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Extraction of Gold Through Leaching Using NaOCN Leaching Reagent from the Tailings Leach Process of Refractory Gold Ore

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Abstract

Gold is increasingly extracted from low-grade and complex ores, commonly referred to as refractory gold ores, as high-grade reserves become progressively depleted. These ores are difficult to process through conventional methods, as direct cyanidation consumes a substantial amount of cyanide but typically achieves gold extraction rates of only 50–80%. The limitation is especially significant for small- and medium-scale mining operations that are not aware of developments in refractory gold ore processing. Several mines in Indonesia continue to apply direct cyanidation, leaving substantial quantities of gold in the resulting tailings. Re-leaching these tailings offers an opportunity to recover residual gold and reduce the need for new mining. Therefore, this study aimed to re-leach the tailings from a direct cyanidation process of refractory gold ore using NaCN for 33 hours at ambient temperature and pH 12. The extraction efficiency was compared with alternative reagents based on NaOCN and a mixture of NaOCN + NaCN. To evaluate the efficiency of gold extraction through leaching, analyses were performed using Atomic Absorption Spectrophotometry (AAS). The results showed that the best experiments extracted up to 71% gold using 0.1% NaCN + 0.5% NaOCN reagent. This mixture can be used as a reference in the search and development of other leaching reagents that are cheaper and environmentally friendly.

Keywords: Extraction; gold-refractories; leaching reagent; re-processing; tailing

1. Introduction

Indonesia is among the largest gold-producing countries in the world [1], with several small-scale mining and processing operations [1],[2]. More than 2,600 artisanal and small-scale gold mining locations were recorded as of 2021, including approximately two million people [3]. There is a depletion in high-grade reserves due to substantial production, which leads to mining of low-grade ore with complex properties. This low-grade ore, often called refractory gold, has significant challenges in terms of processing [4]-[6]. The separation of minerals inherent in refractory gold is very difficult and complex, with a lower recovery [7]-[9].

Gold is commonly extracted from ore through cyanidation, an effective recovery method [10]-[13] that can be applied following mercury-based amalgamation [14]-[16]. Direct cyanidation is ineffective for low-grade ores because a substantial proportion of the gold remains encapsulated within other minerals [7]. The consumption of cyanide during this process is also very high to obtain 50% – 80% recovery [17].

This study was conducted to recover fairly high-grade gold contained in the tailings from the direct cyanidation process of refractory ore [18]. The

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reprocess uses alternative leaching reagents that are more environmentally friendly because the direct application of cyanide is very harmful to the environment and also expensive. Sodium cyanate (NaOCN) leaching reagent was adopted as an alternative to reduce the level of toxicity in the waste produced. This reagent has been studied and recently developed as an alternative to cyanide (NaCN) [10],[19]-[23]. Compared with other non-cyanide alternatives such as thiosulfate and thiourea, NaOCN offers a more favourable balance of stability and cost. Thiosulfate leaching typically requires a copper–ammonia catalyst system and forms a gold complex that is prone to decomposition [9]. Thiourea is chemically unstable, oxidises rapidly, and requires high reagent consumption despite known toxicity concerns [24]. In contrast, NaOCN can be synthesised from relatively inexpensive precursors, namely urea and sodium carbonate, and offers greater stability under alkaline conditions. These properties, coupled with comparatively lower environmental and safety risks, make it a promising reagent for tailings re-leaching [24].

According to the patented technology [25], NaOCN can operate under moderately alkaline conditions (pH 9–12) and at ambient temperature, which makes it more readily adaptable to refractory tailings without the need for aggressive pH adjustment. Theoretically, NaOCN possess significantly lower toxicity than free CN^-. It can be developed as a relatively more environmentally benign leaching agent with low reagent consumption, thereby reducing the burden of subsequent tailings treatment [24].

The primary purpose of this study is to systematically assess the effectiveness and selectivity of NaOCN as a non-cyanide alternative reagent for the recovery of residual gold from tailings produced during the leaching of refractory gold ores. The study provides new scientific evidence and experimental data on the use of NaOCN as a gold lixiviant, an approach that remains underexplored in the open literature. It advances the understanding of leaching mechanisms and gold–cyanate complex formation in previously leached refractory tailings. Technologically, the results provide a basis for developing tailings retreatment methods using reagents that are more stable and pH compatible than other non-cyanide alternatives, such as thiosulfate or thiourea. Previous patented NaOCN-based gold-leaching technologies [25],[26] target fresh ores or concentrates, whereas this study investigates its application to previously cyanidated refractory gold tailings.

2. Research Methods

The material used was tailings from the cyanidation-carbon-in-leach process of refractory gold ore obtained from a medium-scale mine in Indonesia. The leaching reagents in this study were NaCN and NaOCN. Approximately 100 kg of wet tailings were collected and oven-dried at 105 °C for 2 hours to remove moisture prior to grinding and sieving. The dried product was then refined with a grinding machine to obtain a P_{80} -140+200 mesh of size then sampling was conducted for the initial characterisation of the experiment.

The materials and equipment comprised refractory gold tailings, analytical-grade NaCN, and NaOCN synthesised in-house from urea and sodium carbonate. Equipment included an oven for drying at 105 °C, a grinding machine, sieves for particle size reduction to P80 −140 +200 mesh, a mechanical agitator for leaching, and an atomic absorption spectrophotometer (AAS; Shimadzu AA-6300, Shimadzu Corporation, Kyoto, Japan) for elemental analysis of the leach solutions.

The leaching process was conducted for 33 hours at ambient temperature and pH 12, while stirring was performed using an agitator at a speed of 200 rpm, with a solid-to-liquid (S/L) ratio of 1:3. Each experiment was performed in duplicate (two replicates), using covered borosilicate glass beakers as the leaching vessel. After the leaching process, the solution and precipitate were then separated. A total of 150 mL of solution was taken and characterised using Atomic Absorption Spectroscopy (AAS; Shimadzu AA-6300, Shimadzu Corporation, Kyoto, Japan). The reagent used in this experiment was NaOCN, made from urea and sodium carbonate. Various variations of NaOCN concentrations were tested to obtain optimal leachate alternatives. The percent gold extraction from each experiment was calculated from the difference between the grade in the feed (initial tailings) and the leach residue, relative to the feed grade (Equation 1).

$$\% \text{ Extraction} = \frac{\text{feed grade} - \text{residue grade}}{\text{feed grade}} \; x \; 100\% \quad \textbf{.... (Equation 1)}$$

The results were then compared with those obtained using only NaCN reagent and a mixture of NaCN and NaOCN. NaCN at 0.3% was selected as the single-reagent baseline because it falls within the

commonly reported effective range for gold cyanidation of low- to medium-grade ore (0.1%–0.5%), representing conventional industry practice for comparison. NaOCN was tested at an upper practical concentration of 0.6%, the maximum achievable using the in-house synthesis method based on urea and sodium carbonate, to assess its maximum gold extraction potential.

3. Results and Discussion

3.1. Characterisation of sample material

Initial sample characterisation is an important part of the experiment. It enabled the comparison of the experimental results before and after the process. The results of the initial characterisation of the sample showed a relatively high gold content in the tailings from the direct cyanidation process of refractory gold ore, which was more than 10 mg/kg. The relatively high content underscored the need for reprocessing to recover the trapped gold. After experiments using several leaching reagents, the sample was then re-characterised to obtain a comparison and calculation of the % extraction of valuable minerals. The results of mineral characterisation after leaching reprocessing are shown in Table 1.

3.2. Re-leaching process

Reprocessing of refractory gold tailings from direct cyanidation was conducted using 0.3% NaCN as the baseline, mixtures of 0.1% NaCN with 0.4% or 0.5% NaOCN, and 0.6% NaOCN alone [19]-[21].

Chemically, NaCN is highly effective at dissolving gold when free CN^- ions are available to form Au–CN complexes [10]. Based on the reaction $4Au + 8NaOCN + O_2 + 2H_2O \rightarrow 4Na[Au(OCN)_2] + 4NaOH$ [25], gold dissolution by NaOCN was proposed to follow an oxidative complexation mechanism analogous to conventional cyanidation. Metallic gold (Au^0) was oxidised to Au^+ at the mineral surface, after which the Au^+ ion is then stabilised by two OCN^- ligands to form the soluble dicyanate-aurate complex, $Au(OCN)_2^-$ [23],[24]. Dissolved oxygen (O_2) acts as the electron acceptor for Au^0 oxidation and is therefore essential for the dissolution. Insufficient O_2 supply limits oxidation and inhibits dissolution, consistent with the negligible gold extraction observed when NaOCN was used alone [24]. In contrast, NaOCN cannot dissolve gold without the formation of a soluble Au–ligand complex. This explains why extraction efficiency approached 0% in experimental tests. Furthermore, the chemical structure of NaOCN and its derivatives differed, resulting in a weaker affinity for gold compared to CN^-, which forms the $Au(CN)_2^-$ complex [24].

The combination of NaOCN and NaCN can enhance gold extraction by a mechanism that protects CN^- from parasitic reactions and metal competition within the complex tailings matrix [24]. The variation in reagent type and concentration shown in Table 1 had a much more pronounced effect on Au, Ag, and Cu levels than on Pb and Zn. Au concentration in the leach solution increased slightly from 7.10 mg/kg at 0.3% NaCN alone to 7.26 and 7.60 mg/kg with the NaCN–NaOCN mixtures, but decreased to 0 mg/kg at 0.6% NaOCN alone. This trend is consistent with the gold-extraction results presented below, signifying that NaOCN alone was ineffective in dissolving gold. The Ag concentration in the leach solution increased from 12.31 mg/kg with 0.3% NaCN to 16.97 and 16.98 mg/kg with the NaCN + NaOCN mixtures (an increase of about 38%), before falling sharply to 1.23 mg/kg at 0.6% NaOCN. Cu showed the opposite trend, decreasing progressively from 5.56 mg/kg (NaCN 0.3%) to 3.81 and 3.36 mg/kg as NaOCN content increased, but dropped to 0.25 mg/kg with NaOCN. In contrast, Pb and Zn concentrations remained low and comparatively stable across all reagent combinations (Pb: 0.03–0.21 mg/kg; Zn: 0.41–1.41 mg/kg). The results suggest that reagent type and concentration had almost no discernible effect on the dissolution of these two elements under the conditions tested. In contrast, Au, Ag, and Cu minerals in the tailings are more chemically reactive toward the NaCN–NaOCN system, possibly due to the formation of more stable cyanide/cyanate complexes. The Pb- and Zn-bearing phases present are comparatively refractory to these lixiviants. The per cent extraction of each mineral is shown in Figure 1.

According to Figure 1, the NaCN leaching reagent can recover gold by 66%. The use of a mixture of NaCN and NaOCN leachate is known to increase the recovery. This result suggests that the partial substitution with NaOCN may reduce reagent costs while maintaining recovery efficiency. At higher concentrations, the reagent can increase the % of gold extraction, namely 67.44% with 0.1% NaCN + 0.4% NaOCN and 70.61% with 0.1% NaCN + 0.5% NaOCN. The percentage of extraction using this mixed reagent was higher than that of a single application of NaCN. In contrast to the experiment above, the single use of NaOCN leaching reagent did

not affect extracting gold. Based on the results of this study, NaOCN can supplement NaCN in gold extraction, potentially reducing associated leaching costs.

Table 1. The chemical composition of leaching products based on the type and concentration of leaching reagents

Leaching Reagents	Concentration (mg/kg)				
	Au	Ag	Cu	Pb	Zn
NaCN 0.3%	7.10	12.31	5.56	0.21	1.41
NaCN 0.1% + NaOCN 0.4%	7.26	16.97	3.81	0.19	0.42
NaCN 0.1% + NaOCN 0.5%	7.6	16.98	3.36	0.09	0.41
NaOCN 0.6%	0	1.23	0.25	0.03	0.73

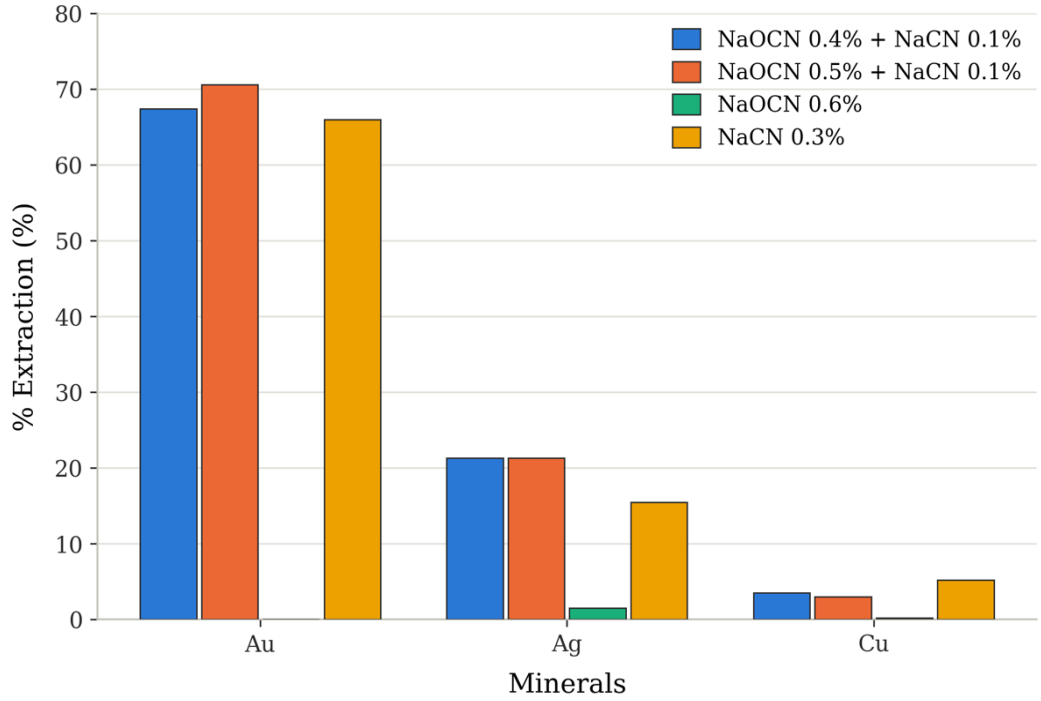


Figure 1. Percent extraction of each mineral with variation concentration of leaching reagents

Previous studies have investigated cyanate-based reagents as alternatives to NaCN for gold extraction, because of the potential to reduce environmental impacts while maintaining effective metal recovery [27]. Potassium cyanate (KOCN) and ammonium cyanate (NH_4OCN) have also been explored, individually or in combination with NaOCN, for cyanide-free gold and silver leaching through the formation of soluble $[Au(OCN)_4]^-$ and $[Ag(OCN)_2]^-$ complexes, respectively, analogous to the NaOCN system used in this study [26]. Beyond cyanate-based systems, alternatives such as deep eutectic solvents have also been shown to recover gold from historical tailings more effectively than conventional cyanidation. This further supports the viability of non-cyanide tailings reprocessing routes [28].

4. Conclusion

In conclusion, efforts to develop alternative gold-leaching reagents that were less toxic, more environmentally friendly, and relatively inexpensive were ongoing, particularly for refractory gold ores. The results of this study suggested that NaOCN could supplement NaCN in gold extraction. The optimal combination of 0.1% NaCN and 0.5% NaOCN achieved an extraction efficiency of 70.61% (approximately 71%). This observation underscored the potential application of NaOCN-based reagents in gold tailings processing. However, several limitations warranted further investigation. The environmental benefits of NaOCN had not been verified through comprehensive assessments, such as life cycle assessment (LCA) or residual toxicity analysis. Furthermore, the tailings were obtained from a

single mine, which limited the applicability of the results to tailings with different compositions. The formation and stability of the proposed $Na[Au(OCN)_2]$ complex, as well as its implications for long-term gold recovery, also required further investigation through extended or repeated leaching experiments. Further optimisation of reagent concentrations, leaching time, aeration, and pH was necessary to improve gold recovery while minimising costs. Replicate experiments to quantify measurement uncertainty, pilot-scale trials, and comprehensive environmental assessments were also needed to validate the results and evaluate the feasibility of scaling up the process for industrial application.

AI Usage Statements

During the preparation of this manuscript, the authors used Claude (Anthropic) to improve the language, grammar and sentence structure of the manuscript and to assist in searching for relevant literature. All AI-generated outputs were critically reviewed and thoroughly edited by the authors to ensure factual accuracy, clarity of expression, and compliance with academic standards. The authors take full responsibility for the integrity and content of this manuscript.

CRediT Authorship Statement

Sitti Ratmi Nurhawaisyah: Conceptualization, Methodology, Project administration, Funding acquisition, and Writing – Original draft. **Nurliah Jafar:** Investigation, Resources, and Data curation. **Mubdiana Arifin:** Investigation, Visualization, and Writing – Review & editing. **Andi Artiningsih:** Methodology, Investigation, and Validation. **La Ifa:** Formal analysis, Validation, and Writing – Review & editing. **Muhammad Ramli:** Data curation, Formal analysis, and Visualization. **Suriyanto Bakri:** Supervision, Validation, and Writing – Review & editing.

Declaration of competing interests

The authors declare that there are no conflicts of interest.

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