Sensitivity analysis and pre-feasibility of reprocessing Au from a tailings dam in the Iron Quadrangle - The case of the Cocoruto Dam, Nova Lima, Minas Gerais

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Abstract

As historical waste has accumulated in dams, the interest in studying the feasibility of reusing mining tailings has grown, offering both environmental and economic advantages. However, given the unique characteristics of each site, conducting site-specific assessments is crucial. Building on a detailed evaluation of the Cocoruto Dam in Nova Lima, Minas Gerais, this study presents a technical feasibility and financial viability analysis of three potential reprocessing scenarios. The primary objective was to assess the viability and potential benefits of reusing Au tailings. The proposed methods involve grinding, calcination and leaching, with designs adaptable for existing metallurgical plants. Considering the economic potential of Au in these inactive mine tailings (with an average grade of 0.95 mg/kg and a total resource of 3,350.55 tonnes), multiple factors were analyzed to determine the feasibility of Au production from this source. Analyzed variables included: cut-off grades and tonnage for each scenario; net present value (NPV) calculated with an 8% annual discount rate; a general slope angle of 20 degrees; three possible final pit configurations; different annual production rates (400,000 t, 800,000 t and 1,000,000 t), and various Au ounce values ($1300/oz, $1500/oz, and $1700/oz). From a financial perspective, for all ounce values and an annual production of 400 tonnes, all scenarios prove profitable. However, other risks and parameters should be further evaluated.

Keywords: circular economy; mining tailings; Au recovery; Benefit Function; feasibility.

1. Introduction

Historically, tailings have often been stored in tailings dams or impoundments, which can pose significant environmental risks, such as water pollution, habitat destruction, and the potential for dam failures (Coffey *et al*., 2021; Araya *et al*., 2021; Lemos *et al*., 2023b), as demonstrated by recent tragedies in Brumadinho and Mariana, Brazil (Lemos *et al*., 2021). However, because these tailings often contain significant amounts of critical elements, both in terms of supply and toxicity, there has been a growing interest in finding ways to reuse or reprocess mining tailings to minimize their environmental impact while also extracting additional value from them (Malli *et al*., 2015; Lemos *et al*., 2021).

The feasibility of tailings reuse can significantly vary between mining operations due to site-specific considerations. Since tailings often comprise a mixture of fine particles, water, and chemicals used in the extraction process, reprocessing them can be a complex task. Therefore, conducting a site-specific assessment is essential to determine the viability and suitability of tailings reuse.

In conducting such a multidisciplinary study, it is crucial to consider several key factors for a comprehensive evaluation. These factors include ore type, processing methods, tailings characterization, environmental assessment, identification of suitable reprocessing technologies, compliance with local regulations, and economic analysis. Additionally, evaluating market conditions, demand, and conducting risk assessments are essential steps in defining a financial model for reprocessing these structures and estimating their potential profitability (Hindle, 2011; Hitch & Dipple, 2012; Pang *et al*., 2012; Rendu, 2014; Suppes & Heuss-Aßbichler, 2021).

Various approaches have been explored thus far (Tayebi-Khorai *et al*., 2019; Lemos *et al*., 2021; Araya *et al*., 2021; Lemos *et al*., 2023a): (i) reclamation and rehabilitation, a common practice aimed at reclaiming land disturbed by mining activities, which can involve using tailings as backfill material for underground mine workings or for reshaping and recontouring the landscape; (ii) tailings reprocessing, which leverages technological advancements to extract additional valuable minerals from tailings, employing techniques such as flotation, leaching, and gravity separation to recover metals or minerals that may not have been effectively extracted during the initial mining process; (iii) utilizing certain types of tailings as construction materials, such as aggregates for concrete, asphalt, or bricks (e.g., tailings with a high silica content can be used in cement production); and (iv) employing specific types of tailings as cover material for landfills, providing a protective layer for waste disposal sites. Several historical studies have investigated the feasibility of reusing mining tailings, with varying outcomes, depending on various local factors (e.g. Zhang *et al*., 2010; Araya *et al*., 2021).

The reuse of mining tailings aligns with the principles of the circular economy, promoting resource efficiency, waste reduction, and contributing to a more sustainable approach to mining by maximizing the utilization of Critical Raw Materials (CRMs) and minimizing environmental impact (European Commission, 2020; Lemos *et al*., 2023a). Furthermore, it offers broader sustainability benefits, including reduced reliance on virgin resources, extended mine life, and a lower carbon footprint. However, while reusing mining tailings can yield environmental and economic benefits, it is essential to carefully assess the specific characteristics of the tailings and evaluate the potential risks associated with their reuse. Factors such as hazardous substances, stability considerations, and long-term environmental impact should be thoroughly assessed before implementing any reuse strategy (Tayebi-Khorami *et al*., 2019).

For this study, samples from the gold (Au) tailings dam in Nova Lima, Minas Gerais, underwent bench-scale metallurgical testing to quantify the overall Au recovery. Subsequently, a technical feasibility and financial modeling analysis was conducted for the entire process, considering three scenarios for potential reuse and the accumulated tonnage available in the tailings storage facility (TSF). This comprehensive feasibility study is essential for determining the viability and potential benefits of reusing the Au tailings.

2. Study area

The studied tailings structure is in the northern part of the Iron Quadrangle (IQ), which is Brazil's primary mineral province. These tailings originate from Au mines hosted in the Rio das Velhas metallogenic Greenstone Belt, the country's most important critical Au district (Lobato *et al*., 2001). The TSF under investigation is Cocoruto (CO) in Nova Lima (Figure 1), Minas Gerais, Brazil. Nova Lima has a rich history of Au mining and played a significant role in the country's Au rush during the colonial period.

The Nova Lima dams and tailings deposits are closely linked to the Queiroz metallurgical plant, which has been processing sulfide Au ores for over thirty years. The materials processed at the plant are divided into two circuits: one currently in operation, which includes a calcination step, and a second, no longer active, known as the Raposos circuit (Lemos *et al*., 2023b). This study focuses on the Raposos circuit, which primarily treated non-refractory sulfide ore from the Raposos mines, consisting mainly of pyrite, pyrrhotite, and subordinate arsenopyrite. However, this circuit, which supplied the CO dam, was deactivated in 1998 following the closure of the underground mine. The Raposos circuit achieved a 90% Au recovery rate and involved various stages, including grinding, gravity concentration, conventional leaching, carbon-in-leach (CIL), elution, and electrowinning (Moura, 2005; Lemos *et al*., 2020).

As reported by Lemos *et al*. (2023a), the CO dam contains approximately 3,350 million tons of tailings, with an estimated Au content of 150 million ounces. The CO dam, part of the old circuit, primarily consists of quartz, carbonates, iron oxides, and phyllosilicates like muscovite and chlorite (Lemos *et al*., 2020). In terms of chemical composition, it contains higher levels of iron (Fe) compared to calcium (Ca), magnesium (Mg), aluminum (Al), manganese (Mn), potassium (K), and sodium (Na). Furthermore, studies like Lemos *et al.* (2023a) and Lemos *et al.* (2023b) have reported achieved Au recovery rates ranging from 70% to 59%, which are crucial figures for conducting financial assessments.

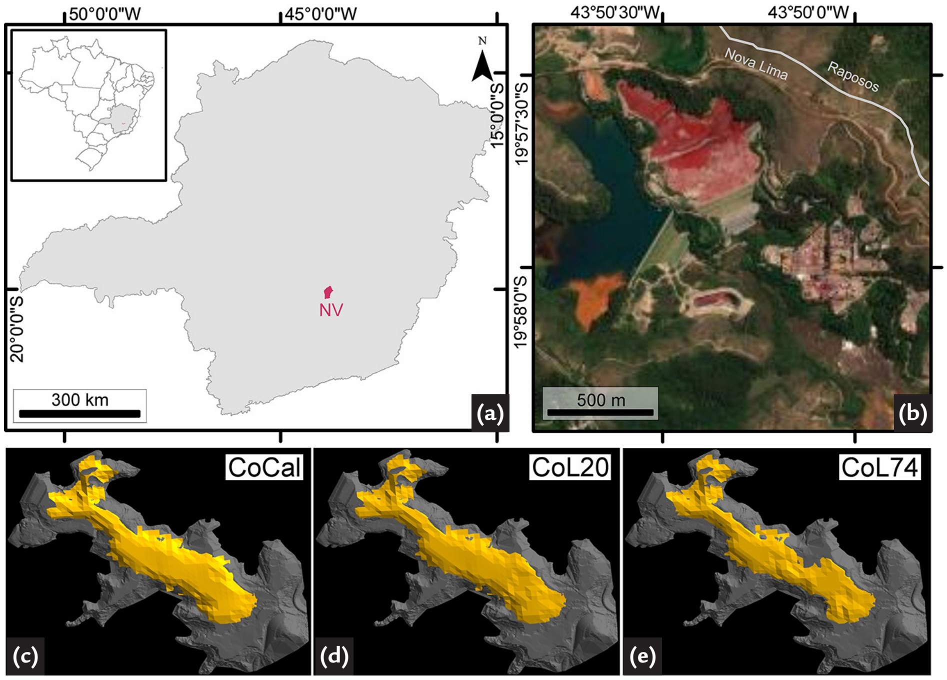

Figure 1 - Co dam setting. (a) Location of Nova Lima city in Minas Gerais state. (b) Co dam, near Queiroz plant. (c) Pit designed for CoCal scenario. (d) Pit designed for CoL20 scenario. (e) Pit designed for CoL74 scenario.

3. Materials and methods

Samples were collected by drilling at a depth of 15 m within a 50x50m survey mesh. During this phase, a total of 291 samples were collected, each representing a 1-meter interval. These individual samples underwent chemical analysis. Subsequently, they were combined to create composite samples, which represent the composition of the CO tailings structure for Au recovery and reuse testing. Each composite sample was further split and subjected to metallurgical testing in three distinct scenarios. These samples were also utilized to construct a grade-tonnage model, which serves as input for the sensitivity analysis (Lemos *et al.*, 2023a). Building up prior results, the final step involved applying financial viability techniques for cost-benefit studies. This step assesses the investment's attractiveness and facilitates informed decision-making.

3.1 Metallurgical testwork

Laboratory-scale experiments were conducted to evaluate the potential for Au recovery, considering the unique characteristics of each tailings structure (Lemos *et al.*, 2022; Lemos *et al.*, 2023a). Three distinct setups were employed, all designed to be adaptable and applicable within existing metallurgical plants should a viable and efficient scenario emerge.

In the first scenario (CoL74), samples underwent griding to achieve a particle size of 74 µm, with 80% of the particles falling within this range, determined through a liberation-by-size analysis for sulfides and Au particles. The calcination step was omitted, and the samples were directly subjected to leaching. Bottle roll tests were performed using a leaching solution containing 2000 mg/kg of cyanide (NaCN) and 4000 mg/kg of lime (CaO), with a solid-to-liquid ratio of 50 (Figure 1(c)).

In the second scenario (CoL20), particle size was reduced to 20 µm, maintaining the previously described leaching setup (Figure 1(b)).

The third setup (CoCal) involved grinding the material to a particle size of 74 µm using ball mills, followed by calcination in a muffle at 700°C. For leaching, the calcinated material was placed in bottles containing a solution with 40% solids, composed of 2000 mg/kg of NaCN and 6000 mg/kg of CaO. This stage took over 24 hours, divided into two stages with a pre-airing period of 2 hours (Figure (1a)).

3.2 Financial analysis

Sensitivity analysis is a decision-making process method commonly employed in a financial-oriented technical study to assess the feasibility or potential success of a project, whether it involves investments, business organization, product launches, or anticipation of success in a new market (Tomaz, 2013). By developing increasingly complex benefit functions that consider characteristics of the TSF, it becomes possible to obtain more precise quantities of tailings that can be effectively reprocessed and utilized.

This step involved the following stages: (i) Definition of input parameters for the *in-situ* CO tailings based on Lemos *et al.* (2023a), utilizing geological resource estimation; and (ii) Incorporation of metallurgical variables as one of the premises in the benefit function

(Benefit Function = Revenue – Cost; Peroni *et al.*, 2012) for tailings extraction, along with other relevant variables. Thus, three scenarios were considered, each related to the metallurgical tests.

Net Present Value (NPV) calculation is a commonly used financial evaluation method in the mining industry to assess the feasibility and profitability of mining projects (Araya *et al.*, 2020). The Discounted Cash Flow (DCF) valuation is a financial model used to assess the worthiness of an investment based on projected future cash flows. It calculates the value of a company by considering its ability to generate cash flows for investors in the future (Fontes *et al.*, 2020). The output of the project analysis consists of a series of pits, each with its potential for mining under specific economic conditions (Peroni *et al.*, 2012). These pits are optimized for each scenario using the Lerchs-Grossmann algorithm (Lerchs & Grossmann, 1965). Subsequently, pit designs were optimized for each scenario (CoL74, CoL20, and CoCal). Sensitivity analysis was conducted, considering different Au prices of $1300, $1500, and $1700, as well as the mining timeframe for each scenario. All analyses were performed using the *Deswik Suite v5.1* software.

4. Results and discussions

4.1 Metallurgical testwork

Table 1 presents the Au recovery results for the three tested scenarios.

Table 1 - Results of metallurgical test for Au reuse in CO samples (after Lemos *et al.*, 2023a).

Calculated Feed Grade (mg/kg)	Au Mineralogical Association	(% Au recovery)		
		CoL74	CoL20	CoCal
0.950	sulfides and quartz	50.67	64.13	79.72

The results indicate a promising potential for Au recovery. Recoveries increased from scenarios 1 to 2, highlighting the essential role of the calcination in Au extraction. This relationship can be explained by the association between sulfides and Au, as detailed in studies by Lemos *et al.* (2023a) and Lemos *et al.* (2023b). These findings are significant, and they suggest that industrial reprocessing of these structures with minimal investment is feasible, especially given their proximity to metallurgical units already equipped for key stages in Au production (Moura, 2005; Lemos *et al.*, 2023a). These data serve as essential inputs for defining the economic scenarios discussed in the following sections.

4.2 Financial model

The economic assessment comprises two main steps. The first step evaluates the economic potential of Au present in inactive mine tailings as an *in-situ* value. The second step analyzes the feasibility of Au production using mine tailings as a source (Araya *et al.*, 2020).

4.2.1 Model and preliminary estimation of resources in the CO dam

Table 2 presents the results related to content and mass after modeling the survey conducted inside the reservoir.

Table 2 - Summary statistics of the global resources in the CO dam (after Lemos *et al.*, 2023a).

Block model variables						
Name	Minimum	Maximum	Range	Average	Standard Deviation	Variance
Au (mg/kg)	0.05	1.79	1.74	0.95	0.24	0.06
Density (g/m^3)	1.322	2.043	0.722	1.787	0.140	0.020
Tonnes	1.26	1,082.30	1,081.04	549.18	189.71	35,989.40
Resource	indicated	inferred	measured	-	-	-

An average Au grade of 0.95 and a total resource of 3,350.55 tonnes are the main assumptions for the block model, as summarized in Table 2. These assumptions were obtained from the model and assessment conducted by Lemos *et al.* (2023).

4.2.2 Bases for the Benefit Function

For the feasibility analysis, costs and economic parameters, as expressed in Table 3, were assumed, taking into consideration the metallurgical recovery scenarios mentioned: CoL74, CoL20, and CoCal.

Table 3 - Parameters of the reference case used for valuation based on the benefit function.

VARIABLE	
Revenue	Revenue from the Block
Mining cost	Mining and Transportation Costs
Processing cost	Processing Costs (GFE + PM_*)
Total cost	Total Cost of the Block
Benefit	Revenue from the Block - Cost of the Block
Type	Benefit greater than 0 = ore

VALUES

Variable	Description	CoCal	CoL20	Col74
Mining cost	Mining and Transportation Costs	R$ 6.45	R$ 6.45	R$ 6.45
GFE	G&A, Filter, and Dry Tailings Management Costs	R$ 56.25	R$ 56.25	R$ 56.25
PM_COCAL	Calcined Process and Maintenance Costs	R$ 51.70		
PM_COL	Leached Process and Maintenance Costs		R$ 38.43	R$ 38.43
USD_RATE	Conversion Rate	R$ 5.05		
OZ	Dollar per Ounce	$ 1,500		
RM_COCAL	Calcined Recovery (%)	79.72		
RM_COL20	Leached Recovery 20μm (%)		64.13	
RM_COL74	Leached Recovery 74μm (%)			50.67
CUT-OFF	Minimum Grade for Benefit = 0 (g/t)	0.59	0.65	0.82

To evaluate the final pits, the same benefit function used in the estimated model through ordinary kriging was employed, as described in Lemos *et al.* (2023a). For the feasibility analysis, costs and economic parameters presented in Table 3 were considered, taking into account the metallurgical recovery scenarios previously mentioned: CoL74, CoL20, and CoCal. Figure 2 illustrates these variations, showing the cut-off grades and tonnage for each scenario.

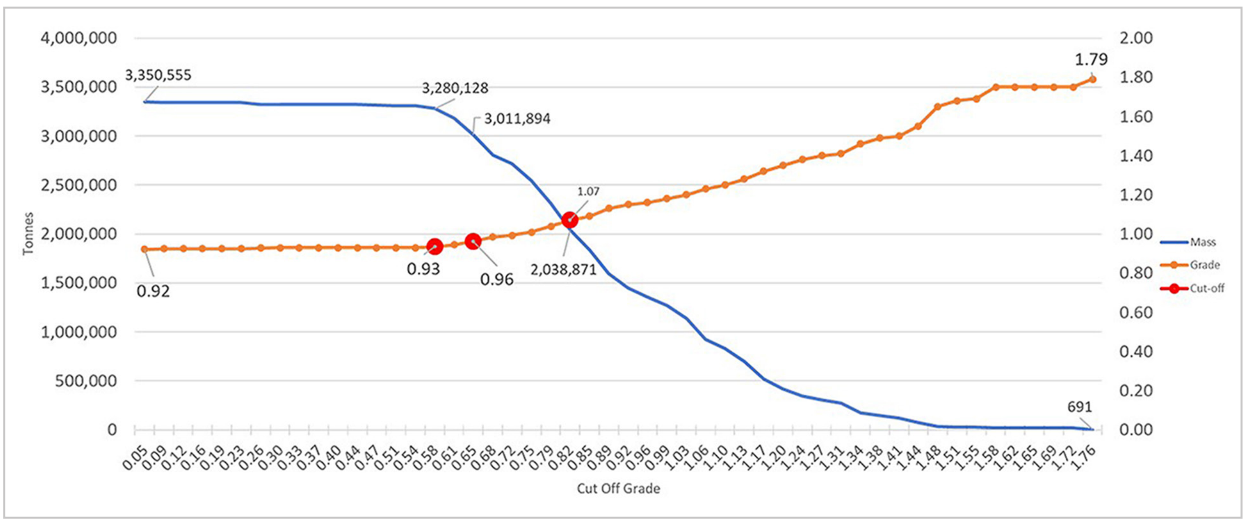

Figure 2 - Cut-of Grade versus tonnage for each considered scenario.

The project's NPV was calculated using an 8% annual discount rate for all developed scenarios, and a general slope angle of 20 degrees, equivalent to 36.4%, was applied.

4.2.3 Pit optimization and analysis of simulated scenarios

For each considered scenario, Table 4 presents the annual production figures.

Table 4 - Variation in annual production for each considered scenario.

Process	Scenario	Annual prod. (t)	Description
CO Calcined	CoCal	65,000	Annual feed limit due to S content
	CoCal-400	400,000	Sensitivity analysis created scenario
CO Leached +20 μm	CoL20	400,000	Base scenario
	CoL20-800	800,000	Sensitivity analysis created scenario
	CoL20-1000	1,000,000	Sensitivity analysis created scenario
CO Leached +75 μm	CoL74	400,000	Base scenario
	CoL74-800	800,000	Sensitivity analysis created scenario

Three final pits were obtained using the inputs illustrated in Table 3, each with production ranges as shown in Table 4 and Figure 1. In the CoCal scenario, a sulfur (S) grade limit in the feed was considered restrictive, as the minimum feed grade for this possible treatment route would be 20% (Moura, 2005; Lemos *et al.*, 2020). Therefore, this scenario has only one base possibility. In general, for the base scenario of these pits, an annual production of 400,000 t and 800,000 t was considered. Only in the case of CoL20 was it possible to simulate operation with 1,000,000 t annually. Therefore, the first two scenarios presented restrictions regarding the feed grade (CoCal) and mass (CoL74). Figure 3 displays the results of total ore, total waste, Au feed grades, and stripping ratio for each scenario.

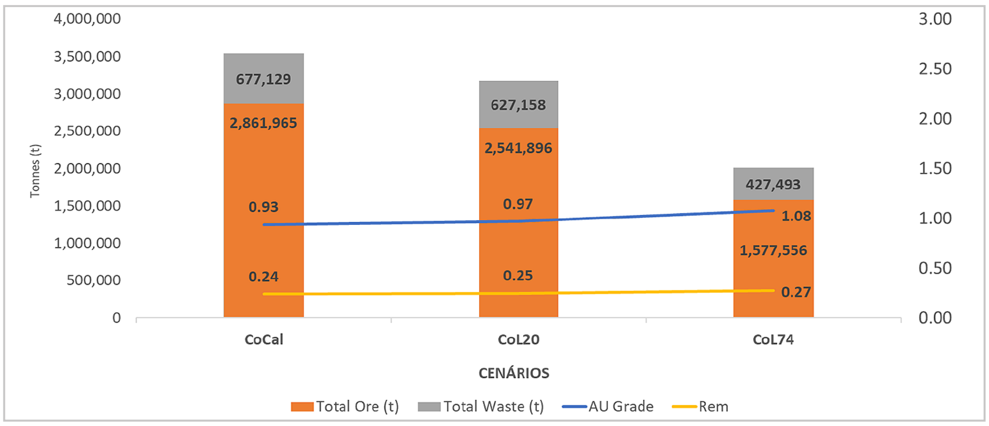

Figure 3 - Results of the pits generated for each scenario: CoCal, CoL20, and CoL74.

Based on the results of the generated pits and considering the base case for each scenario, with production variations of 400,000 t/annum, 800,000 t/annum, and 1,000,000 t/annum, and the value of one ounce of Au (31.108 g) at $1500, Figure 4 demonstrates the potential profit from Au reprocessing in CO. According to Figure 4, the CoL20 scenario, with an annual production of 800 kt, becomes attractive with potential gains of $21,093,647 and a production period of up to six years.

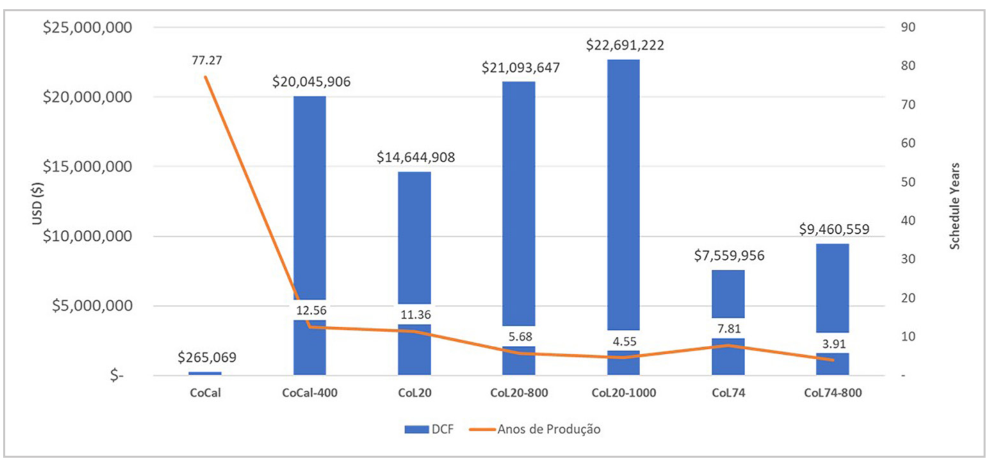

Figure 4 - Results and mine lifespan for each scenario, considering the base scenario for CoCal (65 kt), CoL20 (400 kt) and CoL74 (400 kt), along with the variations for CoCal (400 kt), CoL20 (800 kt and 1000 kt) and CoL74 (800 kt).

4.2.4 Sensitivity analysis

Figure 5 displays the three scenarios along with their respective annual production rates, while varying the value of the produced ounce, thereby affecting the mine's lifespan. The considered values are $1400, $1500 (base scenario), and $1700.

Figure 5 - Results and mine lifespan for each scenario considering different ounce values.

The CoCal 65 kt scenario could be more attractive in terms of both time and money. However, this scenario is restricted due to the high S feed grade for the roaster, exceeding 20%. The CoCal-400kt scenario show gains above $19 million but with a mine life of over ten years. On the other hand, the CoL20-800kt and 1,000 kt scenarios are more attractive compared to CoCal- 400kt and CoL-20-400kt, as they offer a financial return above $20 million and a relatively shorter mine life. The CoL74 scenario is the least attractive compared to the other scenarios.

It is important to consider that, in addition to the parameters presented here, geotechnical and environmental issues should be evaluated for using this resource. Furthermore, an environmental impact assessment, mainly on water resources, as well as ecological and human health risk assessments, should be added to this analysis. Although this structure is located near industrial complexes that currently process Au ores, investment surveys (CAPEX) are suggested to provide further robustness to the potential analysis presented.

5. Conclusion

The financial potential of reprocessing one of the Au metallurgical tailings dams in the IQ has been demonstrated. From an economic perspective, with cost analyses varying at $1300/oz, $1500/oz, and $1700/oz, and with annual productions of 400 t, all scenarios prove profitable.

When comparing the scenarios, CoL20, with annual productions of 800 kt and 1,000 kt, is of particular interest, with a return above $20 million. However, it is worth noting that the choice should not be solely based on financial factors, as it involves exploiting old tailings accumulation structures near essential river systems. In addition to the parameters presented here, geotechnical and environmental issues should be evaluated for using this resource. Furthermore, an environmental impact assessment, mainly concerning water resources, and ecological and human health risk assessments should be added to this analysis.

Although this structure is located near industrial complexes that currently process Au ores, investment surveys are suggested to provide further robustness to the potential analysis presented. Additionally, it is recommended to conduct a financial study on reusing other elements such as S, As, Ag, or even the whole waste. This approach would help avoid the generation of additional waste and improve resource utilization.

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