gical environments, while the petrographic characteristics reveal materials capable of withstanding intense thermal conditions.

One of the main contributions of the article is its reconstruction of the functional role of the clay nails. Their form, darkened tips, and likely vertical placement suggest that they served as collectors of zinc vapor during the extraction process. This interpretation highlights the ingenuity of ancient craftsmen in designing tools that matched the physical and chemical behavior of zinc-bearing ores. The study also underscores the importance of calamine, whose properties made it suitable for a controlled extraction method at comparatively lower temperatures.

More broadly, the article demonstrates that ancient Iranian metallurgists possessed a sophisticated understanding of materials and furnace technology. The evidence presented here enriches our knowledge of early zinc production and reveals a technical tradition grounded in experimentation, adaptation, and practical mastery. As a result, the research makes an important contribution to both archaeology and the history of science, showing that ancient metallurgical innovation in Iran was more advanced and systematic than previously assumed.

dustrial procedure. The clay material served as a practical medium for condensation and collection, demonstrating an ingenious use of locally available resources. Such a system reflects a high degree of experimental knowledge and adaptation to the chemical behavior of zinc at elevated temperatures.

3. Chemical Evidence and Metallurgical Signatures

Chemical analysis provides some of the strongest support for the identification of these artifacts as part of an ancient zinc-production system. The samples from NBB-01 to NBB-04 contain measurable amounts of zinc, along with lead, iron, copper, and, in smaller quantities, calcium, manganese, silver, and cobalt. The presence of zinc is especially important because it directly confirms contact with zinc-bearing vapors or residues. Rather than being ordinary ceramic objects, the clay nails exhibit metallurgical signatures that reveal their role in the extraction environment. Lead and copper may reflect impurities present in the ore or furnace charge, while iron likely derives from both the surrounding geology and the thermal conditions of the operation. The trace elements suggest that the materials were exposed to a complex chemical environment shaped by mineral impurities, furnace design, and oxidation-reduction processes. In this respect, the chemical data transform the clay nails from typological objects into direct evidence of ancient technological performance.

4. Petrographic Features and Ceramic Fabric

Petrographic analysis adds another layer of understanding by revealing the internal fabric and mineral inclusions of the clay nails. The study reports porphyritic textures or quartz phenocrysts, indicating that the clay bodies were made from raw materials containing visible mineral grains and were not highly refined. These characteristics may have improved thermal resistance during furnace use. The petrographic results also help explain how the artifacts withstood high-temperature conditions while still functioning within the extraction system. Their ceramic composition appears to have been deliberately suited to repeated heating and exposure to reactive furnace gases. This points to an empirical understanding of material performance in ancient workshop practice. The petrographic evidence, therefore, complements the chemical results by showing that the clay nails were not only chemically involved in zinc recovery but also mechanically and thermally adapted to the demands of the process.

5. Technological Significance of Calamine-Based Zinc Extraction

The article emphasizes that the use of calamine was a particularly effective strategy because it decomposes more easily at relatively lower temperatures than some other zinc-bearing materials. This made it possible to extract zinc through a controlled sublimation process without requiring the advanced apparatus of modern metallurgy. The method reflects a deep practical understanding of ore behavior, furnace temperature, and vapor capture. In this system, the furnace and the clay nails worked together as parts of a coordinated technological sequence. The choice of calamine suggests that ancient metallurgists were not merely exploiting metal ores in a general sense; they were applying a specific and optimized technique tailored to zinc chemistry. This is one of the most remarkable aspects of the study, because it shows that ancient Iranian metallurgists had developed a specialized extraction method based on observation, experimentation, and accumulated craft knowledge.

6. Broader Implications for Ancient Iranian Metallurgy

The findings collectively demonstrate that ancient Iran possessed a highly developed metallurgical tradition capable of sophisticated non-ferrous metal production. The clay nails provide concrete material evidence of a process that required control over temperature, gas flow, and ore selection. Their survival allows scholars to reconstruct not just the products of metallurgy but the operational logic behind them. The study, therefore, has significance beyond the narrow case of zinc extraction: it contributes to a broader understanding of ancient scientific knowledge in Iran. The evidence suggests that metallurgical expertise was transmitted, refined, and adapted over time within local traditions. This challenges any simplistic view of ancient technology as rudimentary or accidental. Instead, the article presents zinc production as a carefully engineered process rooted in deep empirical knowledge. In this sense, the research also bridges archaeology and the history of technology, showing how material remains can illuminate intellectual and practical achievements in the ancient world.

Conclusion

This study provides compelling archaeological and analytical evidence for an ancient zinc-extraction technology in Iran, centered on the use of clay nails in a calamine-based sublimation process. Through field survey, sample selection, petrographic study, and chemical analysis, the researchers demonstrate that these artifacts were not ordinary ceramic remains but active components of a specialized metallurgical system. Their distribution across multiple sites in the central Bam region, together with associated slag and mining features, indicates that zinc production was part of a broader regional tradition rather than a singular isolated practice. The chemical presence of zinc and related metals confirms exposure to metallurhighly adaptive metallurgical system, one that differed significantly from the extraction methods used for other metals. Rather than relying on direct smelting alone, this technique involved the thermal processing of zinc-bearing ores, especially calamine, under controlled conditions that allowed zinc vapor to be captured and condensed. The research is situated within the broader context of Iranian metallurgical history. It aims to clarify how ancient craftsmen were able to exploit the physicochemical properties of zinc compounds long before modern industrial technologies emerged.

The study emphasizes the importance of identifying, classifying, and evaluating the archaeological remains associated with this extraction method, particularly the clay nails recovered from several sites in central Bam. These objects are not merely incidental remains; they represent functional components of a technological chain that made zinc recovery possible. By examining their distribution, condition, composition, and microstructural features, the research seeks to reconstruct the operational logic of the ancient system. In this sense, the article contributes both to archaeological interpretation and to the history of science and technology in Iran.

A key assumption of the study is that these clay elements are direct witnesses to a sophisticated and localized metallurgical tradition. Their morphology, color changes, and chemical signatures collectively provide evidence for exposure to high temperatures, oxidizing and reducing environments, and zinc vapor. The research thus places ancient zinc extraction within a technological framework that was empirical, regionally adapted, and surprisingly efficient. Overall, the introduction establishes the central question: how did ancient Iranian metallurgists design and operate a system capable of extracting zinc from ore, and what can the surviving clay remains reveal about that process?

Research Methodology

The research is based on field investigations in the central Bam region, where several areas were surveyed and sampled for evidence related to ancient zinc production. The main surveyed zones include the Abarq plain (NBB-01), Deh Bakri and Kuh-e Chah (NBB-02), Morghak village (Deh Redin) (NBB-03), and the Dehno valley (NBB-04). In each locality, the researchers collected archaeological samples with particular attention to the better-preserved clay nails and to traces that could indicate zinc-related metallurgical activity. Selection criteria were primarily based on preservation quality and on visible or probable traces of zinc on the surfaces of the samples.

The methodological approach combines field archaeology with laboratory analyses. After collection, the samples were subjected to petrographic study and chemical analysis to identify their mineralogical composition and elemental content. Petrographic examination helped determine texture, fabric, and inclusions, while chemical analysis was used to detect the presence and concentration of metals such as zinc, lead, iron, and copper. These analyses were essential for distinguishing ordinary ceramic materials from artifacts that had been exposed to zinc vapor or associated with metallurgical furnaces.

The study also incorporated observation of contextual evidence, such as slag deposits and mining tunnel openings, where available, to support the interpretation of the clay nails as components of an extraction system. By combining archaeological context, material description, and laboratory data, the researchers created a multi-layered methodological framework. This made it possible to move beyond simple artifact description and toward a reconstruction of the technological process itself. In short, the method integrates survey archaeology, artifact selection, petrography, and compositional analysis to demonstrate the function and significance of the clay nails in ancient zinc extraction.

Discussion

1. Archaeological Context and Spatial Distribution

One of the most important findings of the study is the wide distribution of clay nails across the surveyed areas of Bam. Their occurrence in multiple locations suggests that zinc-related activity was not isolated to a single workshop but formed part of a broader metallurgical landscape. In some places, the presence of slag and mining-related features further strengthens the interpretation that these remains belong to a system of ore processing and metal recovery. The spatial pattern indicates that ancient zinc extraction was likely organized around accessible ore sources and furnace installations. The association of the artifacts with particular topographic settings also implies that production was influenced by local geology, resource availability, and logistical considerations. This broader distribution helps demonstrate that zinc extraction was a regional technological tradition rather than an accidental or short-lived experiment.

2. Functional Interpretation of the Clay Nails

The clay nails are interpreted as key components in the zinc-extraction process, functioning as devices that absorbed or retained zinc vapor during the thermal treatment of calamine. Their shape, surface darkening, and breakage patterns support this interpretation. The article suggests that the nails were positioned vertically, with their tips facing upward, to maximize the collection of metal vapor. Their darkened ends indicate prolonged exposure to heat and reactive furnace atmospheres. This functional reading is significant because it shows that the objects were not random ceramic fragments but deliberately produced tools integrated into a sophisticated in-

Tracing Tutia Production in Southeastern Iran: Chemical and Mineralogical Studies of Ceramic Nails Associated with Metallurgical Activities Using Petrographic and ICP-OES Analyses

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Owing to its vast and rich mineral resources, the Kerman region is regarded as one of the most significant areas for the identification and extraction of metals in Iran. The city of Bam, located in the southeastern part of this province, has long served as a strategic center linking southeastern Iran with Sistan due to its distinctive geological and geomorphological conditions. Archaeological surveys conducted in the central district of Bam County during 2018–2019 aimed to identify ancient mining areas and metallurgical smelting centers. Drawing upon the results of these field investigations, the present study undertakes chemical and mineralogical laboratory analyses of four ceramic nail samples recovered from four areas associated with metallurgical activities. These analyses were carried out to determine the function of the ceramic nails and to investigate the extraction processes involved. The studied samples were examined through petrographic and geochemical analyses using the ICP-OES method across the four identified sites. Petrographic examination of the ceramic nails indicates high firing temperatures during manufacture and reveals a porphyritic texture containing predominantly igneous inclusions as temper materials. The results of the chemical analyses demonstrate that approximately 72% of the chemical composition of these ceramic nails consists of zinc, thereby confirming the intentional extraction of this metal. The existence of sufficient technological knowledge for the oxidation of zinc and the production of Tutia (zinc oxide) at these sites may indicate the emergence of one of the most sophisticated and technologically advanced metallurgical extraction processes in the ancient world. The analytical results obtained from the ceramic nails recovered from several of these sites further suggest that they were specifically employed in the extraction and production of zinc oxide (Tutia).

Keywords: Ceramic Nails; Archaeometallurgy; Petrography; ICP-OES; Southeastern Iran; Bam.

Introduction

This study investigates an ancient zinc-extraction technology in Iran, with a particular focus on the archaeological evidence preserved in clay nails or clay cylinders associated with the process. The article begins from the premise that zinc production in antiquity required a specialized and