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MAA conceived and designed the study; MAA and NAA supervised the research project and contributed to data analysis and drafting the manuscript; YMSJ and FT co-supervised the experimental design and assisted in the analysis and drafting the manuscript; AM, AK, AA, DA, GA, HAK, HAZ, HE, MA, OA, and TK performed the laboratory experiments, conducted the mechanochemical leaching, prepared the samples for ICP-OES and XRD analysis, and assisted in data collection.

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Chemical Method for Zinc Separation from Ores: Mineral Potential of the Jabali Zinc Deposit from Yemen

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Abstract:

This study examined the mechanochemical leaching method for extracting zinc from Yemeni sphalerite ores, emphasizing both efficiency and environmental sustainability. As high-grade zinc ores decline, it is essential to develop cost-effective and ecofriendly extraction techniques. The research utilizes mechanical activation with a stirring ball mill using stainless steel or corundum balls, alkaline leaching (5 M NaOH at 90°C), and lead carbonate additives to improve zinc recovery. The ores were analyzed via X-ray diffraction (XRD) and infrared (IR) spectroscopy to confirm the presence of zinc in the dolomite samples. Zinc extraction was assessed using ICP-OES, with a calculated leaching efficiency of 0.7%. The study underscores Yemen's mineral potential, particularly in sphalerite-rich basalt rocks, and aims to optimize extraction processes while minimizing environmental impact. Results demonstrate that mechanochemical leaching surpasses traditional methods, presenting a viable approach for sustainable zinc production. These findings could enhance local mineral development and contribute to global zinc supply chains.

Keywords: Mechanochemical leaching, X-ray diffraction (XRD) and infrared (IR) spectroscopy, Yemeni sphalerite ores, Zinc.

INTRODUCTION

Mineral substances are defined as naturally occurring, inorganic compounds that consist of one or more metallic elements combined with non-metallic elements, such as oxygen or sulfur (Klein and Dutrow, 2007; Miller, 2017; Chandra, 2025). These compounds are typically solid and crystalline, characterized by a defined composition that may vary within specific limits, alongside distinct physical properties (Upadhyay, 2025) and vast range of applications (Ali *et al.,* 2020a,b; Iqbal and Ashraf, 2020; Zafar and Fatima, 2018). In contrast, an ore is a naturally occurring aggregation of these mineral substances from which valuable metals or minerals can be economically extracted (Deer *et al.,* 2013). Ores exhibit considerable variations in their composition, physical attributes, and chemical characteristics, making them critical resources for metal extraction (Robb, 2005; Kursunoglu, 2025). The primary source of metals and their compounds is found in ore deposits within the Earth's crust, although metals can also be obtained from ocean waters and recycled materials (Pirajno, 2009; Iqbal *et al.,* 2019; Hein *et al.,* 2020).

In Yemen, significant mineral occurrences include deposits of gold, lead, zinc, copper, silver, nickel, iron, titanium, rare earth elements, tungsten, tin, and radioactive elements (Klein and Dutrow, 2007). Specifically, fewer than twenty zinc-lead mineral occurrences have been identified, mostly along rift system margins, such as the Sab'atayn basin, or within affected fault blocks (Deer *et al.,* 2013). The lead and zinc ore deposits in the Sab'atayn basin are predominantly hosted by Jurassic to Paleocene carbonate rock formations, formingclusters in the Jabali and Tabaq areas (Figure 1) (Pirajno, 2009).

Despite these resources, the mining industry in Yemen remains underdeveloped, except for the extraction of rock salt from the Salif area, which produces several thousand tons annually. The Jabali area, in particular, features several ore concentrations within Jurassic-aged Amran Group carbonate rocks, making it a focal point for potential mineral exploitation (Pirajno, 2009). The geological setting suggests that mineralization is associated with tectonic rifting processes, highlighting its economic and strategic importance for Yemen's mining sector (Misra, 2000).

Fig.1. Rocks view of the wadi jabali.

Given these considerations, the objective of this study is to evaluate the mineral potential of the Jabali zinc deposit and to explore the implications of its geological characteristics for future mining and extraction activities in Yemen.

MATERIALS AND METHODS

The extraction of zinc from its ores involves several key materials and processes.

Materials

Ores: The primary ore of zinc is sphalerite (zinc sulfide, ZnS). In this study, a rock sample containing zinc ore, specifically within a dolomite (Figure 2) was obtained from the Radhrad Mine located on the northern slope of Mount Salb – Nahm, through Dr. Khaled Al.Selwi from the Faculty of Petroleum and Natural Resources.

Fig. 2. Rock sample of dolomite.

Reagents

- Sodium hydroxide (NaOH)

- Lead carbonate ($PbCO_3$)

- Distilled water

Physical Preparation of the Sample

The sample was crushed using a hammer into small pieces and further pulverized with a pestle. The sample was then placed in a rock grinding machine to obtain a fine powder. After obtaining the fine powder it was placed in the mechanical activation device.

Chemical Mechanization Process

The chemical mechanization process was conducted through mechanochemical leaching experiments performed in a stirring ball mill (Hein *et al.,* 2020). The parameters for this process included:

- Activation Medium: 5 mm stainless steel balls or corundum balls.Ball-to-Raw Material Mass Ratio: 30:1.
- Sodium Hydroxide Concentration: 5 mol/L.
- Temperature: 90 °C, with a constant volume maintained by the addition of water.

Lead carbonate was added as an additive during the mechanochemical leaching experiments to enhance the extraction efficiency of zinc from sphalerite.

Steps of Chemical Analysis

1. Preparation of Sodium Hydroxide Solution:

- 100 grams of sodium hydroxide were crushed and weighed.

- The sodium hydroxide was dissolved in 500 ml of deionized water.

- The solution was added to a 500 ml round flask containing the sample.

- The mixture was refluxed at 90 °C.

- 3 grams of lead carbonate were added, and the mixture was left to reflux for four hours.

- The sample was then filtered to separate the solid and liquid phases.

- The clear liquid phase was diluted and analyzed using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) to determine the concentration of zinc.

X-Ray Diffraction (XRD) Analysis

The X-ray powder diffraction patterns of the compounds were obtained using XD-2 (Shimadzu ED-720) powder X-ray diffractometer at a voltage of 35 kV and a current of mA using CuK(α) radiation in the range of $5^o < 2\theta < 70^o$ at 1^o min^{-1} scanning rate and a wavelength of 1.54056 A^o, at Yemen Geological Survey and Mineral Resources Board. The XRD machine settings were adjusted according to the requirements for dolomite. The sample was subjected to X-ray radiation, and the diffracted beams were detected over a range of angles (2θ). The intensity of the diffracted X-rays was collected to generate a diffraction pattern (Klug and Alexander, 1974; Zhang *et al.,* 2016).

Infrared (IR) Spectroscopy

The FT-IR spectra (400-4000 cm^{-1}) of the investigated compounds were reported as KBr discs by using (FT/IR-140, Jasco, Japan) at Sana'a University. IR spectroscopy was employed to analyze the dolomite rock, particularly to identify functional groups such as carbonate ions. By examining specific absorption bands, insights into the mineral composition and formation conditions were obtained (Farmer, 1974; Griffith, 1983; Jenkins and Snyder, 1996).

Chemical Analysis Post-Leaching

After leaching, the pulp was filtered, and the clear liquid phase was analyzed using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) at the General

Organization for Standardization and Metrology. The method involved:

- Taking 10 ml of the sample into a Teflon vessel.

- Adding 3.5 ml of 65% nitric acid and 1 ml of 30% hydrogen peroxide.

- Closing the Teflon vessel and placing it in a microwave oven, with one vessel serving as a blank.

- Operating the microwave at 200 °C for 30 minutes to digest organic substances.

- After cooling, the solution was transferred to a 50 ml volumetric flask and diluted with deionized water.

These methods collectively facilitate the efficient extraction and analysis of zinc from its ores, ensuring accurate results and optimal recovery of the metal.

RESULTS AND DISCUSSION

The sample was taken from the Radhrad mine that was obtained through Dr. Khaled Al.Selwi from Petroleum College. The sample was ground and finely ground to a homogeneous powder and its weight, which was 224 grams, was measured at the Petroleum College. The IR spectrum showed a prominent absorption band around 1375 cm^{-1}, attributed to the bending vibration of the carbonate ion (CO_3^{2-}). Additional peaks near 850 cm^{-1} correspond to the out-of-plane bending of the C-O bonds (Bandfield *et al.,* 2003; Mastandrea *et al.,* 2011). The observed peaks match well with literature values for zinc carbonate, confirming the presence of carbonate functional groups. A weak band near 1640 cm^{-1} suggests the presence of water, possibly indicating some level of hydration in the sample (Mastandrea *et al.,* 2011) as shown in the figure (3).

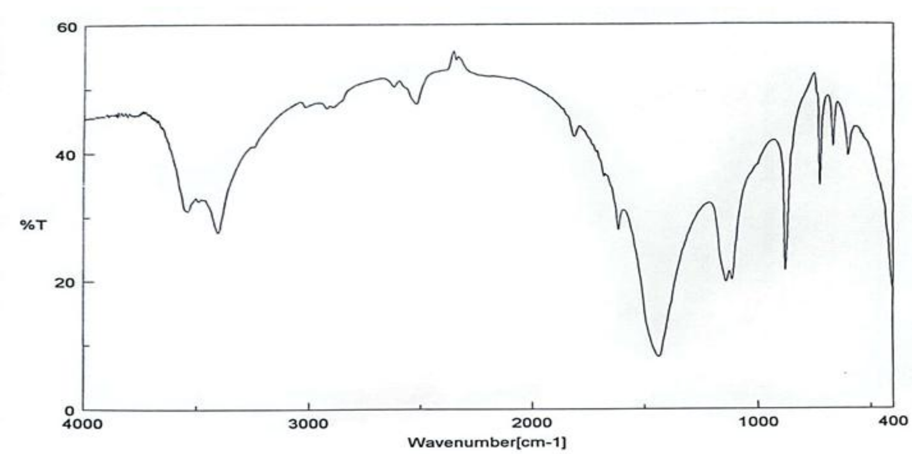

Fig.3. IR spectrum of dolomite rock.

The XRD pattern (Figure 4) of the zinc carbonate sample exhibited characteristic peaks corresponding to the mineral smithsonite ($ZnCO_3$). The principal peaks observed at 2θ values of approximately 24.1°, 28.5°, and 36.3° align with standard reference patterns for zinc carbonate.

Then the homogenized sample was taken to the College of Science laboratories for chemical separation. It used Sodium hydroxide (5 M) for the separation and lead carbonate was added to increase the separation efficiency and was heated at 90 °C for five hours in a hot plate with continuous stirring. Then the precipitate was separated from the filtrate and the filtrate containing zinc was taken to the General Authority for Specifications and Metrology to estimate zinc using a device ICP-OES (Joca *et al.,* 2019; Marguí *et al.,* 2022), which showed that the percentage of zinc in the sample is equal to 0.7% (Figure 5) which is a good result compared to the original sample weight.

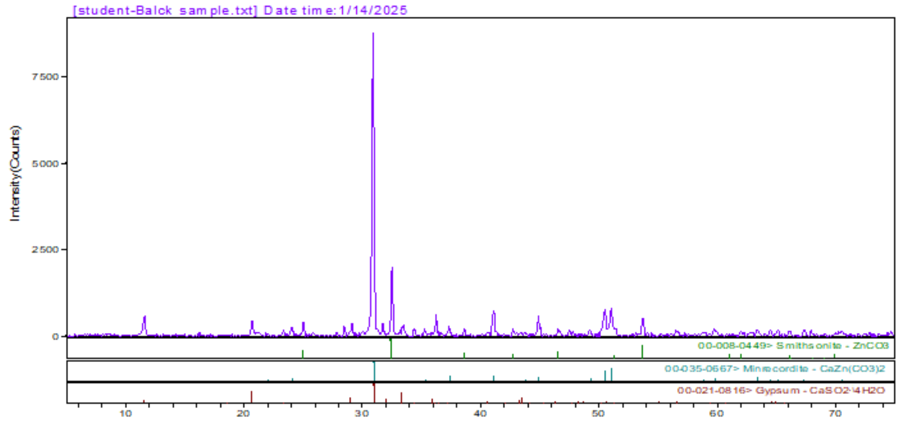

Fig. 4. XRD of dolomite rock.

مختبرات
الهيئة اليمنية للمواصفات والمقاييس وضبط الجودة
YSMO LABORATORIES
RECORD ID:

تقرير نهائي

تقرير فحص مستخلص قلوي لعينة صخرية ( )

العلامة التجارية: --- رقم الدفعة: ---- كود العينة: توجيه رقم
تاريخ الإنتاج: --- الوزن أو الحجم: --- خدمة الجمهور:
تاريخ الانتهاء: --- تاريخ بدء التحليل 2025/01/21 الغرض من الفحص: ---
مصدر العينة تاريخ انتهاء التحليل 2025/01/25 تاريخ وصول العينة: 2025/01/20

م	اسم الفحص	الوحدة	النتيجة	طريقة الفحص	الحالة
1	تقدير الزنك Zn	%	0.70	IL-AM-01	

Fig. 5. Laboratory report for Zinc determination.

CONCLUSION

Through this investigation, despite the small size of the sample provided by the Faculty of Petroleum, a concentration of 0.7% zinc was successfully obtained. The results highlight the efficiency of the mechanochemical extraction steps.

FUTURE RECOMMENDATIONS

Mechanical Activation: Optimize grinding parameters and explore additional additives.

Chemical Extraction: Improve sodium hydroxide use and investigate alternative solvents and lead carbonate effects.

Impact Assessment: Conduct life cycle and economic feasibility analyses.

Scale-Up: Test on other zinc ores and conduct pilot studies.

Collaboration: Partner with research institutions and mining companies.

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CONFLICT OF INTEREST

Authors of this article wish to declare that there is no potential conflict of interest.

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