

Article

Integration of Cyanidation and Roasting Methods for Complex Gold and Silver Ore with Semi-Refractory Behavior

Sadiye Kantarcı 

Department of Mining Engineering, Faculty of Engineering, Şırnak University, 73000 Şırnak, Türkiye;
sadiyekantarci@sirnak.edu.tr

Abstract

Complex and semi-refractory gold–silver ores pose significant challenges for efficient metal recovery using conventional cyanidation methods. This study investigates the effect of roasting thermal pretreatment on the leaching performance and mineralogical structure of a polymetallic gold–silver ore from northeastern Türkiye. The samples were roasted at 220 °C, 420 °C, and 620 °C prior to cyanidation to evaluate roasting-induced mineralogical transformations and their effects on metal recovery. High-temperature roasting markedly improved both gold and silver recovery. Gold recovery increased from 75% for the untreated ore to 95.84%, while silver recovery increased from 69.72% to 86.12% after roasting at 620 °C. XRD analysis indicated the transformation of pyrite to hematite, while the characteristic reflections of kaolinite and sphalerite were no longer detected at 620 °C. Moreover, the lowest cyanide consumption (6.5 kg NaCN/t ore) was observed after roasting at 620 °C, coinciding with the highest Au and Ag recovery. These results indicate that roasting-induced mineralogical transformations enhance the accessibility of precious-metal-bearing phases during subsequent cyanidation. Overall, controlled high-temperature roasting shows potential for improving Au and Ag recovery while reducing cyanide consumption in complex semi-refractory ores.

Keywords: gold/silver cyanidation; roasting; low cyanide consumption

1. Introduction

There are several types of gold ore, including free-milling, intermediate, and refractory gold ore [1]. Historically widespread, production processes requiring only one leaching step are declining due to the depletion of natural gold resources, rising demand, and the exhaustion of highly concentrated free gold ore. In many cases, the problem is due to the presence of precious metals in refractory phases or in the ore matrix, which is a mixed mineral phase that competes with gold and silver for leaching agents. The first type is known as refractory ores, and the second is known as complex ores [2]. While high Au recoveries (>90%) can generally be achieved from free-milling ores, refractory gold ores are often characterized by lower Au recoveries in the range of 50%–80% during conventional cyanidation [3,4]. Refractory ores contain precious metals encapsulated in sulfide or carbonaceous minerals, whereas complex ores contain multiple mineral phases that may compete with gold and silver for leaching reagents and thereby reduce cyanidation efficiency [1,5]. Gold encapsulated in sulfide minerals must be broken down into oxides or other chemical compounds that are easily soluble in water or other solvents during the leaching process in order to release the gold from the refractory gold ore [1].



Academic Editor: Brajendra Mishra

Received: 7 September 2026

Revised: 25 September 2026

Accepted: 26 September 2026

Published: 29 September 2026

Copyright: © 2026 by the author.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

The presence of impurity metals such as copper, zinc, and nickel in refractory gold ores increases the consumption of cyanide and oxidants in the leaching system. It also forms a film layer on the gold surface, which prevents the dissolution of gold into cyanide and causes the leaching efficiency to decrease [6]. Reaction kinetic or thermodynamic obstacles that prevent cyanide diffusion or mineral dissolution, leached gold re-adsorption, and excessive cyanide consumption are frequently blamed for these difficulties [1]. For these reasons, many oxidation pretreatment technologies have been developed to improve gold recovery. Gold can be extracted from the refractory ores by roasting, high-pressure or low-pressure oxidation, bacterial oxidation, and chemical oxidation [7–9].

Au–Ag ores containing pyrite, sphalerite, acanthite, and clay minerals may also present several challenges to conventional cyanidation. Khalid et al. (2018) reported that, among multilayer pyrite–sphalerite–silica systems, silver–mineral addition was beneficial to gold cyanidation, whereas surface-passivating films were observed in pyrite–chalcopyrite–silica and pyrite–stibnite–silica systems [10]. Celep et al. (2019) found that acanthite in a refractory arsenical silver ore occurred mainly as very fine grains associated with Pb–Fe–Sb-bearing phases and silicates, and that cyanide leaching recovered only 71% Ag after 24 h; the authors attributed the limited extraction to restricted cyanide access to the fine acanthite grains [11]. Asamoah et al. (2019) showed that, in refractory gold-ore pulps, mineralogy, alkaline cyanide-leaching time, and alkali type markedly affected pulp chemistry, particle interactions, and rheological behavior [12]. Accordingly, the pyrite-, sphalerite-, acanthite-, covellite-, and kaolinite-bearing mineral assemblage identified in the ore provides a basis for evaluating roasting as a pretreatment.

Roasting is a commonly used pretreatment method for sulfide-rich refractory ores. The process involves the reaction of thermal gases with sulfide minerals and, in some cases, organic carbon, under an oxidizing atmosphere at temperatures ranging from 500 °C to 700 °C [13]. Roasting is often necessary to convert sulfide minerals to sulfate, oxide, or both, thereby increasing the extractability of target metals [14]. Sulfide oxidation by roasting in sulfide gold ores significantly increases gold recovery [5,15–17]. Bas et al. (2015) investigated the electrochemical dissolution of roasted gold ore in cyanide solutions and reported that hematite promoted gold dissolution relative to magnetite, whereas Fe-oxide and Au–C surface products observed by SEM could contribute to partial gold-surface passivation [18]. These results indicate that mineral transformations during roasting may also influence the subsequent cyanidation behavior, in addition to the removal or oxidation of sulfur-bearing phases. In addition, in recent years, it has been established that leaching processes after oxidation by microwaves have a positive effect on gold recovery [1,14,19,20].

Although roasting markedly improves Au recovery, its industrial application should be evaluated together with its technological and environmental limitations. Roasting requires energy for ore heating and for maintaining controlled temperature and atmospheric conditions. Moreover, pyrite oxidation can generate SO₂-bearing off-gas; measurable SO₂ formation from FeS₂ particles has been reported at approximately 400 °C [21]. The management of potentially volatile metalloids is also important in polymetallic feeds. Haga et al. reported substantial Sb volatilization during air roasting of a tennantite/tetrahedrite ore at 600 °C, a temperature close to the upper roasting temperature applied in the present study [22]. Another study also showed that excessive roasting temperatures can cause sintering and secondary encapsulation, which are associated with reduced Au and Ag recoveries in pyritic Au–Ag concentrates [23]. From an economic perspective, roasting involves additional capital and operating costs associated with flue gas treatment and residue management. Therefore, for industrial-scale roasting operations, roasting conditions must be optimized not only for gold recovery but also for energy efficiency, gas emission control, and calcine stability.

The mineralogical composition of the ore is an important factor in determining the efficiency of the roasting process. The roasting process operates through several mechanisms that alter the ore's mineralogical composition and increase interaction between the precious metals and the cyanide solution: oxidation, physical alteration, and chemical reactions. In an oxidation mechanism, roasting oxidizes minerals, releasing precious metals [23]. It changes the physical structure of the ore, thereby increasing its surface area [24]. Moreover, new compounds formed during the roasting process facilitate better cyanide dissolution [15]. By roasting, sulfur components are converted to oxides, allowing the ore to develop a porous structure and releasing the precious metals. Thus, cyanide solution accessibility to the metals increases [23].

Cerattepe Mine, one of the volcanogenic massive sulfide (VMS) deposits in north-eastern Turkey, is located within Late Cretaceous volcanic, intrusive, and sedimentary rocks [25]. Unlike other VMS deposits in the Northeast Pontic, it is distinguished by an unusual base zone of high-grade copper sulfide and a rich oxide zone of Au. The main ore body of the deposit is composed of high-grade, massive copper sulfides, with an oxide zone of gold, silver, and barium, characterized by intense alteration. Mineral parageneses consist of pyrite, chalcopyrite, sphalerite, bornite, marcasite, galena, gold, covellite, tetrahedrite, chalcocite, digenite, cuprite, and cubanite, while quartz, barite, and calcite constitute the gangue. In the oxidation zone, limonite, hematite, malachite, azurite, and jarosite are formed. The Au-Ag gossan zone is found above the VMS deposit [25,26].

The ore at Cerattepe is characterized by strong mineralogical zoning and a complex, refractory polymetallic ore source [27]. Each zone has distinct mineralogical characteristics resulting from different ore-body zoning, and it is important to determine these characteristics and effectively extract gold and silver from complex ore.

The effectiveness of cyanide leaching is strongly dependent on the mineralogical characteristics of the ore and on the transformations occurring during pretreatment. This is particularly important for complex and semi-refractory ores associated with heterogeneous sulfide and gangue mineral assemblages. Although roasting has been widely investigated as a pretreatment for refractory gold ores, the relationship between roasting-induced mineralogical transformations and the simultaneous cyanidation behavior of Au and Ag in complex polymetallic ores requires further investigation. The novelty of this study is the integrated evaluation of roasting-induced mineralogical transformations together with the different cyanidation responses of Au and Ag and cyanide consumption in a complex polymetallic ore. Therefore, this study evaluates the effect of controlled roasting at 220, 420, and 620 °C on the mineralogical characteristics and subsequent cyanidation performance of a complex semi-refractory Au-Ag ore. Particular emphasis is placed on relating roasting-induced mineral transformations to Au and Ag recovery and cyanide consumption.

2. Materials and Methods

2.1. Materials and Characterization

2.1.1. Source and Preparation

The ore sample used in this study was provided by the Cerattepe deposit in Artvin, Türkiye. This ore is classified as a polymetallic, semi-refractory gold-silver ore characterized by its complex mineralogical composition and high sulfide content. The ore contains gold and silver, which offer economic potential. Significant amounts of copper and zinc, as well as trace amounts of lead, are present in the ore along with gold and silver.

As part of the sample preparation procedures, it was pre-crushed using a jaw crusher and sieved to less than 1 mm. After drying at 105 °C, the sample was ground for 3 s in a steel ring mill. To minimize cross-contamination, the steel ring mill was brushed and wiped with acetone between samples. When switching from a different material, the mill was

additionally cleaned by grinding silica sand, followed by the removal of residual powder with compressed air and wiping with acetone. The sample was then divided using an automatic sample divider to obtain representative subsamples for characterization, roasting, and leaching experiments.

2.1.2. Chemical and Mineralogical Characterization

Adequate samples were prepared for characterization analyses of the ore. X-ray Fluorescence (XRF) analysis was conducted at ARGETEST Laboratories to determine major oxides.

In MTA (General Directorate of Mineral Research and Exploration) laboratories, gold (Au) and silver (Ag) analyses were carried out using the high-temperature melting method (fire assay) and acid dissolution and ICP-MS (inductively coupled plasma–mass spectrometry) method. In addition, major and minor element analyses were carried out by the four-acid digestion method, and the results were obtained by ICP-OES (inductively coupled plasma–emission spectroscopy). Pyritic sulfur and sulfate sulfur analyses were also performed. In addition, scanning electron microscope (SEM) imaging and microchemical EDS (energy-dispersive spectrometry) analyses were conducted. These analyses were conducted to obtain detailed information on the mineral components and their properties.

Particle size distributions were analyzed with a Malvern Mastersizer Hydro 2000MU laser diffractometer (Malvern Instruments Ltd., Malvern, UK). In addition, the mineralogical composition was determined by X-ray diffraction (XRD) using a PANalytical X'Pert3 Powder X-ray diffractometer (PANalytical B.V., Almelo, The Netherlands). These analyses were performed by scanning at 5–60° 2 θ angle with Cu-K α 1 radiation (λ = 1.54059 Å) at 40 mA current and 45 kV voltage. Mineral abbreviations used in the XRD patterns were assigned according to the IMA–CNMNC-approved mineral symbols reported in [28]. All analyses were conducted at the Department of Mining Engineering, Karadeniz Technical University.

Thermal analyses were performed by thermogravimetric analysis/differential thermal analysis (TG/DTA) in the range of 25–1100 °C and differential scanning calorimetry (DSC) between –50 and +400 °C at a heating rate of 10 °C/min for 3–5 h. Additionally, Fourier transform infrared (FTIR) spectroscopy analyses were performed using KBr in the 4000–400 cm^{–1} range at the Mehmet Akif Ersoy University Scientific and Technological Application and Research Center.

2.2. Experimental Methodology

2.2.1. Roasting Process

Each test sample was roasted in a porcelain crucible for 1 h at 220 °C, 420 °C, and 620 °C in a laboratory muffle furnace, after weighing in heat-resistant pots. Roasting experiments were carried out in a muffle furnace in air, without additional gas supply. The roasting temperatures were selected based on the thermal transitions observed in the TG/DTA analysis to evaluate the roasting behavior under three representative thermal conditions (220, 420, and 620 °C), rather than to establish an optimum roasting temperature. The upper roasting temperature was limited to 620 °C because strong exothermic reactions associated with sulfide oxidation caused operational difficulties at higher temperatures. Local exothermic reactions during sulfide oxidation may cause particle temperatures to exceed the nominal furnace temperature. Studies on pyritic and arsenopyritic refractory gold ores have shown that temperatures up to 650 °C should be used [29]. After roasting, the roasted products were cooled and weighed, and the mass loss during roasting was calculated relative to the initial sample mass and subsequently subjected to cyanidation.

2.2.2. Cyanidation Leaching Process

Cyanidation experiments were carried out with mechanical stirring at ambient temperature, pH 11, an initial NaCN concentration of 1.5 g/L, a stirring speed of 500 rpm, and a solid ratio of 20% for 15 h. These experimental conditions were selected based on preliminary tests and commonly applied cyanidation conditions reported in the literature, while maintaining the same leaching conditions for all untreated and roasted samples to allow direct comparison of the effect of roasting temperature. Air was supplied to the leaching system using a sparger throughout cyanidation. The pH was initially adjusted to 11 and monitored at regular intervals during leaching; when a decrease in pH was observed, it was readjusted to 11 using a 1 M NaOH solution. During the leaching process, 10 mL slurry samples were withdrawn at predetermined time intervals (1, 3, 6, 12, and 15 h) and centrifuged to separate the solid and liquid phases. The clarified leach solutions were analyzed for Au and Ag by atomic absorption spectrometry (AAS) using an AAnalyst 400 atomic absorption spectrometer (PerkinElmer, Inc., Shelton, CT, USA). The separated solid fraction was resuspended to a total volume of 10 mL and returned to the leaching system after each sampling step, and the slurry volume was restored to its initial level to minimize solid and liquid losses during sequential sampling. Free cyanide concentration was determined by titration with 0.02 mol/L AgNO₃ using rhodanine as the indicator. Based on the measured free cyanide concentration, NaCN was added as required to restore the concentration to 1.5 g/L during leaching. Cyanide consumption was calculated from the cumulative amount of NaCN added during the experiment. Analytical-grade and commercially available chemicals and pure water were used in the experimental studies. Sodium cyanide (NaCN, >95%, Merck KGaA, Darmstadt, Germany) was used as the leaching reagent, and sodium hydroxide pellets (NaOH, 99%–100%, Merck KGaA, Darmstadt, Germany) were used for pH adjustment. Silver nitrate (AgNO₃, 99%–100%, Merck) and rhodanine indicator (Merck KGaA, Darmstadt, Germany) were used for cyanide determination. After the leaching experiments, the slurry was filtered, and the metal concentrations in the solution and solid residues were determined using the same analytical methods described above.

3. Results and Discussion

3.1. Ore Characterization

The chemical composition of the ore sample is presented in Table 1. The major components determined by XRF include Fe₂O₃ (30.90 wt.%), SiO₂ (25.87 wt.%), and SO₃ (11.33 wt.%). The ore contains 4.6 ppm Au and 44.6 ppm Ag, together with considerable amounts of Cu (4669 ppm), Zn (2592 ppm), and Pb (2078 ppm). Separate sulfur analyses indicated 5.56% pyritic sulfur and 0.95% sulfate sulfur, confirming the significant contribution of sulfur-bearing phases to the ore composition.

Table 1. Chemical analysis results of the ore sample.

Analysis	(wt.%)	Analysis	(wt.%)	Analysis	(ppm)	Analysis	(ppm)
SiO ₂	25.87	TiO ₂	0.25	Cu	4669	Sb	124
Al ₂ O ₃	9.46	P ₂ O ₅	0.10	Zn	2592	Co	82
Fe ₂ O ₃	30.90	MnO	0.02	Pb	2078	Se	60
CaO	0.38	Cr ₂ O ₃	0.07	As	1834	Cd	14
MgO	0.38	LOI	15.59	Mn	237	Ag	44.6
Na ₂ O	0.09	BaO	3.34	Mo	281	Au	4.6
K ₂ O	0.96	SO ₃	11.33	Ni	196		

Figure 1 presents the XRD pattern of the untreated ore. The main mineral phases identified were quartz (SiO_2), pyrite (FeS_2), barite (BaSO_4), kaolinite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$), sphalerite (ZnS), covellite (CuS), Jamesonite ($\text{Pb}_4\text{FeSb}_6\text{S}_{14}$), and acanthite (Ag_2S). The phase identification was based on multiple characteristic diffraction peaks. Some reflections of the minor phases overlap due to the complex mineralogical composition of the ore. Therefore, the identification of these phases was also considered together with the SEM–EDS and chemical analysis results. In particular, the presence of Ag- and S-rich regions and Zn- and S-rich regions in the SEM–EDS analysis supports the identification of acanthite and sphalerite, respectively. The coexistence of sulfide, sulfate, and silicate phases shows the complex mineralogical composition of the ore. The presence of clay minerals such as kaolinite may also negatively affect gold dissolution during cyanidation [21]. The coexistence of sulfide, sulfate, and silicate phases confirms the complex mineralogical composition of the ore. In addition, the presence of clay minerals such as kaolinite suggests a potential challenge, as clays are known to hinder gold dissolution during cyanidation [30]. In particular, the occurrence of pyrite and Ag-bearing acanthite provides a mineralogical basis for investigating roasting as a pretreatment prior to cyanidation.

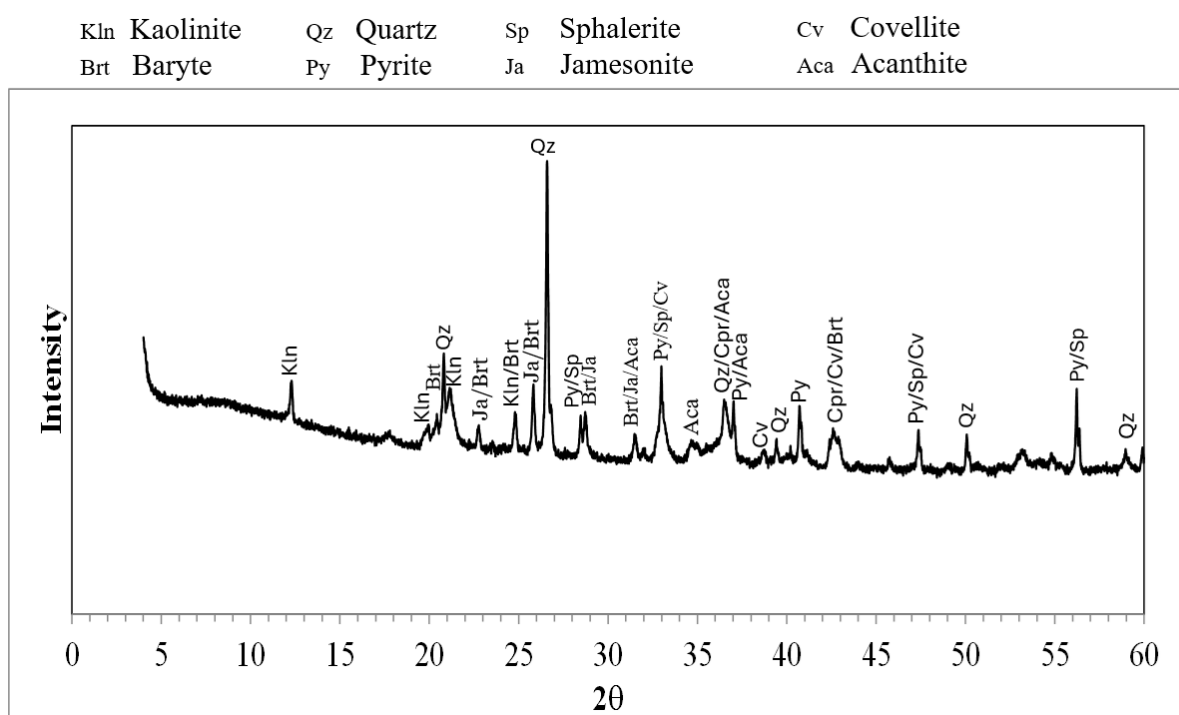


Figure 1. XRD analysis of the ore sample.

Figure 2 displays the SEM–EDS results, showing regions enriched in Ag, Zn, Fe, and S. In the first SEM image (Figure 2a), Spots 1 and 2 show high concentrations of oxygen (O), iron (Fe), antimony (Sb), and lead (Pb). In Spot 2 (Figure 2a), the mineralogical diversity of the ore is highlighted by the high ratio of oxygen (O) (24.80) and antimony (Sb) (12.41). The relatively high O and Sb contents may indicate the presence of oxidized Sb-bearing phases and/or alteration products associated with Pb- and Fe-bearing minerals. The simultaneous occurrence of O and Fe is consistent with the presence of Fe-bearing oxide or altered mineral phases. In contrast, Figure 2b shows regions enriched in sulfide-associated elements more prominently. Spot 1 and Spot 3 show high silver contents (68.28 wt.% and 71.92 wt.%, respectively) together with sulfur. The Ag:S atomic ratios calculated from the EDS results are approximately 1.26:1 for Spot 1 and 1.93:1 for Spot 3. The ratio obtained for Spot 3 is close to the theoretical Ag:S ratio of 2:1 for Ag_2S , suggesting the possible presence

of an Ag_2S -type phase such as acanthite, whereas the composition of Spot 1 does not correspond to the stoichiometric Ag_2S ratio. Spot 2, dominated by zinc (60.04 wt.%) and sulfur (37.22 wt.%), is consistent with the possible presence of sphalerite (ZnS). These results indicate the presence of Ag- and Zn-bearing regions and support the complex mineralogical composition observed by XRD. The SEM-EDS results also indicate the presence of Pb- and Sb-bearing phases, further reflecting the complex polymetallic nature of the ore.

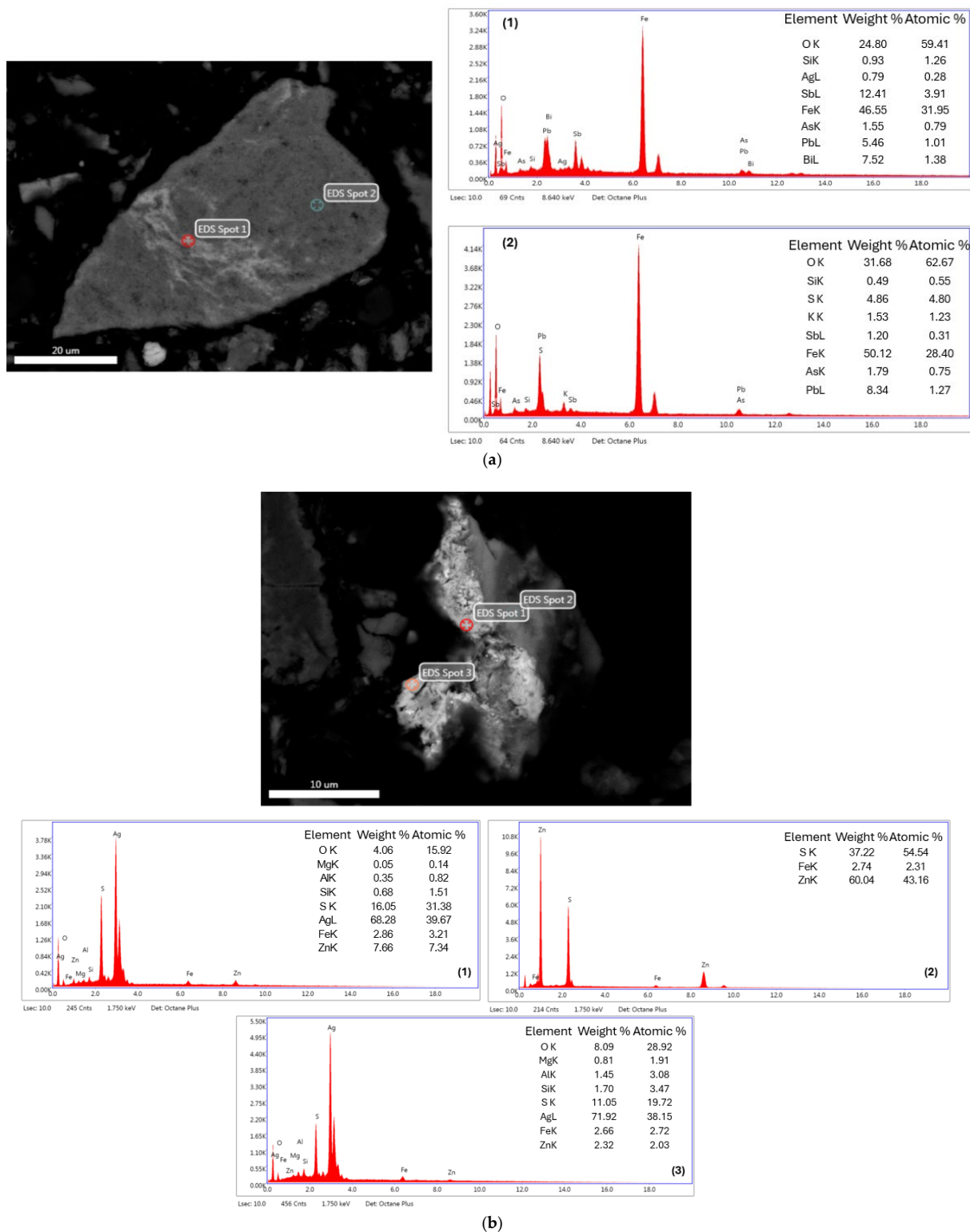


Figure 2. SEM/EDS analysis for the ore sample. (a) Pb-, Sb-, Fe-, and O-bearing regions (Spots 1 and 2); (b) Ag- and Zn-bearing sulfide regions (Spots 1–3). The numbers indicate the EDS analysis spots.

Given the considerable abundance of sulfide minerals in the ore, their influence on gold dissolution in cyanide solution is particularly relevant. Early studies of the dissolution of gold in cyanide solutions in the presence of sulfide minerals demonstrate that the presence of base metals such as Cu, Fe, and Zn significantly increases both cyanide and oxygen consumption during gold dissolution [31]. In addition, sulfide ions tend to passivate the gold surface by forming a passive layer of sulfur adsorption on the gold surface [31,32]. To overcome these challenges, the current study uses a roasting process as a pre-oxidation step prior to cyanidation, aiming to improve metal recovery by decomposing sulfur phases.

The TG/DTA curves of the ore sample are shown in Figure 3. The TG curve reveals a continuous, stepwise decrease in sample mass with increasing temperature; at 971 °C, 81.1% of the initial mass remains, corresponding to a total mass loss of 18.9%. In the low-temperature region, a mass loss of approximately 1.2% occurs from ambient temperature to 118 °C, followed by an additional 1.3% between 118 and 239 °C; these early losses are attributed to the removal of free/adsorbed water and low-temperature dehydration. A more pronounced decrease of approximately 2.5% between 239 and 284 °C is followed by a gradual loss of approximately 1.2% in the 284–434 °C range. One of the most significant mass changes occurs between 434 and 519 °C, where the sample mass decreases by approximately 4.3%, from 93.8% to 89.5%. Between 519 and 601 °C, a further mass loss of approximately 1.8% is observed; the losses in the mid-temperature region can be associated with the dehydroxylation of structural water and the thermal transformation and oxidation of sulfide mineral phases. A gradual loss of approximately 1.8% between 601 and 815 °C is followed by the second major loss of approximately 4.8% between 815 and 971 °C, during which the mass decreases from 85.9% to 81.1%; these high-temperature changes may be associated with further mineral decomposition and the release of volatile components. Overall, the TG results show that the thermal behavior of the ore cannot be explained by a single mechanism; the total mass loss of 18.9% is the combined result of dehydration/dehydroxylation, sulfide transformation and oxidation, and further mineralogical decomposition occurring in different temperature ranges.

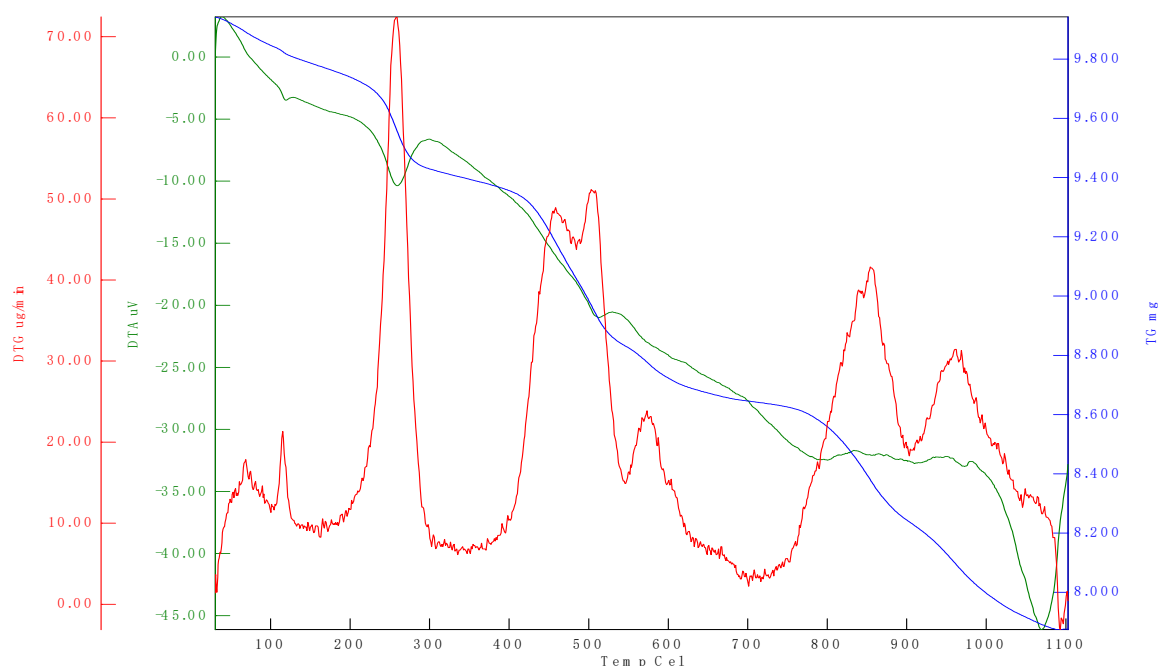
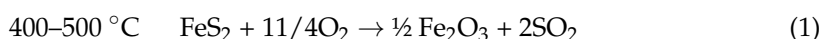


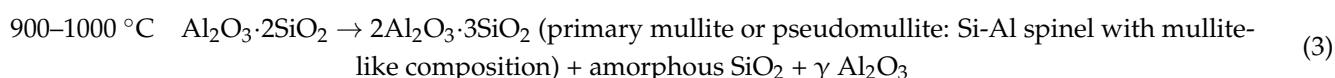
Figure 3. TG, DTG, and DTA curves for the ore sample.

The thermal behavior of sulfide-bearing ores is influenced by several experimental and material-related factors, including sulfur content, oxygen availability, particle size,

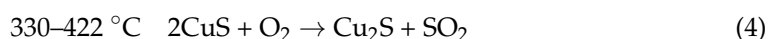
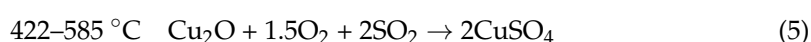
crucible geometry and material, and temperature [33]. These factors can affect the number, position, and intensity of thermal events observed during analysis. Pyrite undergoes significant weight loss in two stages from about 450 °C to above 650 °C. Temperature and oxygen content are the main factors that influence pyrite alteration in an oxygen-containing environment. Under oxidizing conditions, temperature and oxygen content govern pyrite alteration; therefore, reliable thermogravimetric analysis requires a sufficient oxygen supply to the sample. Previous studies have reported that, above approximately 450 °C, pyrite may undergo transformation through intermediate pyrrhotite (Fe_{1-x}S), followed by oxidation depending on temperature and oxygen availability [34,35]. The exothermic reaction of pyrite between 400 and 500 °C (1) is as follows [21,33,36]. Under oxidizing roasting conditions, SO_2 is considered the principal gaseous sulfur species formed during pyrite oxidation [21,36].



Kaolinite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$) undergoes a two-stage dehydroxylation and structural change process. First, OH groups are removed from the external surface; the second stage is the removal of internal OH groups. At 530–590 °C, it undergoes dehydroxylation via an endothermic reaction, as shown in Reaction (2). At 900–1000 °C, it undergoes an exothermic reaction, accompanied by changes in the crystal phase, as shown in Reaction (3) [33].



It has been reported that covellite (CuS) and the resulting decomposition products, such as sulfur dioxide, react in an oxidation reaction to form copper oxysulfate or sulfate at temperatures higher than 330 °C or 600 °C. Reactions (4) and (5) and their temperature changes are given below [37].



Previous studies have reported that ZnS oxidation begins at approximately 525 °C and that the characteristic diffraction lines of cubic ZnS disappear by approximately 600 °C as Zn -bearing transformation products are formed [38].

Overall, the thermal events observed in the TG/DTA analysis are consistent with transformations expected for the sulfide- and clay-bearing phases identified by XRD and provide a basis for interpreting the mineralogical changes observed after roasting.

3.2. Effect of Roasting on Mineral Changes and Grain Size

The solid products obtained after roasting were characterized by particle size analysis and XRD to evaluate the physical and mineralogical changes resulting from thermal treatment.

Figure 4 presents the particle size distributions of the untreated ore and the roasted products. Prior to roasting, 90% of the representative ore sample was finer than approximately 45 μm ($d_{90} \approx 45\text{ }\mu\text{m}$), with an average particle size below 8 μm . After roasting, the d_{90} values were approximately 28.0, 27.8, and 29.8 μm for the samples roasted at 220, 420, and 620 °C respectively, following the 3 s grinding step applied before leaching. This short grinding step was applied to disperse possible agglomerates, particularly clay-related

agglomerates. The particle size distributions obtained after roasting and the subsequent short grinding step were similar for all three roasting temperatures.

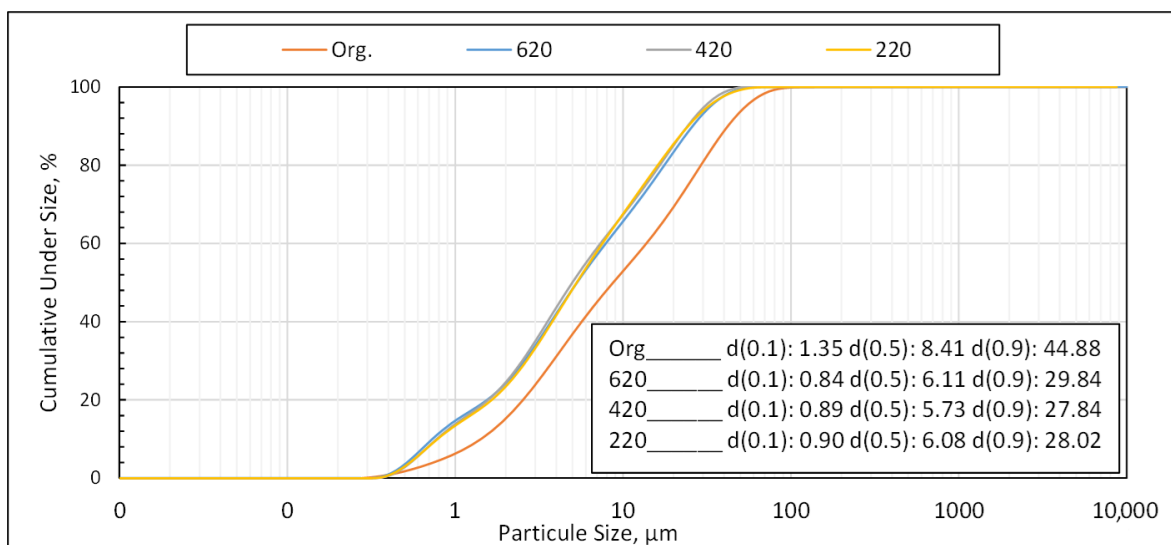


Figure 4. The particle size distribution of the ore sample and roasting products.

Figure 5 presents the XRD patterns of the untreated ore and the products roasted at 220, 420, and 620 °C. Changes in the mineral phases were observed with increasing roasting temperature. The pyrite peaks gradually decreased with increasing temperature, while the hematite peaks became more evident, especially at 620 °C. At 620 °C, the characteristic peaks of kaolinite and sphalerite were no longer detected. These changes indicate the transformation of sulfide and clay-bearing phases during roasting and are consistent with the thermal changes observed in the TG/DTA analysis (Figure 3).

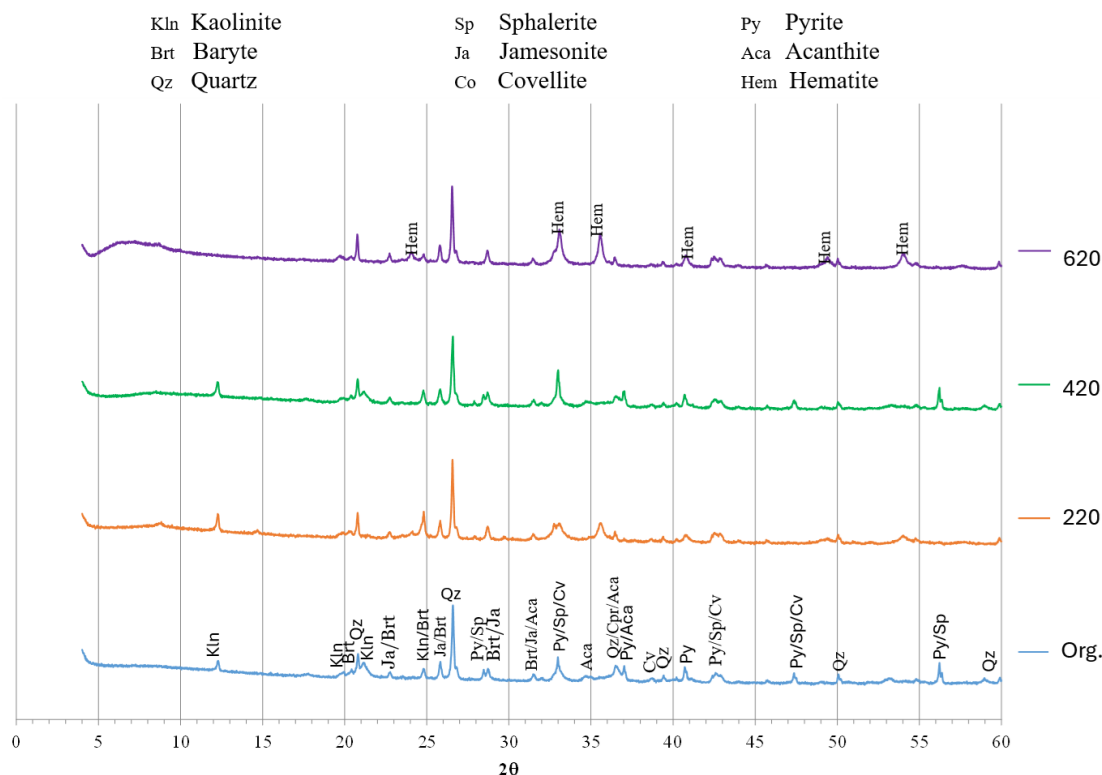


Figure 5. XRD analysis of ore sample and roasting products.

3.3. Effect of Roasting on Leaching Efficiency

Roasting can influence subsequent leaching efficiency by promoting thermal decomposition and oxidation of sulfide-bearing mineral phases. In complex ores such as the one investigated in this study, these transformations may improve the accessibility of precious metals associated with sulfide minerals during subsequent cyanidation. Therefore, the ore was roasted at 220, 420, and 620 °C prior to cyanide leaching to evaluate the effect of roasting temperature on Au and Ag recovery.

Figure 6 shows the relationship between roasting temperature and mass loss. The mass loss increased progressively with increasing roasting temperature, consistent with the thermal transformations observed by TG/DTA. This behavior may be associated with dehydration/dehydroxylation, sulfide transformation, and the release of volatile species during roasting.

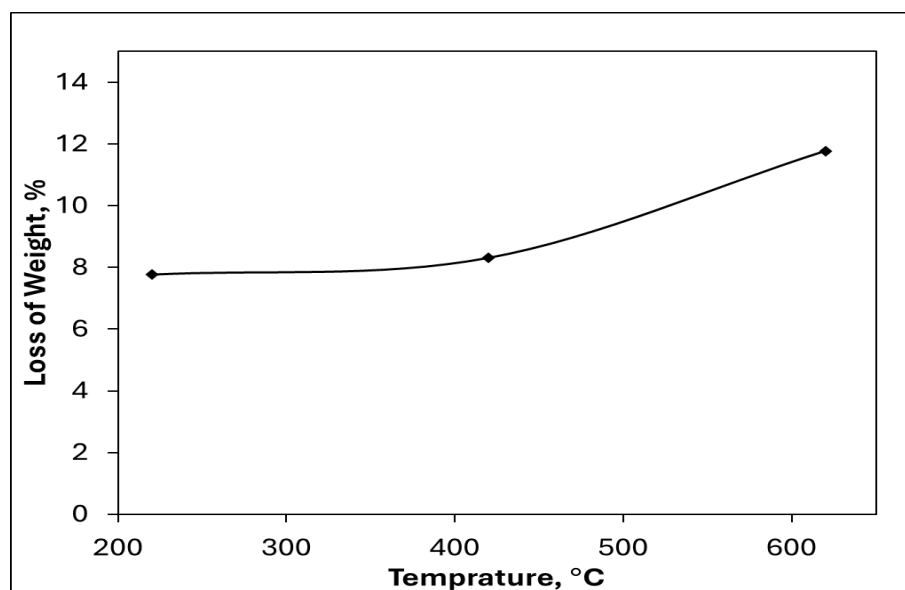
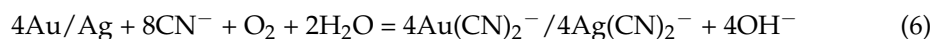
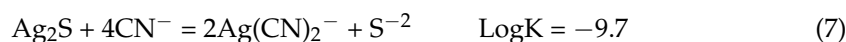


Figure 6. The relationship between weight loss (%) and roasting temperature (°C).

Gold and silver may occur together in the gold ore or concentrate and are recovered by cyanidation, which involves dissolving gold/silver in aerated cyanide solution to form gold and silver cyanide complexes [39]. The relationship between cyanide and oxygen derived from the Elsner equation is given in Reaction (6).



However, studies have shown that silver recovery is significantly lower than gold under typical cyanidation conditions, and sometimes silver recovery is only half that of gold. The different mineralogies of gold and silver in the ore are thought to be the main reason for this [39,40]. In particular, the dissolution of silver from the Ag₂S structure in cyanide solution in the absence of oxygen is described by Reaction (7) [41].



The equilibrium constant for silver sulfide dissolving in cyanide to form silver cyanide complexes and sulfide anions is too low to ensure satisfactory silver recovery. Therefore, to obtain better silver recovery, the sulfide in acanthite must be oxidized during cyanidation [39]. Therefore, the effect of the roasting process on the dissolution efficiency of Au and Ag through the oxidation of minerals in sulfur-bearing form was examined in this study.

Au recovery results according to the 15 h cyanidation leaching process after conventional cyanidation and roasting at different temperatures (220 °C, 420 °C, and 620 °C) are given in Figure 7, and Ag recovery results are given in Figure 8.

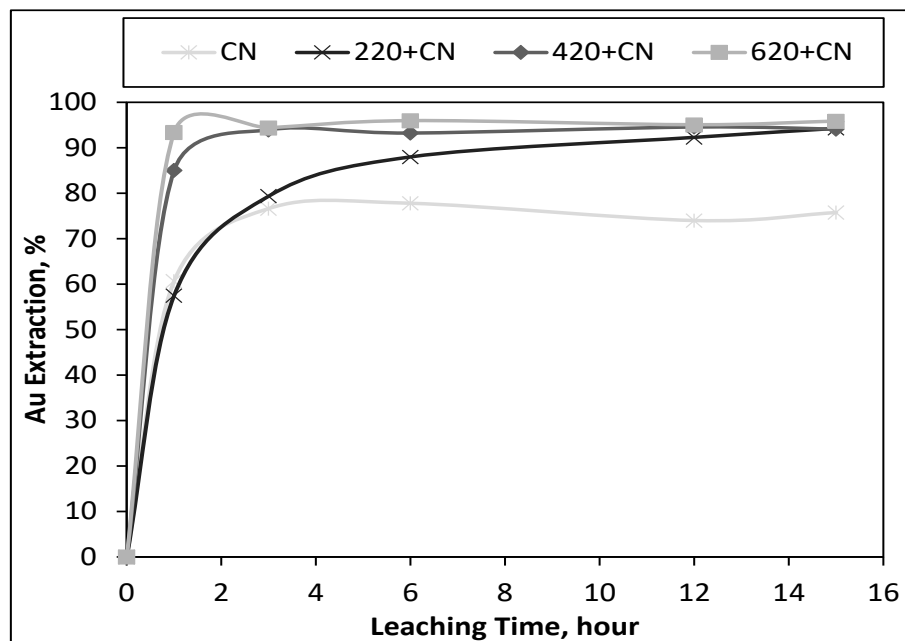


Figure 7. Recovery of gold from the complex ore by cyanidation (1.5 g/L NaCN, 15 h, pH 11, 500 rpm, and 20% solids) after roasting at different temperatures.

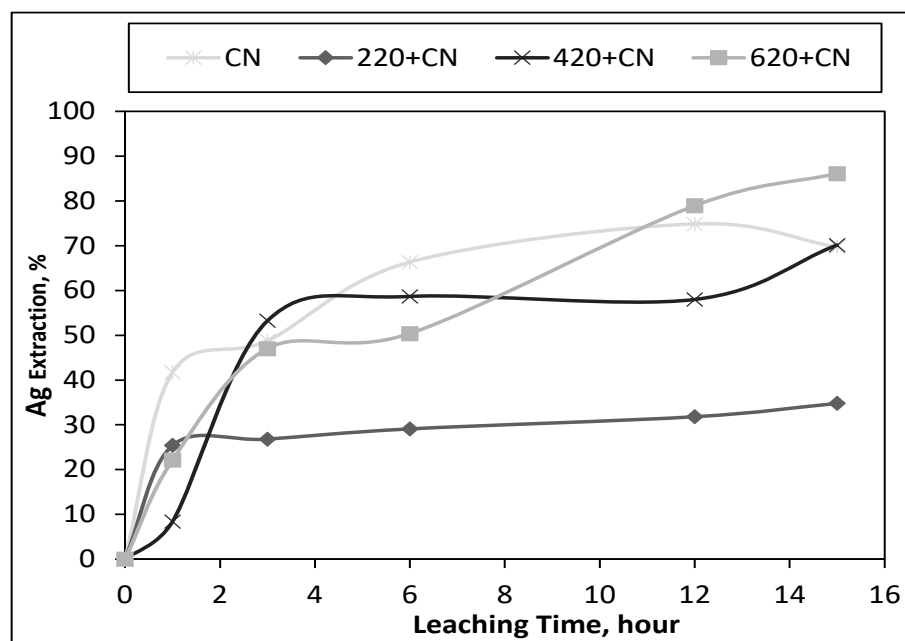


Figure 8. Recovery of silver from the complex ore by cyanidation (1.5 g/L NaCN, 15 h, pH 11, 500 rpm, and 20% solids) after roasting at different temperatures.

Figure 7 shows the gold recovery obtained after 15 h of cyanidation for the conventional process and after roasting at 220 °C, 420 °C, and 620 °C. The numerical Au recovery values at each sampling time are presented in Table 2. In the conventional cyanidation process, the maximum gold recovery reaches approximately 75%. According to the recovery-based classification proposed by La Brooy [4], gold ores showing 50%–80% recovery are

classified as moderately refractory. The approximately 75% Au recovery obtained for the untreated ore in this study therefore falls within the moderately refractory range. Similarly, Abdollahi et al. [13] reported a maximum Au recovery of 76.88% by direct cyanidation for a semi-refractory massive sulfide ore. Following roasting, a marked improvement in recovery is achieved, with 95.84% Au recovery obtained at the end of 15 h. Notably, the samples roasted at 420 and 620 °C reached approximately 94% Au recovery within the first 3 h, indicating that roasting not only increased the final recovery but also markedly accelerated the initial dissolution of gold. In contrast, the leaching process performed after roasting at 220 °C demonstrates slower initial leaching rates, with Au recovery increasing progressively over time. Nevertheless, by the end of 15 h, a recovery yield of 94% is attained. These improvements can be attributed to several roasting-related factors, including the oxidation of minerals, leading to the liberation of valuable metals [23]; the alteration of the ore's physical structure, which may have modified the particle surface and porosity [42]; and the formation of new compounds during roasting, which exhibit improved solubility in cyanide solutions [15]. During cyanide leaching of sulfide gold ores, sulfide minerals dissolve into the leach solution, forming metastable sulfide species, including sulfide, bisulfide, polysulfide, elemental sulfur, and thiocyanate. Gold exhibits a high affinity for these species in solution. Consequently, it has been reported that the gold surface often becomes passivated, reducing leaching efficiency due to interactions between various sulfide species and gold [43]. Therefore, this phenomenon may also be applicable to this ore, which contains a significant sulfur content, potentially explaining the observed low leaching efficiency. Although the mineralogical characteristics of the ore are considered an important factor in the relatively low Au recovery obtained without roasting, the influence of the applied cyanidation conditions on the measured recovery should also be considered.

Table 2. Au recovery values of untreated and roasted samples at different cyanidation times.

Cyanidation Time (h)	Etraction (%)	Etraction (%)	Etraction (%)	Etraction (%)
	Untreated	220 °C	420 °C	620 °C
1	60.65	57.48	85.00	93.34
3	76.61	79.35	93.93	94.36
6	77.77	87.99	93.23	95.94
12	73.98	92.29	94.56	95.04
15	75.73	94.26	94.08	95.84

Figure 8 shows that roasting temperature strongly governs silver recovery during subsequent cyanidation. Relative to conventional cyanidation of the untreated sample, which achieved a Ag recovery of 69.72%, roasting at 220 °C decreased recovery to 34.80%, whereas roasting at 420 °C produced only a marginal improvement, reaching 70.15%. For the untreated sample, Ag recovery reached 74.87% at 12 h and subsequently decreased slightly to 69.72% at 15 h. This decrease may be associated with the re-adsorption of dissolved Ag species. Tremolada et al. (2010) reported that clay minerals can adsorb Ag during cyanidation, with Ag adsorption capacities exceeding 80% under the investigated conditions [44]. Since kaolinite was identified in the untreated ore, such an interaction may have contributed to the observed decrease. In contrast, after 15 h of leaching, the sample roasted at 620 °C achieved 86.12% Ag recovery. These results indicate that low-temperature roasting was insufficient to improve the cyanide accessibility of the silver-bearing phases, whereas roasting at 620 °C substantially enhanced Ag recovery. The limited dissolution of Ag₂S in cyanide solution, as represented by Reaction (7), may contribute to this behavior. Similarly, Jiang, Xie, and Dreisinger reported limited leachability of

acanthite (Ag_2S) in aqueous cyanide media and showed that supplemental oxidation can promote its cyanidation [39]. In the present study, the pronounced decrease in Ag recovery after roasting at 220 °C, followed by substantially higher recovery at 620 °C, demonstrates a strong dependence of Ag leaching behavior on roasting temperature. The roasted products exhibited similar particle size distributions ($d_{90} \approx 28\text{--}30\text{ }\mu\text{m}$), whereas their Ag recoveries differed substantially, indicating that the observed differences cannot be attributed solely to particle size variations. Temperature-dependent roasting behavior has also been reported for refractory Au–Ag pyrite concentrates, with maximum Ag recovery observed at 500–600 °C, while excessive roasting temperatures may adversely affect Ag recovery through secondary mineral formation or encapsulation [23]. In the present study, the characteristic reflections assigned to acanthite remained detectable in the XRD patterns after roasting; therefore, complete transformation of this phase cannot be inferred from the available mineralogical data. Accordingly, changes in the overall sulfide mineral assemblage and mineralogical environment during roasting are suggested as possible factors influencing the observed Ag recovery behavior rather than evidence of a confirmed transformation of the Ag-bearing phase itself.

Figure 9 summarizes the final Au and Ag recovery obtained after 15 h of cyanidation. Roasting at 620 °C produced the highest recovery for both metals, reaching 95.84% Au and 86.12% Ag. In contrast, the effect of lower roasting temperatures was more pronounced for Ag, particularly at 220 °C, whereas Au recovery remained comparatively high after roasting.

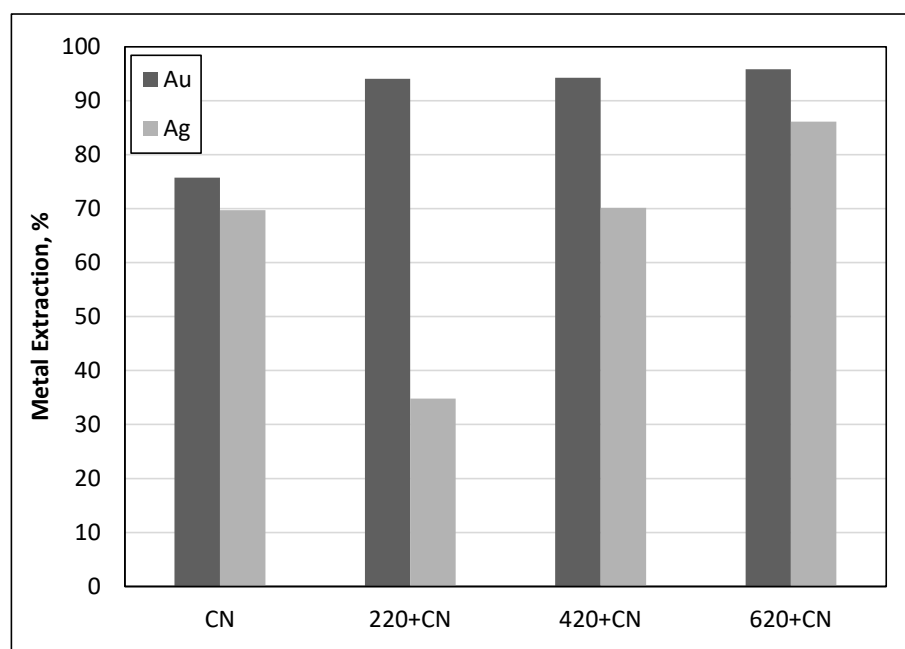


Figure 9. Recovery of gold and silver from the complex ore by cyanidation after roasting.

In the leaching study applied after roasting, it was determined that cyanide consumption decreases as roasting temperature increases [15]. Figure 10 shows that NaCN consumption was not substantially reduced after roasting at 220 and 420 °C, whereas a pronounced decrease was observed at 620 °C. When evaluated together with Figures 8 and 9, the highest Au and Ag recoveries coincide with the lowest NaCN consumption at 620 °C. The highest recovery yields (95.84% Au and 86.12% Ag) and the lowest cyanide consumption (a total of 6.5 kg NaCN/ton of ore) are achieved at 620 °C. Chen et al. [45] reported a cyanide consumption of 84.68 kg/t ore during cyanidation of a complex sulfide concentrate. However, their experiments were conducted using a considerably higher initial NaCN concentration (0.50 mol/L) (approximately 24.5 g/L) and a longer leaching time (24 h).

Therefore, this value is not directly comparable with the present results, but it illustrates the potentially high cyanide demand of complex sulfide ores. Sulfide minerals such as chalcopyrite (CuFeS_2), pyrite (FeS_2), and sphalerite (ZnS) may consume cyanide through side reactions, thereby potentially resulting in insufficient cyanide and/or oxygen to effectively leach gold [45]. The results of this study suggest that roasting-induced transformations of sulfide minerals contributed to the improved Au and Ag recovery and reduced NaCN consumption observed at 620 °C.

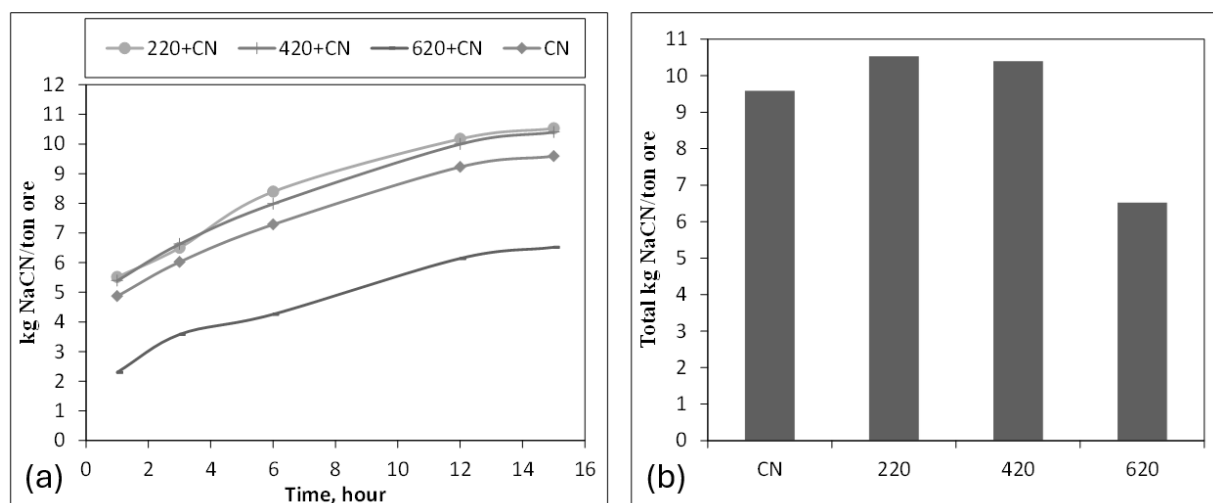


Figure 10. Cyanide consumption (kg NaCN/ton ore) in cyanidation after roasting: (a) a period of 15 h; (b) total consumption.

4. Conclusions

Complex gold and silver ores generally exhibit low metal recovery rates in conventional cyanidation due to their semi-refractory mineralogy. This study investigated the effect of roasting as a thermal pretreatment on the processability of such complex ores. The roasting process promoted the transformation of sulfide minerals in the ore, thereby improving the accessibility of precious metals during subsequent cyanidation. Roasting at 220, 420, and 620 °C resulted in pronounced changes in the mineralogical characteristics of the ore. Notably, the characteristic XRD reflections of kaolinite and sphalerite were no longer detected at 620 °C, while the disappearance of pyrite reflections together with the appearance of hematite indicated extensive transformation of the Fe-bearing sulfide phase. These mineralogical changes were associated with improved precious-metal recovery during subsequent cyanidation.

Cyanidation after roasting increased Au recovery from approximately 75% for the untreated ore to 95.84% after roasting at 620 °C and leaching for 15 h. For the samples roasted at 420 and 620 °C, approximately 94% Au recovery was achieved within the first 3 h, indicating faster initial gold dissolution. Ag recovery showed a stronger dependence on roasting temperature, decreasing from 69.72% for the untreated ore to 34.80% after roasting at 220 °C, remaining nearly unchanged at 70.15% after roasting at 420 °C, and increasing to 86.12% after roasting at 620 °C following 15 h of cyanidation. These findings demonstrate that the response of Ag to roasting was strongly temperature-dependent. In particular, the pronounced decrease in Ag recovery at 220 °C suggests that low-temperature treatment was insufficient to promote favorable transformation of Ag-bearing sulfide phases, whereas the highest Ag recovery was obtained after roasting at 620 °C. Additionally, the lowest NaCN consumption (6.5 kg/t ore) was observed at 620 °C, coinciding with the highest Au and Ag recovery.

Overall, the results suggest that roasting-induced mineralogical transformations at 620 °C improved the cyanidation performance of the investigated ore by enhancing Au and Ag recovery while reducing NaCN consumption. However, the study is limited to batch-scale laboratory conditions and does not address continuous industrial processing challenges such as energy costs, scaling effects and ore heterogeneity. Although roasting at 620 °C would require higher thermal-energy input than lower roasting temperatures, it produced the highest Au (95.84%) and Ag (86.12%) recoveries and the lowest NaCN consumption (6.5 kg NaCN/t ore). These metallurgical benefits should therefore be considered together with the additional energy requirement when selecting the roasting temperature. Future pilot-scale studies, including energy consumption, reagent costs, and off-gas treatment requirements, would be useful for determining the most economically suitable roasting conditions.

Future research should investigate the feasibility of this approach at pilot or industrial scales, particularly in continuous-flow systems. Future studies should also evaluate alternative or energy-efficient thermal pretreatment strategies and assess their effects on mineralogical transformations, reagent consumption, and overall process performance.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The author would like to thank ETİ Bakır A.Ş. in Artvin, Türkiye, for the sample supply, as well as the managers of the Karadeniz Technical University Mining Engineering Department for the provision of laboratory facilities for the experiments.

Conflicts of Interest: The author declares no conflicts of interest.

References

1. Hapid, A.; Zullaikah, S.; Mahfud, M.; Kawigraha, A.; Azmi, M.U.; Haryanto, I.; Soewoto, H.P.; Go, A.W.; Assabumrungrat, S. Optimization of Microwave-Assisted Roasting: Box-Behnken Design for Oxidation of Sulfide Minerals and Control of Atmospheric Sulfur in Refractory Gold Ore Pretreatment. *Case Stud. Chem. Environ. Eng.* **2024**, *10*, 100826. [\[CrossRef\]](#)
2. Torres, R.; Lapidus, G.T. Base Metal Citrate Pretreatment of Complex Ores to Improve Gold and Silver Leaching with Thiourea. *Hydrometallurgy* **2020**, *197*, 105461. [\[CrossRef\]](#)
3. Adams, M.D. Advances in Gold Ore Processing. In *Developments in Mineral Processing*; Elsevier: Amsterdam, The Netherlands, 2005.
4. La Brooy, S.R.; Linge, H.G.; Walker, G.S. Review of Gold Extraction from Ores. *Miner. Eng.* **1994**, *7*, 1213–1241. [\[CrossRef\]](#)
5. Yoğurtcuoğlu, E.; Alp, İ. The Effect of Roasting on the Mineralogical Structure and Cyanidation Performance of Gossan Type Oxidized Refractory Gold-Silver Ores. *Min. Metall. Explor.* **2023**, *40*, 1667–1679. [\[CrossRef\]](#)
6. Peng, K.; Gao, L.; Rao, B.; Gong, Z.; Shen, H.; Gao, G.; He, F.; Zhang, M. Research Progress of Non-Cyanide Gold Leaching in Gold Mines. *Chin. J. Eng.* **2021**, *43*, 871–882.
7. Ahtiainen, R.; Liipo, J.; Lundström, M. Simultaneous Sulfide Oxidation and Gold Dissolution by Cyanide-Free Leaching from Refractory and Double Refractory Gold Concentrates. *Miner. Eng.* **2021**, *170*, 107042. [\[CrossRef\]](#)
8. Gui, Q.; Hu, Y.; Wang, S.; Zhang, L. Mechanism of Synergistic Pretreatment with Ultrasound and Ozone to Improve Gold and Silver Leaching Percentage. *Appl. Surf. Sci.* **2022**, *576*, 151726. [\[CrossRef\]](#)
9. Piervandi, Z. Pretreatment of Refractory Gold Minerals by Ozonation before the Cyanidation Process: A Review. *J. Environ. Chem. Eng.* **2023**, *11*, 109013. [\[CrossRef\]](#)
10. Khalid, M.; Larachi, F.; Adnot, A. The Role of Silver Minerals on the Cyanidation of Gold Particles Embedded within Multi-Sulphidic Mineral Matrices. *Can. J. Chem. Eng.* **2018**, *96*, 2299–2307. [\[CrossRef\]](#)
11. Celep, O.; Yazici, E.Y.; Altinkaya, P.; Deveci, H. Characterization of a Refractory Arsenical Silver Ore by Mineral Liberation Analysis (MLA) and Diagnostic Leaching. *Hydrometallurgy* **2019**, *189*, 105106. [\[CrossRef\]](#)
12. Asamoah, R.K.; Skinner, W.; Addai-Mensah, J. Pulp Mineralogy and Chemistry, Leaching and Rheological Behaviour Relationships of Refractory Gold Ore Dispersions. *Chem. Eng. Res. Des.* **2019**, *146*, 87–103. [\[CrossRef\]](#)
13. Abdollahi, H.; Karimi, P.; Amini, A.; Akcil, A. Direct Cyanidation and Roasting Combination of a Semi-Refractory Massive Sulfide Ore. *Miner. Metall. Process.* **2015**, *32*, 161–169. [\[CrossRef\]](#)

14. Kamariah, N.; Kalebic, D.; Xanthopoulos, P.; Blannin, R.; Araujo, F.P.; Koelewijn, S.F.; Dehaen, W.; Binnemans, K.; Spoor, J. Conventional versus Microwave-Assisted Roasting of Sulfidic Tailings: Mineralogical Transformation and Metal Leaching Behavior. *Miner. Eng.* **2022**, *183*, 107587. [\[CrossRef\]](#)
15. Lin, Y.; Hu, X.; Zi, F.; Chen, Y.; Chen, S.; Li, X.; Li, J.; Jiang, Y.; Zhang, Y. Rapid Gold Cyanidation from a Sulfur-High and Arsenic-High Micro-Fine Concentrate via Facile Two-Stage Roasting Pre-Treatment. *Miner. Eng.* **2022**, *190*, 107938. [\[CrossRef\]](#)
16. Qin, H.; Guo, X.; Tian, Q.; Yu, D.; Zhang, L. Recovery of Gold from Sulfide Refractory Gold Ore: Oxidation Roasting Pretreatment and Gold Extraction. *Miner. Eng.* **2021**, *164*, 106822. [\[CrossRef\]](#)
17. Yang, W.; Wang, Q.; Wang, Y.; Long, T.; Deng, S. Effects of Pyrite, Quartz and Sodium Sulfite on Roasting of a Refractory Sulfide Concentrate and Gold, Silver, Copper Leaching during Cyanidation. *Hydrometallurgy* **2024**, *226*, 106306. [\[CrossRef\]](#)
18. Bas, A.D.; Zhang, W.; Ghali, E.; Choi, Y. A Study of the Electrochemical Dissolution and Passivation Phenomenon of Roasted Gold Ore in Cyanide Solutions. *Hydrometallurgy* **2015**, *158*, 1–9. [\[CrossRef\]](#)
19. Kim, B.J.; Cho, K.H.; Lee, S.G.; Park, C.Y.; Choi, N.C.; Lee, S. Effective Gold Recovery from Near-Surface Oxide Zone Using Reductive Microwave Roasting and Magnetic Separation. *Metals* **2018**, *8*, 957. [\[CrossRef\]](#)
20. Yoğurtcuoğlu, E. Investigation of the Effect of Cyanidation after Microwave Roasting Treatment on Refractory Gold/Silver Ores by Characterization Studies. *Physicochem. Probl. Miner. Process.* **2023**, *59*, 157487. [\[CrossRef\]](#)
21. Hansen, J.P.; Jensen, L.S.; Wedel, S.; Dam-Johansen, K. Decomposition and Oxidation of Pyrite in a Fixed-Bed Reactor. *Ind. Eng. Chem. Res.* **2003**, *42*, 4290–4295. [\[CrossRef\]](#)
22. Haga, K.; Altansukh, B.; Shibayama, A. Volatilization of Arsenic and Antimony from Tennantite/Tetrahedrite Ore by a Roasting Process. *Mater. Trans.* **2018**, *59*, 1396–1403. [\[CrossRef\]](#)
23. Zhang, Y.P.; Yang, K.; Fang, Y.; Robledo-Cabrera, A.; Peng, C.S.; Lopez-Valdivieso, A. Roasting Temperature Effect on the Recovery of Refractory Gold and Silver in Pyrite Concentrates. *J. Min. Metall. Sect. B Metall.* **2021**, *57*, 235–243. [\[CrossRef\]](#)
24. Li, H.; Xiao, W.; Jin, J.; Han, Y. Oxidation Roasting of Fine-Grained Carbonaceous Gold Ore: The Effect of Aeration Rate. *Minerals* **2021**, *11*, 558. [\[CrossRef\]](#)
25. Akpınar, İ.; Çiftçi, E. Ore Mineralogical Study of Cerattepe Au-Cu (–Zn) VMS Deposit (Artvin-Turkey). In Proceedings of the 14th International Congress for Applied Mineralogy (ICAM2019), Belgorod, Russia, 23–27 September 2019; pp. 7–10.
26. Ucurum, A.; Demir, C.S.; Otlı, N.; Ertürk, M.; Ekici, T.; Kirk, J.; Ruiz, J.; Mathur, R.; Arehart, G.B. Re-Os Age and Stable Isotope (O-h-s-Cu) Geochemistry of North Eastern Turkey's Kuroko-Type Volcanogenic Massive Sulfide Deposits: An Example from Cerattepe-Artvin. *Minerals* **2021**, *11*, 226. [\[CrossRef\]](#)
27. Seyrankaya, A.; Yontar, U.; Canbazoglu, M.; Özel, G.; Kabaloğlu, S. Beneficiation of Artvin-Cerattepe Copper-Zinc Ore by Flotation. *Physicochem. Probl. Miner. Process.* **2023**, *59*, 167499. [\[CrossRef\]](#)
28. Warr, L.N. IMA–CNMNC Approved Mineral Symbols. *Mineral. Mag.* **2021**, *85*, 291–320. [\[CrossRef\]](#)
29. Turan, A. Fire Assay Optimization of Keban Region Pyritic Refractory Gold Ores. Master's Thesis, Istanbul Technical University, Istanbul, Türkiye, 2009.
30. Arham, L.O.; Mufakhir, F.R.; Putri, I.A.; Wahab; Hakim, H.Z.; Handoko, A.S. Sudibyo Characterization of Gold Ore from Babakan Loa Sub-District and Leaching Study in Cyanide Solution. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *882*, 012027. [\[CrossRef\]](#)
31. Surimbayev, B.; Yessengarayev, Y.; Khumarbekuly, Y.; Bolotova, L.; Kanaly, Y.; Akzharkenov, M.; Zhumabai, S. Effect of Sodium Acetate Additive on Gold Leaching with Cyanide Solution: Laboratory and Semi-Pilot Leaching Tests. *Heliyon* **2024**, *10*, e35805. [\[CrossRef\]](#)
32. Aydın, B.; Basturkcü, H.; Gül, A. Influence of Pre-Aeration on Cyanide Leaching of a Non-Refractory. *Physicochem. Probl. Miner. Process.* **2015**, *51*, 647–660.
33. Foldvari, M. *Handbook of Thermogravimetric System of Minerals and Its Use in Geological Practice*; Occasional Papers of the Geological Institute of Hungary; Geological Institute of Hungary: Budapest, Hungary, 2011; Volume 213, 180p.
34. Hu, G.; Dam-Johansen, K.; Wedel, S.; Hansen, J.P. Decomposition and Oxidation of Pyrite. *Prog. Energy Combust. Sci.* **2006**, *32*, 295–314. [\[CrossRef\]](#)
35. Xu, H.; Guo, X.; Seaman, L.A.; Harrison, A.J.; Obrey, S.J.; Page, K. Thermal Desulfurization of Pyrite: An in Situ High-T Neutron Diffraction and DTA-TGA Study. *J. Mater. Res.* **2019**, *34*, 3243–3253. [\[CrossRef\]](#)
36. Zhang, Y.; Li, Q.; Liu, X.; Xu, B.; Yang, Y.; Jiang, T. A Thermodynamic Analysis on the Roasting of Pyrite. *Minerals* **2019**, *9*, 220. [\[CrossRef\]](#)
37. Sarapajevaite, G.; Baltakys, K. Thermal Stability and Decomposition Mechanism of Synthetic Covellite Samples. *J. Therm. Anal. Calorim.* **2022**, *147*, 10951–10963. [\[CrossRef\]](#)
38. Perraud, I.; Ayral, R.M.; Cammarano, C.; Rouessac, F.; Hulea, V.; Ayral, A. Sulfidation and Sulfur Capacity of Fine ZnO Powder Derived from Thermal Oxidation of Mechanothesized ZnS Powder. *Chem. Eng. J.* **2014**, *241*, 360–365. [\[CrossRef\]](#)
39. Jiang, H.; Xie, F.; Dreisinger, D.B. Comparative Study of Auxiliary Oxidants in Cyanidation of Silver Sulfide. *Hydrometallurgy* **2015**, *158*, 149–156. [\[CrossRef\]](#)

40. Xie, F.; Dreisinger, D.B. Use of Ferricyanide for Gold and Silver Cyanidation. *Trans. Nonferrous Met. Soc. China (Engl. Ed.)* **2009**, *19*, 714–718. [[CrossRef](#)]
41. Xie, F.; Dreisinger, D.B. Leaching of Silver Sulfide with Ferricyanide-Cyanide Solution. *Hydrometallurgy* **2007**, *88*, 98–108. [[CrossRef](#)]
42. Rzepa, G.; Bajda, T.; Gawel, A.; Debiec, K.; Drewniak, L. Mineral Transformations and Textural Evolution during Roasting of Bog Iron Ores. *J. Therm. Anal. Calorim.* **2016**, *123*, 615–630. [[CrossRef](#)]
43. Kim, R.; Ghahreman, A. A Mechanism of Metastable Sulfur Speciation and the Adsorption on a Gold Surface in the Presence of Sulfidic Ore and Lead in Cyanide Medium. *Hydrometallurgy* **2020**, *193*, 105294. [[CrossRef](#)]
44. Tremolada, J.; Dzioba, R.; Bernardo-Sánchez, A.; Menéndez-Aguado, J.M. The Preg-Robbing of Gold and Silver by Clays during Cyanidation under Agitation and Heap Leaching Conditions. *Int. J. Miner. Process.* **2010**, *94*, 67–71. [[CrossRef](#)]
45. Chen, J.; Xie, F.; Wang, W.; Fu, Y.; Wang, J. Leaching of Gold and Silver from a Complex Sulfide Concentrate in Copper-Tartrate-Thiosulfate Solutions. *Metals* **2022**, *12*, 1152. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.