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Experimenting with Dimethyl Sulfoxide to Leach Gold from a Colombian Artisanal Gold Ore

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Abstract: The diverse uses of gold and its crucial role in the global economy are growing, particularly during cycles of economic crises. The broad use of cyanide by conventional gold-mining companies and mercury by artisanal miners poses environmental and health concerns for local communities. This article introduces an innovative gold-leaching process using a non-toxic organic reagent, dimethyl sulfoxide (DMSO), a water-free lixiviant that extracts gold from ores/concentrates in combination with copper halides. The results of laboratory experiments using dimethyl sulfoxide and a sample of high-grade gold ore from Colombia show that 96.5% of the gold was extracted in 2 h at room temperature. The typical cyanidation process using 5 g/L of CN^- at pH 10.5 on the same ore sample obtained 97% gold extraction in 24 h at ambient temperature. The gold extracted using DMSO was precipitated by adding a mild acidic solution, and the reagent can be recycled via distillation and reused in repeating cycles. The results show that DMSO can be used as a promising agent for gold leaching, offering a straightforward, cost-effective, and eco-friendly procedure with minimal chemical waste.

Keywords: dimethyl sulfoxide (DMSO); organic solvent; gold extraction; CN-free

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1. Introduction

Different gold recovery techniques have been explored as alternatives to the traditional practices of cyanidation, which is commonly used by conventional mining companies, and amalgamation, preferred by artisanal miners. The primary goal with these reagents, either cyanide or mercury, is to extract gold from high-grade materials such as gravity or flotation concentrates [1–4]. While aqueous solutions for gold dissolution have been the mainstay for decades [5,6], recent years have seen an interest in non-aqueous solutions [7–11]. However, despite their efficacy, their high toxicity, flammability, and cost have hindered their large-scale industrial adoption [12,13].

Various research has delved into the potential use of non-aqueous solvents. One method employs an iodine–iodide–acetonitrile solution for gold dissolution [7], offering the advantage of reusing the leaching solvent. Another method uses chloroform solutions of cetyltrimethylammonium bromide (CTAB) for gold oxidation [8]. A different study investigated mixtures of thionyl chloride ($SOCl_2$) and certain organic solvents/reagents for gold dissolution [9]. Yet, the high toxicity and flammability associated with these solutions limit their industrial potential. Glycine, a non-toxic amino acid, presents an environmentally benign alternative for gold leaching, offering potential selectivity advantages over traditional methods like cyanidation. While glycine shows promise, it is challenging to use. Its leaching kinetics can be slower than those of traditional methods, meaning it might take longer to dissolve the same amount of gold. Additionally, the cost of glycine and the need for its recovery and recycling in a process circuit are economic considerations. Ongoing research aims to optimize glycine-based processes, addressing challenges to make them more viable for industrial application [12,14].

Yoshimura et al. (2014) [15] have already successfully used industrial-grade dimethyl sulfoxide (DMSO), with copper bromide as an oxidant, to dissolve gold from gold-rich e-waste. DMSO is a water-free polar solvent that is FDA-approved, low-cost, and biodegradable. Regulatory authorities do not consider DMSO to be carcinogenic, and it is classified as a class 3 solvent with low toxic potential [16,17]. DMSO is widely used in the pharmaceutical, electronic, and chemical fields as a solvent for cosmetics, cleaning applications, paint stripping, and the synthesis and processing of polymers [18]. Dissolved gold can be recovered by adding a sufficient amount of water or an aqueous acidic solution to the gold-loaded DMSO [15,19]. The gold-leaching process using DMSO is based on the solvation potential of both Cu(I) and Cu(II) ions in DMSO. As a result, the addition of $CuBr_2$ or $CuCl_2$ to DMSO causes the Cu^{2+} ions to act as a potent oxidizing agent, oxidizing the gold while reducing Cu^{2+} to Cu^+ until it reaches equilibrium [19]. The dissolved gold, Au(III), forms a complex with halogens and remains in the solution [5]. The dissolution of gold in DMSO containing $CuCl_2$ occurs via the following overall reactions (1,2):

$$Au + 3Cu^{2+} + 4Cl^- = [AuCl_4]^- + 3Cu^+ \tag{1}$$

$$Au + Cu^{2+} + 2Cl^- = [AuCl_2]^- + Cu^+ \tag{2}$$

NaCl is added to supply enough Cl^- ion for the effective complexing of Au. Moreover, for Br^- treatment using $CuBr_2$ and KBr, the same reactions occur with the Br^- ion [15].

Incorporating water into the DMSO alters the solution's properties, leading to elevated redox potentials for gold within the mixture. Unlike when forming an azeotrope, DMSO and water can be easily separated through simple distillation, facilitating the reuse of the solution [15]. Additionally, the study posits that introducing an aqueous acid solution to the gold-bearing DMSO can prevent copper precipitation, ensuring the selective precipitation of only gold.

Yates Frank introduced the Yates algorithm in 1937 [20]. It is used to compute estimates of the main effects and the interactions of variables in a factorial experiment. For k binary-coded variables, it is possible to run 2^k experiments to include all the combinatorial possibilities of the variable states. In a more generalized scheme, however, one may ignore the effect of, say, p variables, leading to 2^{k-p} experiments [21]. This method enables the analysis of data from a designed experiment and determines if any of the factors included will significantly affect the response under consideration. In chemical analysis, this algorithm can distinguish the critical chemical components and combinations that optimize gold extraction from the ore. It allows the study of the effect of each factor and the effects of interactions between factors on the response variable [22]. Here, we used it to determine the most important chemical component(s), conditions, and combination(s) for optimizing gold extraction.

Building on the foundational work by [15] on the use of DMSO for gold extraction, our research seeks to further explore the potential of DMSO in the recovery of gold from different ore types. The primary objectives of our study are as follows:

1. To evaluate the efficacy of DMSO in comparison to other non-aqueous solvents for gold dissolution.
2. To understand the mechanism behind gold dissolution in DMSO in the presence of halides and determine the optimal conditions for this.
3. To assess the scalability and environmental implications of using DMSO for gold recovery, especially considering its interaction with various materials and its recycling potential.

DMSO, beyond its application in gold recovery, plays a pivotal role in several industries, notably pharmaceuticals, electronics, and chemicals. Its global production is dominated by regions such as the United States, France, Japan, and China. Key players in the DMSO market include Gaylord, Toray Fine Chemicals (TFC) and Arkema, among others [23]. Although valued at USD 226.1 million in 2020, the DMSO market is expected to surge to USD 417.2 million by 2030 [24]. However, the DMSO market was not immune to the ramifications of the COVID-19 pandemic, experiencing significant disruptions during 2020 and early 2021. Despite China's substantial contributions to DMSO production, various challenges, including environmental concerns and market competition, have nudged several manufacturers to reconsider the scale of their operations. Nevertheless, projections from Future Market Insights [25] indicate a promising CAGR of 5.4% for DMSO between 2022 and 2032.

2. Materials and Methods

2.1. Ore Sample

This sample, representative of the Colombian Central Cordillera, does not exhibit the characteristics of refractory gold, which can often be occluded in sulfides, making its extraction challenging. Instead, it is a product of a hydrothermal alteration zone characterized by quartz–pyrite–chalcopyrite–gold veins interspersed with potassic feldspar. Approximately 20 kg of ore from the La Maria deposit was generously provided by the Gramalote Mine Project (jointly owned by B2Gold and AngloGold Ashanti Ltd., Antioquia, Colombia) to the UBC Dept of Mining Engineering. This head sample underwent crushing and grinding in a lab disk mill until a grain size below 0.13 mm was achieved, and was subsequently homogenized. Eight samples of 100 g each were dispatched to Met-Solve Analytical Services Inc. (Vancouver, BC, Canada) for a 30 g fire assay chemical analysis. This was followed by bead dissolution using aqua regia and atomic absorption spectrometry (AAS) measurement. The results indicated an average gold content of 48.87 ± 6.30 (2 std) g/tonne, with a silver grade of 95 g/tonne. The copper grade was recorded at 0.41% Cu, equating to roughly 1.19% chalcopyrite, which, alongside pyrite, was identified as the primary sulfide in the sample through X-ray diffraction. Furthermore, the X-ray diffraction analysis of the gravity concentrate and the head sample discerned that quartz (originating from quartz veins) was the dominant mineral, with lesser amounts of pyrite, chalcopyrite, and amphibole.

The sample was devoid of large gold nuggets, primarily comprising medium to small gold particles, making it well suited to concentration techniques such as centrifugal processes or flotation. This granularity facilitates outstanding sample homogeneity. Initial sample grades, derived from metallurgical balance evaluations during each leaching trial, consistently portray a gold grade with minimal variation. The leaching tests further support the non-refractory nature of this gold. Specifically, when this ground sample was treated with 1 g/L CN (sourced from NaCN) for 24 h, at pH 10.5 and at ambient temperature, gold extraction peaked at 84% [26]. Impressively, increasing the CN concentration to 5 g/L yielded a 97% gold extraction under identical conditions.

2.2. Gold Extraction Experiments Using DMSO

The experiments were conducted using commercial DMSO kindly donated by Gaylord Chemical Co., (Covington, LA, USA). Each experiment involved dissolving the assigned amounts of $CuCl_2$ and NaCl in DMSO, followed by adding 10 g of La Maria ground ore (80% below 0.13 mm), which remained constant in all tests. The amount of DMSO used in each experiment depended on the intended solid–liquid (S:L) ratio. Each sample was agitated (speed: 100 rpm) for a specific time (8 or 24 h). Tables 1 and 2 show the variable values and their combinations for the DMSO tests. After the leaching process, each sample was washed thoroughly and filtered. The solid residue was sent to the laboratory for analysis of the remaining gold content via AAS. The gold dissolution in the DMSO was calculated based on the gold grade of the residues obtained after filtration.

$$\text{Au Extraction (\%)} = [(\text{Initial Au content} - \text{Residual Au content})/\text{Initial Au content}] \times 100 \quad (3)$$

Table 1. Variables and levels in DMSO experiments.

Acronym	**Variable**	**Levels**	
S	S:L (Ore:DMSO)	10% ($S_{0.1}$)	30% ($S_{0.3}$)
N	NaCl	0.6 g (N1)	1.16 g (N2)
C	$CuCl_2$	1.34 g (C1)	2.7 g (C2)
T	Time	8 h (T1)	24 h (T2)

Table 2. Different combinations of variables in DMSO experiments.

Sample ID	**Combination**	**S:L**	**Time (h)**	**NaCl (g)**	**$CuCl_2$ (g)**
A1	$S_{0.3}$T2N2C2	30	8	1.16	2.7
A2	$S_{0.3}$T2N1C1	30	24	0.6	1.34
A3	$S_{0.3}$T2N2C1	30	24	1.16	1.34
A4	$S_{0.3}$T2N1C2	30	24	0.6	2.7
A5	$S_{0.1}$T1N1C2	10	8	0.6	2.7
A6	$S_{0.1}$T1N2C1	10	8	1.16	1.34
A7	$S_{0.1}$T1N2C2	10	8	1.16	2.7
A8	$S_{0.1}$T1N1C1	10	8	0.6	1.34
A9	$S_{0.3}$T1N1C1	30	8	0.6	1.34
A10	$S_{0.3}$T1N2C1	30	8	1.16	1.34
A11	$S_{0.3}$T1N2C2	30	8	1.16	2.7
A12	$S_{0.3}$T1N1C2	30	8	0.6	2.7
A13	$S_{0.1}$T2N2C2	10	24	1.16	2.7
A14	$S_{0.1}$T2N1C2	10	24	0.6	2.7
A15	$S_{0.1}$T2N1C1	10	24	0.6	1.34
A16	$S_{0.1}$T2N2C1	10	24	1.16	1.34

2.3. Yates Method

To study the effect of each variable in more depth, we designed the model predictions using the Yates method, so that one factor and its combination with other factors were ignored in each run.

The experimental conditions had four variables: solid–liquid ratio, NaCl, $CuCl_2$, and time (at two levels), culminating in a total of sixteen experiments.

$$\text{Response (Y)} = \text{Constant} + 0.5 \times (\text{all factor and interaction estimates} = \text{Effects}) \quad (4)$$

$$\text{Coefficient} = 0.5 \times \text{Effects} \quad (5)$$

Y represents the predicted amount of gold extracted based on the Yates model [22]. After the leaching process, each sample was filtered (using Whatman filter paper, Grade 5:2.5 µm), and the residues were sent to a commercial analyzer to analyze the amount of gold not extracted; then, the % gold extracted by DMSO using $CuCl_2$ and NaCl was obtained.

2.4. Gold Precipitation

The gold precipitation process of the loaded DMSO was carried out by adding a weak acidic solution to the DMSO. The pH of the solution was kept low to prevent the precipitation of other metals, such as Cu or Fe [10,11]. We used 20 g of La Maria ore with varying concentrations of $CuBr_2$ and KBr dissolved in 100 mL of DMSO. The $CuBr_2$ concentrations ranged from 8.2 g/L to 32.7 g/L, and for KBr, concentrations ranged from 2.9 g/L to 11.6 g/L. The leaching was conducted for 12 hours at 40 °C, during which the gold was completely dissolved.

For the precipitation tests, the following solutions were tested: CH_3COOH (commercial vinegar, pH 2.5), 1.0 M H_2SO_4 (pH 0), pure lemon juice (pH 2.0), and 50% diluted lemon juice (pH 2.5). The gold precipitation process involved agitation of the gold-loaded DMSO for 24 h, using a volume of precipitation solution equal to that of the gold-loaded DMSO at room temperature (25 °C). Table 3 summarizes the experimental conditions.

Table 3. Different combinations of variables using $CuBr_2$ and KBr in DMSO experiments.

Sample ID	Ore (g)	DMSO (mL)	Time (h)	KBr (g/L)	$CuBr_2$ (g/L)	Acid Used for Precipitation
LM-1	20	100	12	11.6	32.7	Commercial vinegar
LM-2	20	100	12	5.8	16.4	H_2SO_4 (1.0 M)
LM-3	20	100	12	2.9	8.2	H_2SO_4 (1.0 M)
LM-4	20	100	12	5.8	16.4	Diluted (half) lemon juice
LM-5	20	100	12	5.8	16.4	Undiluted lemon juice

3. Results and Discussion

3.1. Gold Extraction

The % of gold extracted from the 10 g of La Maria ore using DMSO was calculated based on the gold grade analyzed via fire assay for all sixteen residues obtained after filtration (Table 4). The conditions of samples A13, A14, A15, and A16, listed in Table 2, obtained the most effective variable combinations for gold extraction, yielding results of 94.68%, 93.72%, 91.28%, and 91.20%, respectively.

Table 4. Results of the initial tests of gold extraction by DMSO.

Sample ID	% Gold Extracted by DMSO
A1	49.52
A2	62.14
A3	79.84
A4	30.16
A5	86.31
A6	78.84
A7	80.66
A8	82.50
A9	89.91
A10	65.95
A11	59.87
A12	81.03
A13	94.68
A14	93.72
A15	91.28
A16	91.20

During the gold extraction process, several observations were made. The ore particles remained consistently suspended throughout the mixing phase. As the extraction progressed, a subtle transition to a greener hue was noted in the solution, though no other significant physical changes were observed.

The primary mechanism for gold extraction in this process revolves around the oxidation of gold by Cu(II) ions from $CuCl_2$, facilitated by the solvent DMSO. As the gold is oxidized, it forms soluble gold–halide complexes in the DMSO solvent. DMSO, a polar solvent, enhances this dissolution by effectively solvating the reactive species. The copper ions, acting as the oxidizing agents, are reduced in the process. This change in oxidation state, from Cu(II) to Cu(I), signifies the effective transfer of electrons, with gold being the electron donor.

Table 5 includes the analyzed and calculated gold extraction results from the laboratory experiments and the results predicted via the Yates model. The columns labeled Prediction 2, Prediction 3, Prediction 4, and Prediction 5 in Table 5 represent the predictions generated by the model, while column 1 presents the laboratory % gold recovery results. For instance, in Prediction 2, we assumed that factor S (solid–liquid ratio) and its interactions with other factors would not affect the gold recovery. Similar assumptions for the other factors were considered in Predictions 3, 4, and 5.

Table 5. Comparisons between DMSO gold extraction in the lab and Yates predictions.

Au Extracted %	Pred. 1	Error %	Pred. 2 (No S)	Error %	Pred. 3 (No N)	Error %	Pred. 4 (No C)	Error %	Pred. 5 (No T)	Error %
82.5	88.62	1.52	86.21	4.50	80.67	2.22	84.40	2.30	86.89	5.32
89.91	77.64	5.45	86.21	4.12	77.93	13.32	85.48	4.93	76.03	15.44
78.84	87.36	1.46	72.41	8.16	80.67	2.32	79.76	1.17	85.03	7.85
65.95	75.34	25.41	72.41	9.80	77.93	18.17	62.92	4.59	72.89	10.52
86.31	92.34	1.55	83.67	3.06	83.47	3.29	84.40	2.21	90.01	4.29
81.03	58.04	19.28	83.67	3.26	70.45	13.06	85.48	5.49	55.59	31.40
80.66	89.48	1.80	70.27	12.88	83.47	3.48	79.76	1.12	87.75	8.79
59.87	56.3	6.35	70.27	17.37	70.45	17.67	62.92	5.09	54.69	8.65
91.28	85.36	1.59	76.71	15.96	91.23	0.05	92.50	1.34	86.89	4.81
62.14	73.3	6.10	76.71	23.45	70.97	14.21	46.14	25.75	76.03	22.35
91.2	82.5	1.46	85.51	6.24	91.23	0.03	93.02	2.00	85.03	6.77
79.84	71.56	19.60	85.51	7.10	70.97	11.11	64.66	19.01	72.89	8.70
93.72	87.48	1.21	61.93	33.92	94.27	0.59	92.50	1.30	90.01	3.96
30.16	54.26	55.47	61.93	105.34	39.81	32.00	46.14	52.98	55.59	84.32
94.86	86.22	1.34	72.17	23.92	94.27	0.62	93.02	1.94	87.75	7.50
49.52	51.96	9.96	72.17	45.74	39.81	19.61	64.66	30.57	54.69	10.44
AVERAGE		9.97		20.30		9.48		10.11		15.07

$$\begin{gathered}\text{Y (\%Au extracted)} = 76.1 + 11.3\,(S) - 1.03\,(N) - 4.11\,(C) - 2.03\,(T) - 0.02\,(SN) \\ + 5.55\,(SC) + 7.35\,(ST) + 0.22\,(NC) + 5.77\,(NT) - 2.94\,(CT) - 0.34\,(SNC) - 4.5 \\ (SNT) + 2.98\,(SCT) + 0.12\,(NCT) + 0.26\,(SNCT)\end{gathered} \tag{6}$$

As a result, the results in column 4 (Prediction 2, No S) indicate the impact of factor S on the gold recovery percentage predicted using the Yates algorithm. In the next column, the percentage error is calculated based on observations made during the experiments and the predicted values (Equation (7)):

$$\%\ \text{Error} = (\text{ABS (Lab observ.} - \text{Yates predict.)/Lab observ.}) \times 100 \tag{7}$$

The higher percentage of error implies that the desired factor has a greater effect on gold recovery in the experiments. Based on the calculated percent of error in the Yates model, the solid–liquid (S:L) ratio and time had the highest impact, while $CuCl_2$ and NaCl had the lowest impact, respectively.

Figure 1 illustrates the percentage of gold extraction from the lab experiments juxtaposed with the outcomes derived from the Yates model (as seen in Table 5, under the "Prediction 1" column). The anticipated results from the Yates model were determined utilizing the Y formula (Equation (6)), previously discussed in this segment, taking into account all the pertinent variables of the process. A commendable alignment is evident between the predicted gold extraction rates and the actual results from lab trials, even though there is an associated error margin of 9.97%. Considering the obtained results and the Yates analysis, we concluded that the DMSO volume and time are the key factors that likely contributed to the highest gold extraction. Additionally, samples A13 and A14, which exhibited the highest gold extraction rates (>91%) among the four best extraction conditions, had the same $CuCl_2$ concentration.

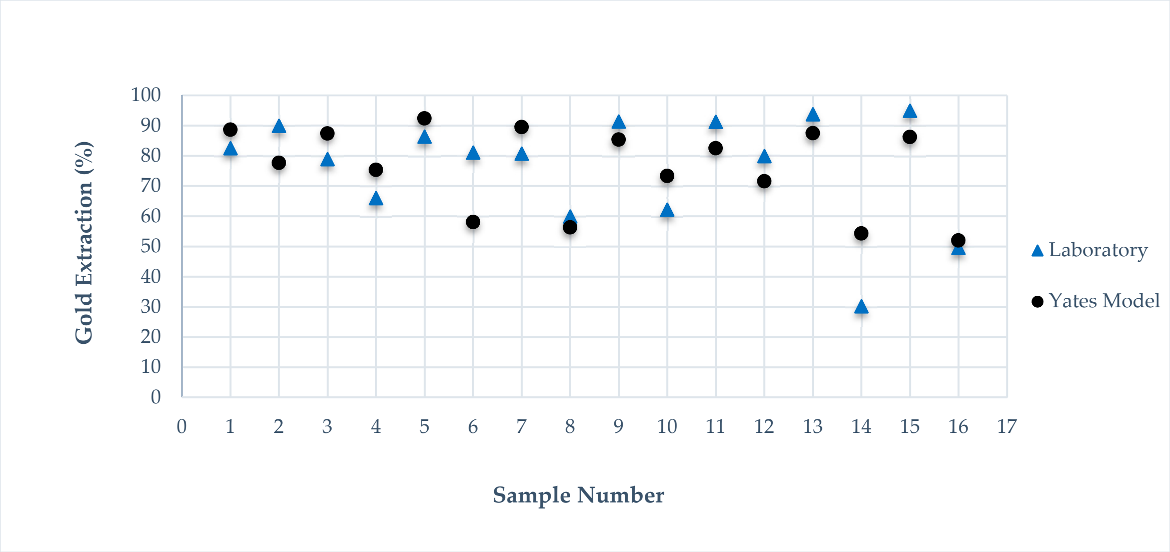

Figure 1. Observed vs. predicted DMSO gold extraction results.

After finding the most adequate combination of variables, the next phase of tests aimed to check the effect of the temperature. Tests were conducted using the conditions of the A13 test at ambient temperature (25 °C) and 40 °C. As is shown in Table 6, over 98% gold extraction was achieved after 2 h of leaching. The laboratory analysis shows that even when this process is conducted at ambient temperature, gold extraction rates exceed 95%.

Table 6. Analytical conditions of the highest gold extractions achieved by DMSO (S:L = 10%).

Sample ID	Time (h)	Temperature	Au Extracted by DMSO (%)
1	2	40 °C	98.81
2	4	40 °C	97.12
3	6	40 °C	97.36
4	8	40 °C	97.91
5	2	Ambient	96.5
6	4	Ambient	96.17
7	6	Ambient	95.42
8	8	Ambient	95.4

3.2. Gold Precipitation

Starting with the dissolution mechanism, gold in the ore is oxidized by Cu^{2+} ions, forming gold–halide complexes that are soluble in DMSO. When transitioning to precipitation, the gold-laden DMSO solution destabilizes the gold–halide complexes when introduced to a more aqueous or acidic environment. This destabilization causes the gold to precipitate out of the solution. Using acidic conditions, such as diluted H_2SO_4 or citric acid from lemon juice, ensures that gold selectively precipitates. At the same time, other metals like copper remain solvated in the solution due to their stable complexes in these conditions.

Focusing on our gold precipitation experiments, a sample of La Maria ore underwent bromide leaching at 40 °C (refer to Table 3), achieving a complete (100%) extraction of gold. Interestingly, minimal amounts of $CuBr_2$ and KBr were sufficient for this outcome. The gold-loaded DMSO was then subjected to precipitation tests (Table 7). Both diluted H_2SO_4 (pH 0) and a 50%-diluted lemon juice solution (with a pH range of 2.0–2.5) effectively recovered nearly all the dissolved gold.

Table 7. Gold precipitation results with different acidic solutions.

Sample ID	Acid Used for Precipitation	Gold Precipitation (%)
LM-1	Commercial vinegar	25
LM-2	H_2SO_4 (1.0 M)	100
LM-3	H_2SO_4 (1.0 M)	89.6
LM-4	diluted (half) lemon juice	100
LM-5	undiluted lemon juice	100

These results align with a study by Yoshimura et al. (2014) [15], which utilized a pure gold sample. However, it is important to note that our recovered material contained other elements, notably copper and sulfur. Their presence is likely due to DMSO's partial interaction with the 1.1% chalcopyrite in the ore [27]. This study [27] shows the solution does not dissolve pyrite, indirectly suggesting that iron from chalcopyrite might not be readily soluble in this specific DMSO solution.

We also explored gold precipitation using just water, but with a result of 60%, the recovery could have been more satisfactory. Given DMSO's boiling point of 189 °C, it can be recycled by boiling off the water at 100 °C. Vacuum distillation offers an alternative for low-temperature processing. However, considering the boiling point of H_2SO_4 is 290 °C, and citric acid decomposes at 200 °C, these acidic components would likely remain in the DMSO.

It is crucial to recognize the reactivity of DMSO with specific plastics, and the corrosive nature of $CuCl_2$ or $CuBr_2$ towards iron commonly used in leaching tanks. According to the Gaylord Chemical Company, materials like polyethylene, polypropylene, and ethylene–propylene rubber are suitable for use up to 120 °F (65.5 °C), while metals like stainless steel 304 or 316 or aluminum are recommended due to their prolonged resilience against DMSO. Additionally, while diluted sulfuric acid and citric acid are less potent, they still pose risks of skin, eye, and respiratory system irritation, especially when combined with DMSO's ability to enhance skin absorption. There are also potential reactivity concerns when mixing these chemicals, even in diluted forms. Environmental considerations are paramount, given that even diluted forms of these chemicals can be harmful to aquatic life [28]. Thus, enforcing proper disposal measures and having a spill response strategy is imperative. Adherence to safety protocols is essential, and consultation with chemical safety experts or Material Safety Data Sheets (MSDS) is advised when uncertainties arise.

4. Conclusions

The ongoing demand for gold and the concomitant environmental and health concerns associated with the conventional methods of gold extraction using cyanide and mercury necessitates alternative, environmentally friendly, and efficient gold-leaching techniques. The study presented herein offers a promising alternative in the form of a DMSO gold-leaching process. Some salient conclusions drawn from this research are as follows:

Efficacy of DMSO: Laboratory experiments with dimethyl sulfoxide (DMSO) have demonstrated its capability to extract gold efficiently. Compared to the 24-h duration required for a 97% gold extraction via cyanidation, DMSO achieved 96.5% gold extraction within just 2 h at room temperature.

Eco-friendliness: Apart from being efficient, DMSO represents a more environmentally friendly option. Unlike cyanide and mercury, which are toxic and can have adverse environmental and health effects, DMSO is non-toxic, FDA-approved, biodegradable, and can be recycled and reused, leading to a reduction in chemical waste.

Precipitation: Gold extracted using DMSO can be effectively precipitated by adding an acidic solution, such as diluted H_2SO_4 or lemon juice. While gold precipitation via water yielded less than 60% recovery, the use of acidic solutions proved to be more efficient.

Factorial Analysis using Yates' Algorithm: Analysis using Yates' algorithm helped determine the key factors that contribute to optimal gold extraction. Among the various conditions tested, DMSO volume and time emerged as the most significant factors.

Effects of Temperature: The efficiency of the DMSO gold-leaching process is not adversely affected by ambient temperature. Experiments conducted at both ambient temperature and 40 °C achieved gold extraction rates exceeding 95%.

Material Compatibility: While DMSO demonstrates impressive gold-leaching capabilities, considerations regarding its compatibility with specific materials, particularly plastics and metals, are vital. Suitable materials for storage and processing include polyethylene, polypropylene, ethylene–propylene rubber, stainless steel 304 or 316, and aluminum.

Potential for Small-scale Operations: While the limited global production of DMSO might pose challenges for large-scale operations, the non-toxic nature of DMSO and the simplicity of its production process make it a promising candidate for small-scale plants and artisanal mining operations. Furthermore, with the market indicating an upward trend, a significant increase in DMSO production is anticipated, underscoring its potential as a vital component in promoting environmental sustainability and economic viability within the gold-mining sector.

In conclusion, this study underscores the potential of DMSO as an innovative, eco-friendly, and efficient gold-leaching agent, paving the way for its adoption in the gold-mining industry, especially for high-grade ores or concentrates. Further research and larger pilot tests are warranted to explore the scalability and commercial viability of this method.

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Data Availability Statement: The data presented in this study are fully available within the article.

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