI methods lie in their ability to analyze complex relationships between operational parameters, enhancing prediction accuracy from 94.46% to 98.06% for gold recovery (Xu et al., 2020). The AI methods include Artificial Neural Network (ANN), support vector machines (SVM), Bayesian networks (BN), gated recurrent units (GRU), long short-term memory (LSTM) networks, Light Gradient Boosting Machine (LightGBM), and radial basis function (RBF) networks (Dong et al., 2023; Zulu et al., 2023; Gomez-Flores et al., 2022; Dong et al., 2022). The ANN, SVM, and BN are used for pattern recognition and prediction in dynamic systems, offering potential for modeling and optimizing leaching processes (Saldaña et al., 2022). The GRU and LSTM are used to predict errors in mechanism models, providing high accuracy and generalizability in modeling leaching systems. Studies by Dong et al. (2022) and Dong et al. (2023) indicate that Gated Recurrent Units (GRUs) and Long Short-Term Memory (LSTMs) are effective for predicting errors within mechanism models, yielding high-accuracy and generalizable results for leaching systems. RBF networks are applied for intelligent control of the non-linear leaching process, offering stability and adaptability in control algorithms

(Dong et al., 2022). Light Gradient Boosting Machine (LightGBM) is used to predict gold leaching and compare results with fast computation and high accuracy (Xu et al., 2020).

Despite these advancements, the intricate nature of leaching processes presents challenges, including potential prediction errors from model parameter mismatches and issues with system compatibility and scalability (Dong et al., 2022). In response to these limitations, Niu et al. (2022) proposed a solution utilizing an Integrated Dynamic Model Predictive Control (IDE-MPC) integrated with an improved Particle Swarm Optimization (PSO) algorithm. This method seeks to address the intractability and improve the anti-disturbance performance of the leaching process's economic optimization.

E. *Application of Neural Networks*

The ANNs have been used to predict gold cyanidation performance by learning complex nonlinear relationships between process variables and gold recovery, as shown in Table 3. The topology of ANNs typically includes an input layer, one or more hidden layers, and an output layer (Montesinos López et al., 2022). In gold cyanidation, the process input variables include Cyanide concentration, pH, solid percentage, particle size, temperature, and leaching time, while the output is the gold recovery (Khoshjavan et al., 2011). Hidden layers serve as the essential processing units located between the input and output layers, allowing the network to learn complex and nonlinear relationships among input data variables (Mathew et al., 2020). The hidden layers consist of small neurons that transfer data from one layer to another (Karsoliya, 2012).

The number of hidden layers and neurons depends on the complexity of the process being modeled. Hornik, et al (1989) established that with a non-linear activation function, a neural network with one hidden layer and enough neurons can approximate any continuous function on a compact set to any degree of accuracy (Lu et al., 2017; Mienye & Swart, 2024). Deep neural network architectures with multiple hidden layers are needed to achieve more complex data representations. However, training them creates a strong demand for computing power and storage (Bouzar-Benlabiod et al., 2021). The prediction accuracy of the neural network structure increases with the number of hidden layers; however, computational time increases with the number of hidden layers (Sharkawy, 2024).

Khoshjavan et al. (2011) utilized an artificial neural network to model gold dissolution in the cyanidation process based on 85 datasets. Their model consisted of 6 input variables and one output. They observed that four hidden layers with an architecture of 20-15-10-5 neurons were optimal. The square correlation coefficients (R^2) obtained for training, testing, and validation were greater than 0.99, indicating an excellent model fit. Azizi et al. (2012) applied a back-propagation neural network (BPNN) to estimate gold recovery in the cyanide leaching process. The network architecture comprised a single hidden layer with seven neurons, seven neurons in the input layer, and one output neuron. The R^2 values were 0.952 and 0.884 for training and testing, respectively. The relatively lower performance in terms of R^2 implies that the network architecture, specifically the number of hidden layers or neurons within the hidden layer, may be insufficient to fully capture the complex, nonlinear relationships in the leaching process.

A complex network with fewer hidden layers might not be trained effectively, whereas increasing the number of hidden layers beyond the optimal provides less gain in accuracy relative to the increase in time complexity (Uzair & Jamil, 2020). Multiple hidden layers in the neural network may cause the network to fall into bad local minima during training (Liu et al., 2007). For a complex problem, using too few neurons can lead to underfitting. Conversely, adding an unnecessarily large number of neurons may cause overfitting (Karsoliya, 2012). Generally, the drive for higher accuracy has led to increasingly deep and wide neural network models with multiple hidden layers and neurons; however, this has been accompanied by a quadratic rise in computational complexity. The optimal architecture remains a moving target, balancing the theoretical capacity of the model with the practical constraints of data, time, and computational resources.

F. *Environmental Effects of Cyanide and Global Management Code Thresholds*

Cyanide is chemically unstable in natural settings and breaks down through processes such as evaporation, exposure to light, oxidation, and the action of microorganisms. Under suitable conditions, the half-lives of cyanide in surface waters can vary from a few hours to several days, which results in less long-term stability compared to metals like mercury or arsenic. The quick breakdown of cyanide is frequently mentioned by the industry as proof that the risks associated with cyanide can be controlled. However, this viewpoint overlooks the long-term sub-lethal effects, the harmfulness of metal-cyanide compounds, and the dangers to closed or low-oxygen environments (Johnson, 2015). Weak-acid dissociable (WAD) cyanide complexes, such as Cu–CN and Zn–CN, are important because they can break down in environmental conditions and release free cyanide. Recent research indicates that focusing solely on total cyanide is inadequate and that WAD cyanide is a more relevant measure for environmental considerations (Akcil, 2010; Tran et al., 2019).

Free cyanide (CN^- and HCN) is highly toxic to aquatic life, as it disrupts cellular respiration by binding to cytochrome oxidise. The levels of acute toxicity that can harm fish are usually below 50 μg/L, which means accidental spills could have severe consequences (Jaszczak et al., 2017). Past incidents of tailings dam failures and pipeline breaks have demonstrated that brief exposure to cyanide can lead to significant fish deaths and disruption of ecosystems, even if long-term contamination is minimal (Tran et al., 2019).

The International Cyanide Management Code (ICMC) aims to mitigate risks associated with cyanide by implementing best practices that focus on minimizing exposure and ensuring safe handling throughout its entire lifecycle, including production, transportation, use, and disposal. The ICMC states that a typical regulatory limit for cyanide in wastewater from mineral processing activities should be below 50 ppm. This standard addresses issues related to both WAD cyanide and total cyanide, although regulations may differ between regions (Akcil, 2010). For example, Nevada usually measures cyanide levels using WAD cyanide, whereas New Mexico evaluates total cyanide. The effective execution of the ICMC seeks to guarantee that cyanide usage does not pose risks to human health or the environment, highlighting the necessity of closely following these limits. As awareness of the dangers of cyanide grows worldwide, it is essential to continue promoting responsible practices outlined in this Code to reduce the long-term environmental impacts related to cyanide used in mining activities (Johnson, 2015; Tran et al., 2019).

Table 3. Gold leaching prediction with neural network

S/N	AI method	Training Algorithm	Hidden Layers	Neurons per Layer	Model Performance			Sources
					Metrics	Train	Testing	
1	Radial Basis Function ANN	Simulated Annealing optimization algorithm	1	5- 550- 2	R^2	-	-	Jun et al. (2019)
					RMSE	0.0003	0.0265	
					MAE	0.0001	0.0189	
					MAPE	1.31×10^{-6}	0.0002	
2	Long Short-Term Memory - NN.	Adaptive Moment optimizer	3	50-100- 1	Mean	0.00033		Dong et al. (2023)
					Variance	5.81×10^{-6}		
3	Adaptive neuro-fuzzy inference system (ANFIS) prediction of DO	Generalized Bell Function	3	-	R^2	1	1	Behnamfard & Rivaz (2022)
					RMSE	1.66×10^{-5}	1.5×10^{-5}	
					MAPE	0.04	0.039	
4	Backpropagation Neural Network (BPNN)	Levenberg-Marquardt Algorithm (LMA)	4	20 - 15 - 10 – 5	R^2	0.9991	0.9964	Khoshjavan et al. (2011)
5	Back Propagation Artificial Neural Network (BPANN)	-	-	-	R^2	0.9803	0.8213	Azizi et al. (2016)
					RMSE	1.08	1.22	

G. *Performance Analysis of Gold Leaching Input-Variables*

Two performance analyses were conducted: the first used 34 datasets with six input variables (excluding oxygen concentration and temperature, as these data were not reported in the experiments) and one output variable related to direct cyanidation. The second employed 28 datasets with seven input variables (excluding oxygen concentration, which was not reported) and one output variable based on different pretreatment methods followed by cyanidation. From the datasets assessed, the minimum, maximum, mean, standard deviation, and coefficient of variation values were computed, and they are shown in Tables 4 and 5. In a gold leaching context where the coefficient of variation is very high (e.g., for NaCN concentration, 109% without and 94% with pretreatment methods), this indicates large experimental variability in how NaCN behaves in the heterogeneous ore mineralogy and operational conditions such as pH, solution chemistry stability, and reaction kinetics.

The dataset/samples were further used to calculate grey relational degrees for both direct cyanidation and pretreatment methods followed by cyanidation, across different gold ore samples. The relational degree has the highest influence on gold recovery when the coefficient is closer to 1, or vice versa (Mahmoudi, et al., 2020). Fig. 2 shows the relational degrees for direct cyanidation of gold ore samples, with a mean approaching 0.59 and a coefficient of variation of 9.0%. The Grey relational degrees order started with slurry density, pH level, agitation, particle size, leaching time, and sodium cyanide concentration. Fig. 3 shows the Grey relational degrees; the mean approached 0.54, and the coefficient of variation was10.8%. The Grey relational degrees ranked pH, slurry density, agitation, leaching time, temperature, sodium cyanide concentration, and particle size. The low coefficient of variation values indicated consistent, narrow distributions of the variables (Arora, 2012).

Table 4. Statistical summary of the input variables and gold recovery during direct leaching of gold ore samples

	NaCN, ppm	Slurry density, %	pH	Particle size, μm	Agitation, rpm	Leaching time, h	Gold recovery, %
Minimum	210	10	10	20	40	12	8
Maximum	10000	60	12	150	1000	90	97
Mean	2164	35	11	70	431	32	74
Standard deviation	2361	12	0	28	262	17	25
CoV, %	109	33	5	39	61	53	33

Table 5. Statistical summary of the input variables and gold recovery based on the different pretreatment methods followed by cyanidation of different gold ore samples

	NaCN, ppm	Slurry density, %	Temperature, °C	pH	Particle size, μm	Agitation, rpm	Leaching time, h	Gold recovery, %
Minimum	450	10	20	10	29.6	150	4	27
Maximum	13000	50	50	12	300	1050	72	99
Mean	3570	26	27	11	70	494	30	84
Standard deviation	3365	10	9	0	48	271	14	17
CoV, %	94	37	32	4	69	55	46	20

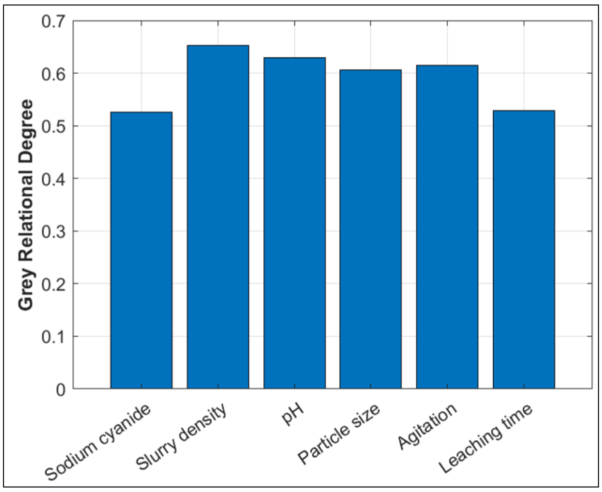

Fig. 2. Strength effect of input variables with different relational degrees without pretreatment methods

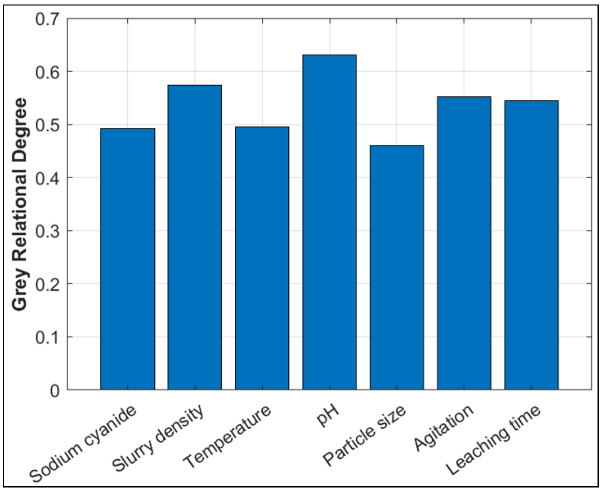

Fig. 3. Strength effect of input variables with different relational degrees for different pretreatment methods of gold ore samples

IV. CONCLUSIONS

This study evaluated the common extraction of gold from ore using cyanidation. The literature-revieweddata related to the cyanidation process for gold, including leaching lixiviants with different concentrations, were collected. Apart from NaCN concentration, the other common performance variables presented in this study include slurry pH, particle size, oxygen concentration, residence time, temperature, slurry density, and agitation. Different types of gold ores were treated with different leaching parameter levels to achieve the promised gold recovery. For ores treated by direct cyanidation, the input variables had a coefficient of variation below 50%, including pH, slurry density, particle size, and gold recovery; other variables, including leaching time, agitation, and NaCN concentration, had coefficients of variation above50%. For ores pre-treated with various methods before cyanidation, only the pH, gold recovery, temperature, slurry density, and leaching time variables had the coefficient of variation below 50%. However, in this study, sodium cyanide concentration had the highest coefficient of variation with or without pretreatment methods for different gold ore samples. The high values of the coefficient of variation in this study indicated that there are high distribution effects among input performance variables during the gold leaching process. Generally, overall grey relational analysis indicated an average relational degree of 0.57 and a coefficient of variation of 9.9% for both with and without pretreatment methods in different gold grade samples studied.

Many AI methods are applied in mineral extraction. In this study, ANNs with different algorithms and statistical modifications were reviewed to predict gold recovery with low error, suggesting that they are a potential tool for future use. Ongoing research should focus on characterizing minerals based on dosage thresholds and integrating the ANN method with other statistical methods to improve gold recovery prediction. In summary, achieving optimal gold recovery needs a careful balance and integration of input performance variables for efficient, economical, and environmentally sustainable gold leaching operations.

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