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A Scientific Analysis of Early Iron Age Metal Objects from the Excavations at Pachkhed, District Yavatmal, Maharashtra, India

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Abstract: *This study presents a comprehensive archaeometallurgical analysis of selected metal artefacts excavated from the Early Iron Age levels at the site of Pachkhed, District Yavatmal, Maharashtra, India. Through a multi-analytical approach employing X-ray Diffraction (XRD), X-ray Fluorescence (XRF) and Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDS), we investigate the compositional, microstructural and mineralogical characteristics of an iron nail and a bronze bowl. The results confirm deliberate alloying practices, with the bronze object showing a Cu-Sn alloy composition (Sn ~51.77%, Cu ~37.59%) and the iron artefact dominated by ferric compounds, indicative of low-carbon wrought iron with significant surface oxidation. Stratigraphic and contextual data suggest long-term occupation at Pachkhed from the Early Iron Age through the late Medieval period. This study contributes to the growing corpus of metallurgical research in South Asia, situating Pachkhed within broader technological trajectories of protohistoric Deccan metallurgy.*

Keywords: *Archaeometallurgy, Early Iron Age, SEM-EDS, XRD, XRF, Deccan Metallurgy, Pachkhed.*

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Introduction

The emergence and development of metallurgy marked a transformative phase in human history, fundamentally altering socio-economic structures, craft production, warfare and ritual practices (Pigott, 1999; Tylecote, 1987). In the Indian subcontinent, the transition from the Chalcolithic to the Early Iron Age represents a critical juncture in technological evolution, particularly in central India, where iron production and alloying techniques became widespread by the early first millennium BCE (Chakrabarti, 1992; Tripathi, 2008).

The Vidarbha region of Maharashtra has emerged as a key area for understanding Early Iron Age societies, evidenced by the numerous megalithic habitational and burial sites such as Naikund, Mahurjhari, Borgaon etc. (Deo and Jamkhedkar, 1982; Park & Shinde, 2013a,b). However, despite the archaeological significance of this region, detailed material characterisation of metal artefacts remains limited.

Among these, the recently excavated site at Pachkhed presents compelling evidence of long-term occupation and metallurgical activity. The stratigraphic sequence of the site spans from the Early Iron Age through the Satavahana and Medieval periods, revealing a rich cultural continuity. Notably, the discovery of iron tools, copper artefacts and alloyed metal objects such as bronze bowls and ornaments underscores the advanced metallurgical knowledge possessed by the inhabitants of this region.

Scientific characterisation of ancient metals through physicochemical techniques provides critical information on alloy composition, manufacturing technology, resource procurement and corrosion behaviour (Pollard et al., 2008; Hauptmann, 2007). Non-destructive and minimally invasive methods such as XRF, XRD and SEM-EDS have become standard tools in archaeometallurgy, enabling detailed analysis while preserving artefact integrity (Martinón-Torres & Rehren, 2009).

This study applies these methods to investigate the compositional and structural features of two key artefacts from Pachkhed: an iron nail and a bronze bowl. By situating these findings within the broader context of South Asian metallurgy, we aim to address the following questions:

- What do the elemental and microstructural characteristics of the artefacts reveal about the metallurgical knowledge of Early Iron Age societies in Vidarbha?
- Can the Pachkhed materials be compared meaningfully with regional precedents such as Daimabad, Naikund, or other such archaeological sites?

Through this interdisciplinary approach, the paper seeks to expand the corpus of scientifically documented metal artefacts in India and contribute to ongoing debates on the origins and regional diversification of metal technologies in the subcontinent.

Site Background and Archaeological Context

Geographical and Environmental Setting of Pachkhed

The archaeological site of Pachkhed is located at latitude 20°39′06″N and longitude 78°14′54″E, positioned strategically on the left bank of the Chandrabhaga River, approximately one-kilometre southeast of its confluence with the Wardha River. The site falls within the administrative boundaries of Babulgaon tehsil in the Yavatmal district of Maharashtra and is situated about 3 km east of the village Shindhi, along the Pulgaon-Babulgaon road. It lies 43 km from the district headquarters at Yavatmal (Figure 1). Locally, the habitational mound is referred to as “Sasu-Suneche Ukhade” and “Barad”, indicating its longstanding recognition in the cultural memory of local communities, and was first reported by Vilas Vahane (Vahane, 2009). The mound itself measures approximately 250 × 70 meters with an estimated 10-meter-thick occupational deposit, now divided into two segments due to unregulated earth quarrying. This geomorphological setting suggests prolonged human settlement and stratified cultural activity.

Geologically, the region is dominated by the Deccan Trap basalts of Upper Cretaceous to Lower Palaeocene, characterized by alternating flows of massive and vesicular basalt. In addition, other prominent lithologies include granitic-gneiss of the Peninsular Gneissic Complex, sedimentary units

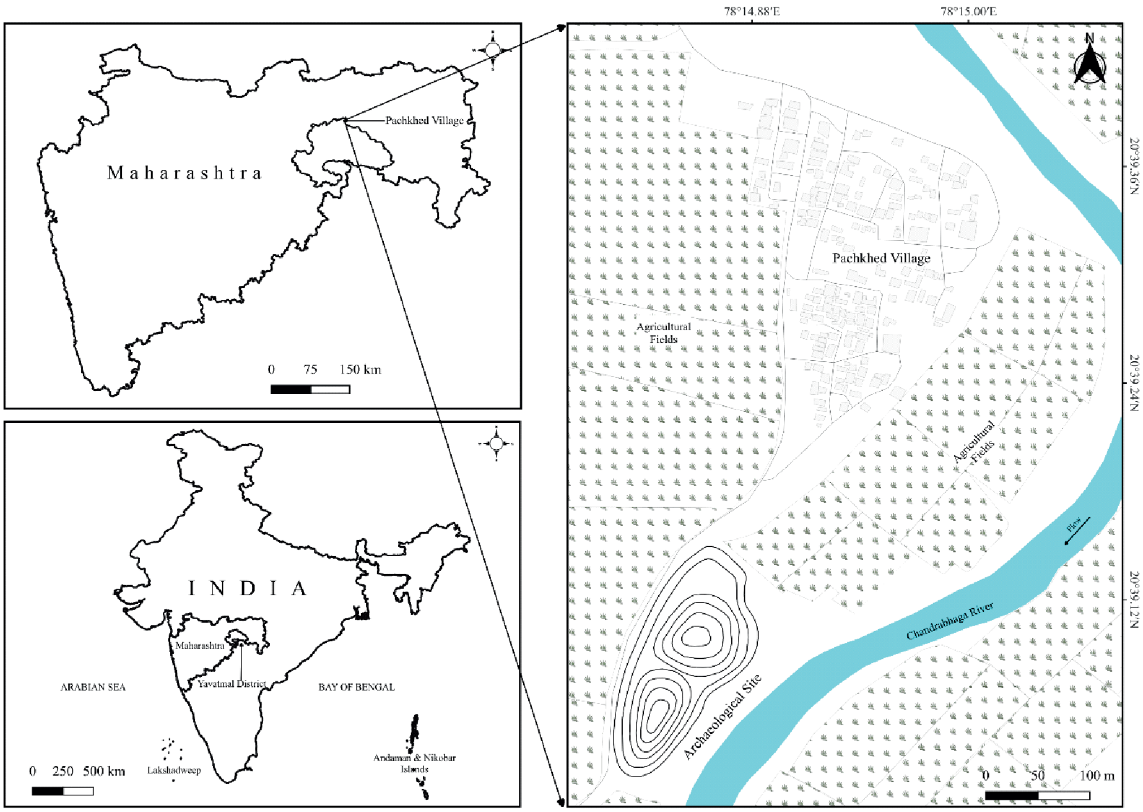

Figure 1: Map showing the overview of village Pachkhed

of the Penganga Group (limestone, shale, dolomitic limestone), and formations from the Gondwana Supergroup, including Talchir, Barakar, and Kamthi sequences, which are significant for their coal deposits. The Lameta Group, comprising cherty limestone, grit, and sandstone, unconformably overlies the Gondwana rocks and is found in localized exposures. The Quaternary alluvium consists of gravel beds, siltstones, and clays, which further enhance the agricultural potential of the landscape (GSI, 2020).

The region experiences a tropical climate, with the monsoon season extending from June to September, receiving an average annual rainfall of 912.79 mm. The summer months (March to May) are intensely hot, with temperatures reaching a maximum of 41.8°C and a minimum of 28.3°C. Wind patterns shift seasonally, with light to moderate winds prevailing, intensifying during the monsoon. During the post-monsoon and winter periods, winds predominantly flow from the east and northeast, while in summer and monsoon months, they shift to a southwest and northwest direction (CGWB, 2013).

The Excavation and Cultural Context

The systematic excavation at the Pachkhed site was undertaken by the Department of Ancient Indian History, Culture and Archaeology during the 2023–24 field season, with the primary objective of establishing the site's cultural sequence and understanding its diachronic occupation. The site is marked by a prominent habitational mound, measuring approximately 250 × 70 meters, with a cultural deposit over 10 meters thick. Due to modern quarrying activities by local villagers, the mound has been bifurcated into northern and southern sectors. Excavations were concentrated in the southern half, with trenches opened at key loci-specifically, Trench ZB3 (Quadrants I and II), Trench ZB4 (Quadrant III), Trench ZC2 (Quadrant III), and Trench XC4 (Quadrant III).

Trench XC4 revealed a complex stratigraphy comprising 32 cultural layers, including the structural remains of a medieval-period well. Trench ZB3 yielded evidence of a furnace at a depth of 5.25 meters. In Trench ZC2, a substantial concentration of faunal remains was recorded, indicative of dietary practices and animal usage. Additionally, floral remains in the form of ornamental beads were retrieved from ZB3 Quadrant II, suggesting both aesthetic and symbolic artefact production.

Ceramic assemblages form a major component of the material culture, with a wide typological and technological variety. The pottery repertoire includes micaceous red ware, red slipped ware, chocolate slipped ware, dull red ware, black slipped ware, buff ware, black and red ware and black-on-red ware. Diagnostic vessel forms comprise bowls, basins, dishes, vases, storage jars, and miniature pots. Painted sherds, although limited, show black-on-red decorative motifs, and several pottery fragments bear graffiti and incision marks, indicative of utilitarian or symbolic functions.

Among the notable artefacts recovered are iron implements, copper and bronze bowls, sling balls, ear studs, pendants, areca nut-shaped beads, annular beads, shell bangles, bone points and coins (Figure 2). This diverse material culture not only underscores the multifunctional character of the site but also reflects a complex socio-economic and technological landscape across multiple historical periods.

Figure 2: Metal Artefacts from the Pachkhed Excavation.

The cultural sequence established at Pachkhed reflects a long and continuous occupation that began in the Early Iron Age and extended through the Medieval phases (Figure 3). The sequence is categorised as follows:

- Period IA: Early Iron Age
- Period IB: Iron Age
- Period II: Satavahana Phase
- Hiatus

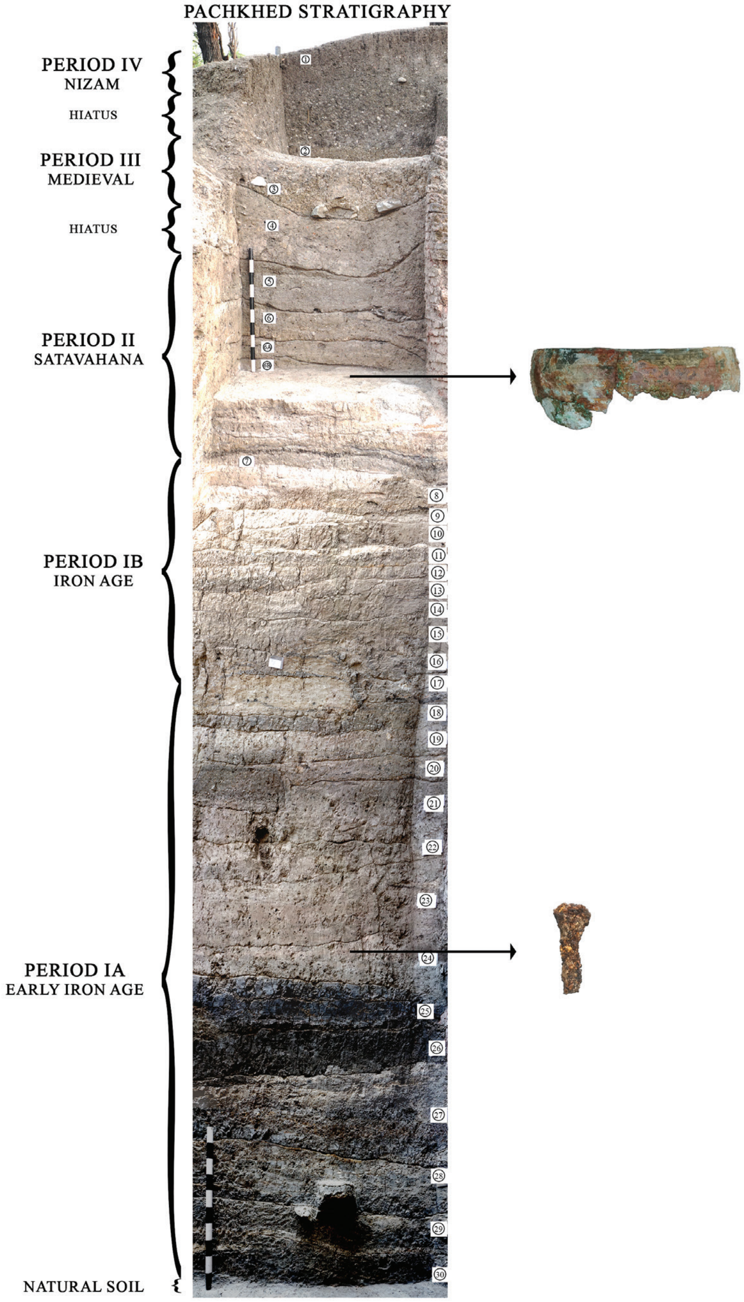

Figure 3: Stratigraphy of a trench XC4/III and Samples taken from Pachkhed Excavation.

- Period III: Medieval Period
- Hiatus
- Period IV: Nizam Era

Materials and Methods

Collection of Samples

The metallurgical analysis presented in this study is based on two selected artefacts excavated from the Early Iron Age levels of the Pachkhed site: an iron nail and a bronze bowl. These artefacts were chosen due to their well-preserved condition, typological significance and their potential to offer information on early metallurgical practices in the Vidarbha region. The samples were carefully retrieved under controlled excavation contexts from stratified deposits to ensure chronological integrity.

Following standard archaeological protocols, each artefact was documented in situ, photographed and assigned a unique registration number. The objects were then subjected to minimal cleaning to preserve corrosion layers and patina, which are often indicative of the burial environment and manufacturing technology. No chemical treatment or mechanical abrasion was employed that might compromise the artefact's integrity or surface features. The samples were subsequently transferred to the X-ray Research Lab Facility, Rashtrasant Tukadoji Maharaj Nagpur University, for detailed physicochemical analysis.

Analytical Techniques

To examine the compositional, mineralogical, and morphological properties of the samples, a multi-instrumental, minimally invasive analytical protocol was followed:

X-Ray Diffraction (XRD)

Crystalline analysis was carried out using a Rigaku Miniflex 600 X-ray Diffractometer equipped with CuKα radiation (λ = 0.1546 nm). Diffraction patterns were recorded in the 2θ range of 10° to 80° at a scan speed of 2°/min. Peak identification was performed using standard reference patterns from the ICDD (International Centre for Diffraction Data) database, allowing identification of corrosion products and alloy phases.

Scanning Electron Microscopy with Energy-Dispersive X-ray Spectroscopy (SEM-EDS)

Surface morphology and microstructural characterization were conducted using a JEOL JSM-6380 SEM operated under high-vacuum mode. Micrographs were obtained at various magnifications (5–500 µm) to assess corrosion layers, grain boundaries, porosity and inclusions. EDS analysis was performed on targeted areas of each artefact to obtain semi-quantitative elemental composition, using an acceleration voltage of 15 kV and a working distance of 10 mm. Elemental maps were generated where appropriate to examine the distribution of alloying and trace elements.

X-Ray Fluorescence (XRF)

In-situ non-destructive compositional screening of the bronze bowl was conducted using a Bruker S1 TITAN Handheld XRF Analyzer. The device operated in mining and alloy mode with a 60-second integration time per measurement point. Data were calibrated against certified reference standards for bronze and iron alloys. Measurements were repeated at multiple points on the artefact surface to ensure reproducibility and account for surface heterogeneity due to corrosion.

Data Processing and Interpretation

All analytical datasets were cross-referenced to eliminate outlier values and ensure consistency across methods. Elemental concentrations from XRF and EDS were normalized and converted to oxide forms where appropriate. The results were compared with published datasets from Vidarbha and other Iron Age and Chalcolithic sites in India (e.g., Daimabad, Naikund, Mahurjhari, etc.) to assess technological parallels. Morphological features observed in SEM were interpreted in conjunction with burial corrosion typologies and known copper alloy degradation patterns (Scott, 2002).

Results

The analytical results from XRD, SEM-EDS and XRF examinations of two artefacts - an iron nail (Sample 1) and a bronze bowl (Sample 2) provide information on alloy composition, corrosion processes and manufacturing signatures. The results are reported in three categories: (1) surface morphology via SEM, (2) elemental composition via EDS and XRF, and (3) crystallographic phases via XRD.

Sample I: Iron Nail

Surface Morphology (SEM)

Scanning Electron Microscopy revealed a heavily corroded surface with dense oxide layering and micro-pitting across the exposed area. At higher magnifications (Figure 4a-f), the iron nail showed a

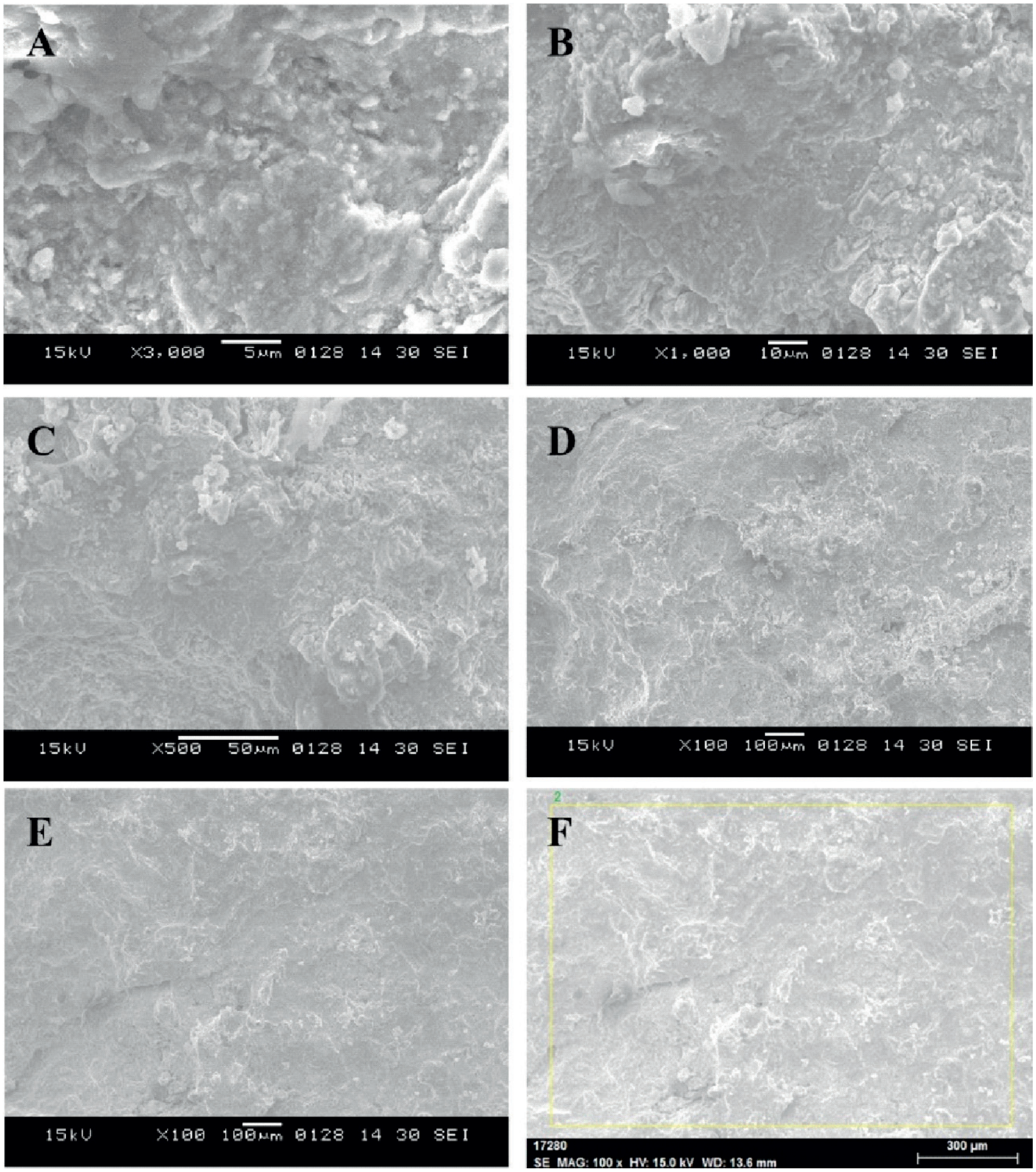

Figure 4: SEM micrographs of the iron nail at various magnifications (5–500 µm), illustrating extensive surface corrosion, microcracking and delamination consistent with prolonged burial exposure.

rugged and porous topography with irregular flakes and microcracks indicative of stratified corrosion. SEM images taken at 5 µm, 10 µm, 50 µm, 100 µm, 300 µm and 500 µm magnifications (Figure 4) show features consistent with soil-induced corrosion, including the formation of granular ferric oxides and sedimentary inclusions.

Elemental Composition (EDS)

Energy Dispersive X-ray Spectroscopy (EDS) of the iron nail identified major elements as iron (Fe: 51.12 wt.%) and oxygen (O: 34.46 wt.%), consistent with iron oxides such as hematite or goethite. Minor elements included carbon (C: 5.20%), calcium (Ca: 2.62%), silicon (Si: 1.47%), sulphur (S: 1.41%), chlorine (Cl: 1.07%), and trace levels of aluminium, magnesium, phosphorus and potassium (Table 1; Figure 5).

The elevated oxygen levels and low carbon percentage support the identification of a low-carbon wrought iron composition, now heavily oxidised. The presence of Si, Ca and S suggests soil-derived contamination or slag-related inclusions.

Table 1: Elemental concentration (wt.%) from SEM-EDS analysis of the iron nail

Element	Fe	O	C	Ca	Si	S	Cl	Mg	Al	P	K	Total
wt.%	51.12	34.46	5.20	2.62	1.47	1.41	1.07	0.19	0.15	0.07	0.01	97.77

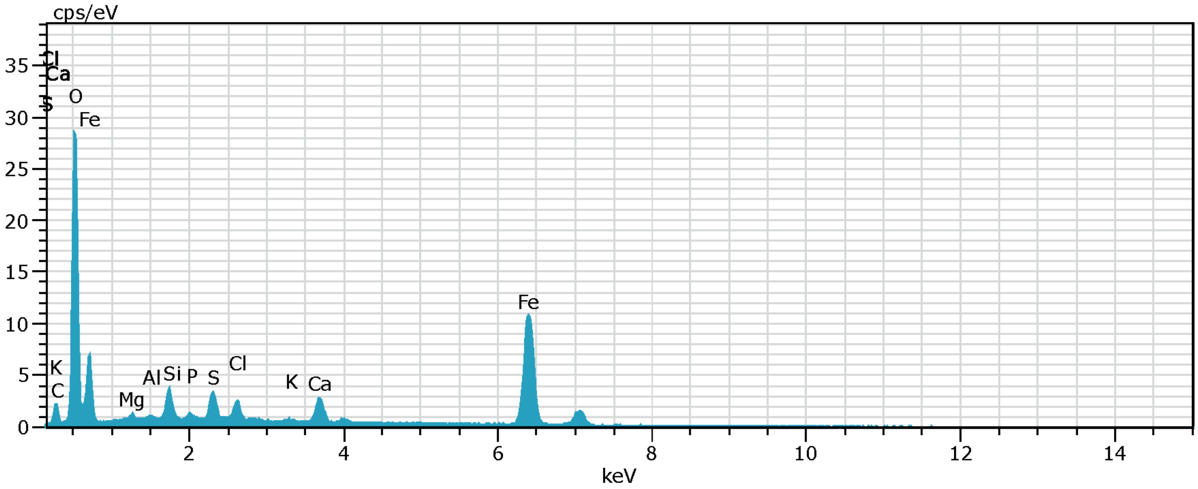

Figure 5: EDS spectrum of the iron nail showing major peaks for Fe and O, along with minor peaks for C, Si, Ca, S and other trace elements.

Crystallographic Phases (XRD)

XRD analysis was not conducted on the iron nail due to surface instability and corrosion-induced heterogeneity. However, the high Fe-O ratios and morphology suggest the presence of corrosion products such as hematite (Fe_2O_3) or goethite ($FeO(OH)$), which are consistent with post-depositional transformation of low-carbon iron in oxygen-rich, acidic soil environments (Scott, 2002).

Sample 2: Bronze Bowl

Crystallography (XRD)

The X-ray Diffraction (XRD) analysis of the bronze bowl (Figure 6) reveals distinct peaks at ~43°, 50°, and 74° 2θ, corresponding to metallic copper (Cu). Additional peaks near 36° and 61° are assigned to cupric oxide (CuO) and cuprite (Cu_2O), indicating surface patination likely caused by burial in an oxygen- and moisture-rich environment.

Despite a high tin content (Sn: 51.77 wt.%) confirmed through XRF, no crystalline tin oxide phases (SnO_2) were identified in the XRD pattern, suggesting that tin remains in solid solution within the copper matrix or exists in amorphous or non-detectable corrosion states.

The minor SiO_2 content detected via XRF (1.63 wt.%) does not correspond to any major quartz peak in the XRD data and may originate from soil particulates or residual surface sediment. The diffraction profile confirms that the bowl is composed of a well-crystallized Cu–Sn alloy with evidence of surface oxidation typical of long-term burial.

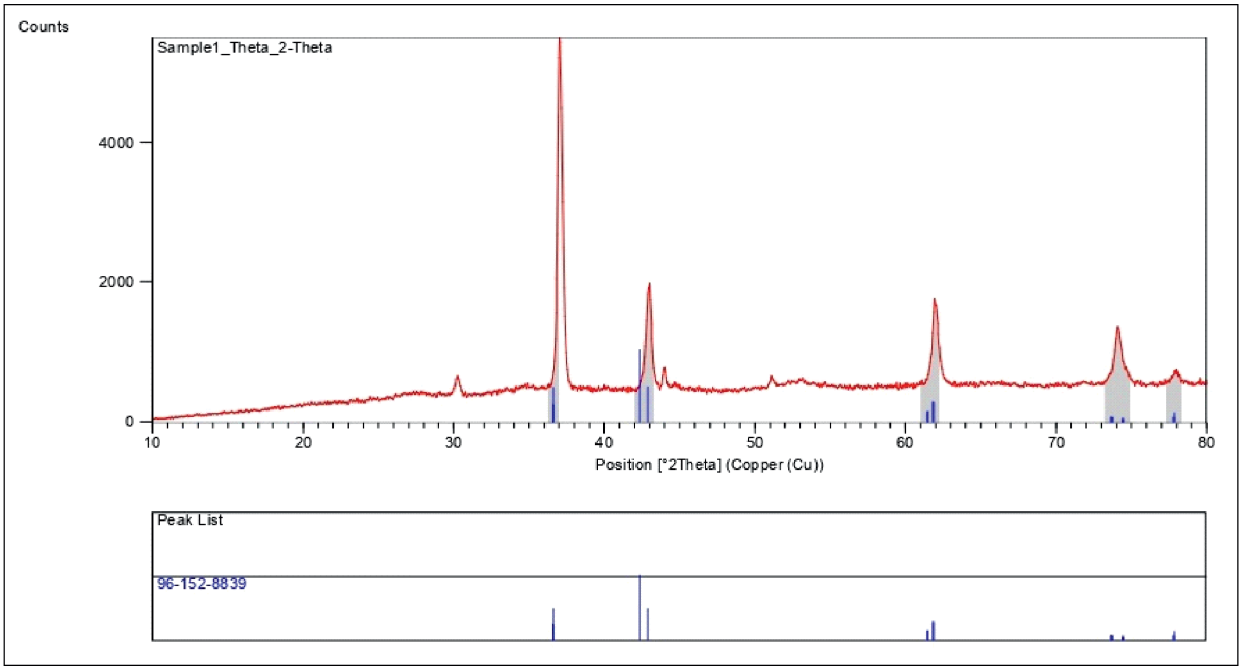

Figure 6: XRD pattern of the bronze bowl showing major diffraction peaks for metallic copper (Cu) and secondary peaks attributed to copper oxides (CuO and Cu_2O).

Elemental Composition (XRF)

Handheld XRF analysis (Table 2) revealed that the bronze bowl is composed predominantly of tin (Sn: 51.77 wt.%) and copper (Cu: 37.59 wt.%), indicating a high-tin bronze alloy. Minor components include silicon (reported as SiO_2: 1.63%), phosphorus (P: 0.09%), arsenic (As: 0.08%), cobalt (Co: 0.02%), and iron (Fe: 0.08%). Trace levels of chlorine (Cl: 0.09%), sulfur (S: 0.03%), molybdenum (Mo: 0.05%), and silver (Ag: 0.01%) were also detected. Notably, rare earth and heavy metals such as lanthanum (La: 0.20%), hafnium (Hf: 0.04%), lead (Pb: 0.007%), and bismuth (Bi: 0.01%) were present in trace quantities.

These results suggest the use of polymetallic ore sources or recycled materials, practices common in ancient metallurgical traditions. The elevated tin content points to a composition tailored for casting and ceremonial use, potentially linked to elite or ritual contexts during the Early Iron Age.

Table 2: Elemental composition of the bronze bowl by XRF (wt.%)

Element	*SiO2*	*P*	*S*	*Cl*	*Cr*	*Fe*	*Co*	*Cu*	*As*	*Mo*	*Ag*	*Sn*	*La*	*Hf*	*Pb*	*Bi*
wt.%	1.6343	0.0898	0.0271	0.0890	0.0159	0.0833	0.0236	37.5892	0.0794	0.0496	0.0143	51.7746+	0.1958	0.0447	0.0072	0.0121

Elemental Composition (SEM-EDS)

SEM-EDS analysis of the bronze bowl corroborates the XRF data, revealing 32.05 wt.% tin (Sn) and 26.56 wt.% copper (Cu) as the primary alloy components (Figure 7; Table 3). High levels of oxygen (25.11%) and carbon (8.82%) reflect extensive surface corrosion and organic or soil-derived residues.

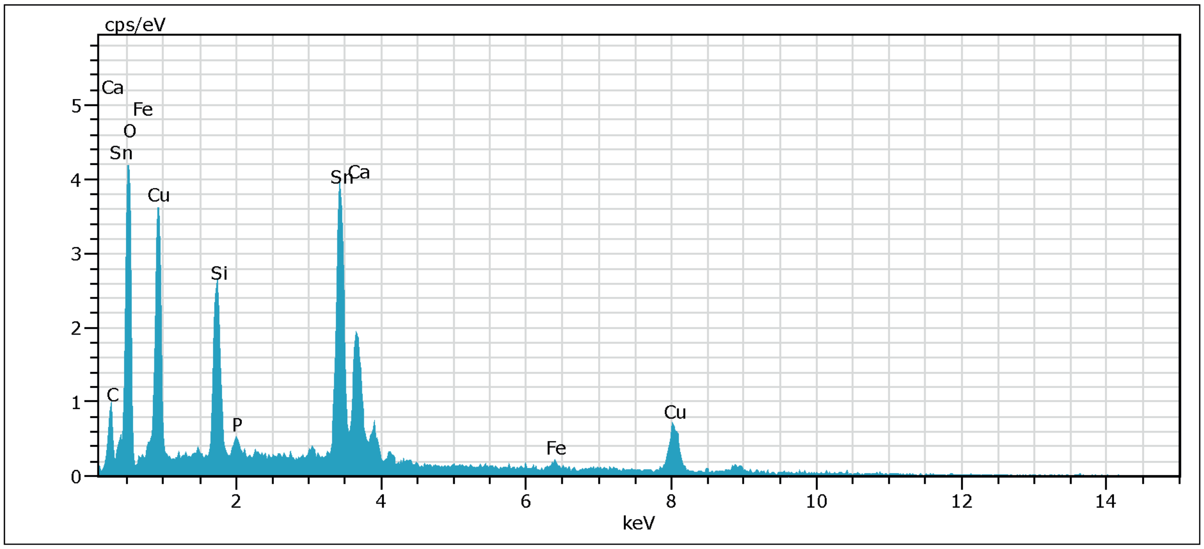

Figure 7: EDS spectrum of the bronze bowl showing major peaks for Sn and Cu, with secondary peaks for O, Si, and Fe.

Minor elements, including silicon (4.80%), iron (1.57%), calcium (0.33%), and phosphorus (0.26%), likely originate from burial conditions or smelting by-products. The absence of elements such as lead (Pb) or zinc (Zn) supports the identification of a binary high-tin bronze alloy rather than a complex multi-component formulation.

Table 3: Elemental concentration (wt.%) from SEM-EDS analysis of the bronze bowl

Element	Sn	Cu	O	C	Si	Fe	Ca	P	Total
wt.%	32.05	26.56	25.11	8.82	4.80	1.57	0.33	0.26	99.33

Surface Morphology (SEM)

SEM analysis of the bronze bowl surface at increasing magnifications (Figure 8A-F) reveals a complex corrosion landscape characterized by granular encrustations, microcracks and layered oxidation products. At high magnification (Figure 8A-B), the surface shows dense crystalline features and mineral clustering, consistent with advanced bronze patination. Mid-level views (Figure 8C-D) show localized corrosion pits, particle detachment and flaky deposits likely resulting from long-term burial in a chemically active environment.

At lower magnification (Figure 8E–F), broader microfractures, sediment adhesion and surface delamination are visible, suggesting mechanical stress and soil interaction. While microbial corrosion cannot be confirmed visually, the overall degradation pattern is consistent with prolonged burial exposure and post-depositional weathering in fluctuating environmental conditions.

Discussion

The metallurgical analysis of iron and bronze artefacts from the Early Iron Age levels at Pachkhed offers significant information on technological practices in Vidarbha during the first millennium BCE.

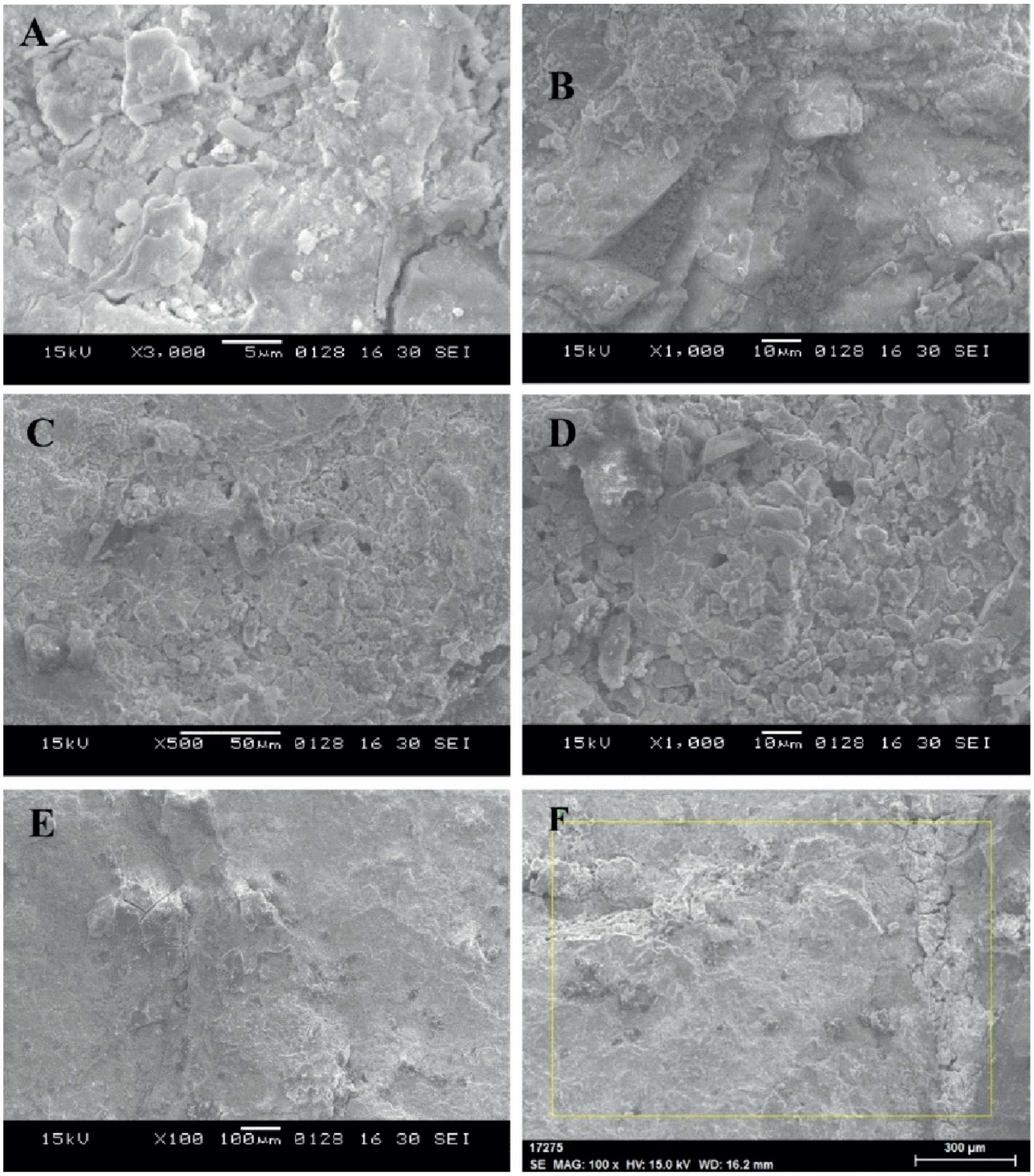

Figure 8: SEM micrographs of the bronze bowl at various magnifications (A-F).

The results reflect deliberate alloying strategies, mature bloomery iron production and the use of diverse material sources. When viewed in the context of regional archaeology, the findings bridge the technological traditions of the Chalcolithic Deccan with Early Iron Age advancements in Vidarbha.

Iron Technology and Manufacturing Traditions

The iron nail from Pachkhed reveals characteristic features of low-carbon wrought iron, with Fe (51.12 wt.%) and O (34.46 wt.%) dominating its composition, and minor components such as C, Si, S, and Ca likely arising from smelting slag and burial contamination. The absence of elevated carbon content or hardening structures suggests that the artefact was produced using non-carburised bloomery smelting, a hallmark of early Indian iron technologies (Chakrabarti, 1992; Tripathi, 2008).

Surface microstructure, as observed under SEM, reveals exfoliation, pitting, and stratified corrosion typical of post-depositional environments. These signatures are comparable to those found at Naikund, where bloomery iron implements (ploughshares, nails, chisels) showed similar surface textures and low-carbon compositions (Deo & Jamkhedkar, 1982). Mahurjhari (Deshpande, 1974, 1975; Thapar, 1981), Borgaon (Mittra, 1983), Khairwada (Mittra, 1984), Bhagi Mohari (Nagrajarao, 1985) and Raipur (Tripathi, 1987; Deglurkar & Lad, 1992) also yielded forged iron artefacts with minimal evidence of heat treatment or alloying, suggesting a shared technological foundation across Vidarbha Iron Age communities (Park & Shinde, 2013a). Iron objects from these previous Vidarbha Iron Age sites often co-occur with megalithic burials and typologically resemble the Pachkhed iron nail in form and function, pointing to widespread utilitarian iron use across both domestic and funerary contexts.

High-Tin Bronze and Complex Alloying Practices

The bronze bowl yielded a high-tin Cu–Sn alloy composition (Sn: 51.77 wt.%, Cu: 37.59 wt.%), with no crystalline SnO_2 detected in XRD, suggesting the tin was retained in solid solution or amorphous form. CuO and Cu_2O peaks in the XRD data confirm surface oxidation, a result of long-term burial. SEM-EDS observations further reveal mineral accretions, corrosion pitting, and sediment inclusions typical of ancient bronze artefacts exposed to moisture-rich environments (Scott, 2002).

The alloying composition, specifically its high tin content, implies intentional casting strategies and potentially ceremonial or symbolic use, rather than utilitarian function. Similar bronze items, including bowls and other decorative elements, have been recovered from Borgaon, Khairwada, Bhagi Mohari, Mahurjhari and Raipur, where they are often associated with elite burial goods (Park & Shinde, 2013a,b). Notably, these sites' bronzes typically feature low to moderate Sn content (~1–17%), making the Pachkhed bowl exceptional in its metallurgical formulation (Park & Shinde, 2013b).

Trace element analysis at Pachkhed, including arsenic, cobalt, lanthanum and hafnium, further supports the hypothesis of polymetallic ore sources or recycled alloy streams, aligning with observations from the Borgaon, Khairwada, Bhagi Mohari, Mahurjhari and Raipur sites complex, where alloy variability is often linked to re-melting and metal circulation (Park & Shinde, 2013a,b). The absence of lead and zinc suggests that alloying was tightly controlled, avoiding common later-period multi-metal bronzes.

Broader Technological Context: Deccan Chalcolithic to Vidarbha Iron Age

To understand the significance of Pachkhed's metallurgy, it is instructive to compare it with the Chalcolithic metallurgical record at Daimabad, a prominent site in the upper Godavari valley. Daimabad's copper artefacts include anthropomorphic figures, bowls and flat tools, most of which are composed of near-pure copper or low-tin bronze (Sali 1986; Sarkar & Shinde 2014; Agrawal 2002). The metallurgy at Daimabad reflects an experimental phase, where alloying was inconsistently applied and metallurgical control was limited (Agrawal et al. 1978).

In contrast, the high-tin bronze from Pachkhed shows clear signs of intentional alloy design, possibly tailored for ritual or high-status use. This shift from low-tin or pure copper to high-tin bronze suggests a technological evolution from Chalcolithic practices to more advanced alloying in the Early Iron Age. Furthermore, the presence of trace rare earths (e.g., La, Hf) and minor heavy metals at Pachkhed, absent in Daimabad artefacts, indicates either access to more geologically diverse resources or metallurgical recycling practices not yet evident in earlier traditions.

Therefore, Pachkhed represents not only a continuation of metallurgical traditions from earlier Chalcolithic roots but also an advancement in alloying precision, tool diversity and possibly symbolic metallurgy. Its comparative position between Daimabad's copper horizon and Iron Age Vidarbha sites highlights a period of innovation and technological maturation.

Conclusion

This study presents the comprehensive scientific characterisation of metal artefacts recovered from the Early Iron Age levels at Pachkhed, a newly excavated multi-phase archaeological site in the Yavatmal District of Maharashtra, India. By integrating archaeological field context with advanced analytical techniques-including X-ray Diffraction (XRD), Scanning Electron Microscopy with Energy-Dispersive Spectroscopy (SEM-EDS), and X-ray Fluorescence (XRF), this research offers critical information into ancient metallurgical practices in peninsular India.

The results indicate a distinct dichotomy in technological application on one hand, the iron nail reflects a utilitarian, bloomery-based production system typical of the Early Iron Age Vidarbha region. The artefact displays low-carbon wrought iron composition with characteristic corrosion morphology, aligning it with known iron technologies from sites such as Naikund, Mahurjhari, Borgaon, etc. On the other hand, the bronze bowl reveals a high-tin Cu–Sn alloy with over 51% tin, an alloying concentration that exceeds the typical ranges observed in regional contemporaries. The presence of trace elements such as arsenic, cobalt, lanthanum and hafnium suggest the use of polymetallic ores or recycled materials, pointing toward a nuanced understanding of alloy formulation and resource variability.

When considered within the broader cultural framework, the Pachkhed assemblage bridges the metallurgical continuum from the Deccan Chalcolithic-represented by sites like Daimabad, known for its predominantly pure copper artefacts, to the more technologically diversified Iron Age traditions of Vidarbha. Unlike the early experimentation with copper at Daimabad, Pachkhed demonstrates a mature alloying strategy, both in ferrous and non-ferrous metallurgy. The site reflects not only continuity with earlier traditions but also innovation in alloy design, possibly linked to ritual, symbolic, or social functions.

Pachkhed emerges as a key site in understanding the development of ancient metallurgy in Central India. Its dual evidence of bloomery iron production and high-tin bronze casting improves our understanding of resource access, technological proficiency, and cultural complexity during the Early Iron Age. This study not only contributes new archaeometallurgical data from an underexplored region but also underscores the value of integrated analytical approaches in reconstructing ancient technological systems. Future investigations involving ore provenance studies, metallographic sectioning and experimental reconstructions would further illuminate the choices and capabilities of early metalworkers in this dynamic cultural landscape.

Competing Interest

The authors declare that they have no conflicts of interest in this paper.

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