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Hydrochloric Acid Concentration, Exposure Time and Material Loss in Cleaning Early Uninscribed Copper Cast Coins

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Abstract

Severe corrosion obscures the surface symbols of Early Uninscribed Copper Cast Coins (EUCCC), and mechanical cleaning could not remove compact encrustations from coins from Malpar, India. Five coins were characterised by X-ray fluorescence and X-ray diffraction, which indicated copper with surface cuprous oxide and siliceous deposits. Each coin was then cleaned in a different hydrochloric acid (HCl) concentration (10–50%) in 10-minute stages, with weight loss recorded and dissolved copper measured by atomic absorption spectroscopy. Total weight loss ranged from 5.75% to 12.61% and copper loss from 2.43% to 6.89%, both highest at 30% HCl; at 50% HCl the visual end point was reached in one stage. Because each concentration was tested on a single coin, concentration effects cannot be separated from coin-to-coin variation. After rinsing and Paraloid B-72 coating, symbols were legible and no macroscopic damage was seen. Findings are exploratory and need replicated, microscopic validation.

Introduction

The conservation of ancient metal artefacts, particularly copper coins, constitutes a fundamental aspect of archaeological research and cultural heritage management [1,2]. Coins serve not only as monetary objects but also as important historical records, providing insights into political authority, trade networks, symbolic systems, and metallurgical practices of past societies [3–5]. In ancient societies, it was common to hide valuables (coins or ornaments) in ceramic or metal containers and bury them underground for safekeeping [3]. Today, these coins emerge as hoards, providing valuable historical and economic insights into past practices. However, prolonged burial in a soil environment triggers complex corrosive processes that significantly alter the surfaces of metal artefacts [6]. Copper coins are especially susceptible to corrosion, resulting in the formation of products such as cuprous oxide, malachite, azurite, and siliceous encrustations [3,7,8]. These corrosion layers often obscure surface features such as

symbols, legends, portraits, and decorative motifs, making it difficult to determine coin ascription and chronology. In such cases, appropriate cleaning and conservation methods become essential for recovering archaeological information while preserving the material integrity of the antiquarian find.

During an archaeological exploration at Malpar in the Rewa district of Madhya Pradesh, India, a hoard of 125 copper coins was discovered inside a ceramic pot within a habitation deposit [9] (Fig. 1). The coins were found inside the pot, all rectangular in shape and in a heavily corroded condition, with thick, firmly adhered encrustations (Fig. 2). These deposits prevented the identification of surface features and limited their historical interpretation. Initial attempts at mechanical cleaning using standard tools were insufficient to remove these compact corrosion layers, particularly where deposits were strongly bonded to the metal surface.

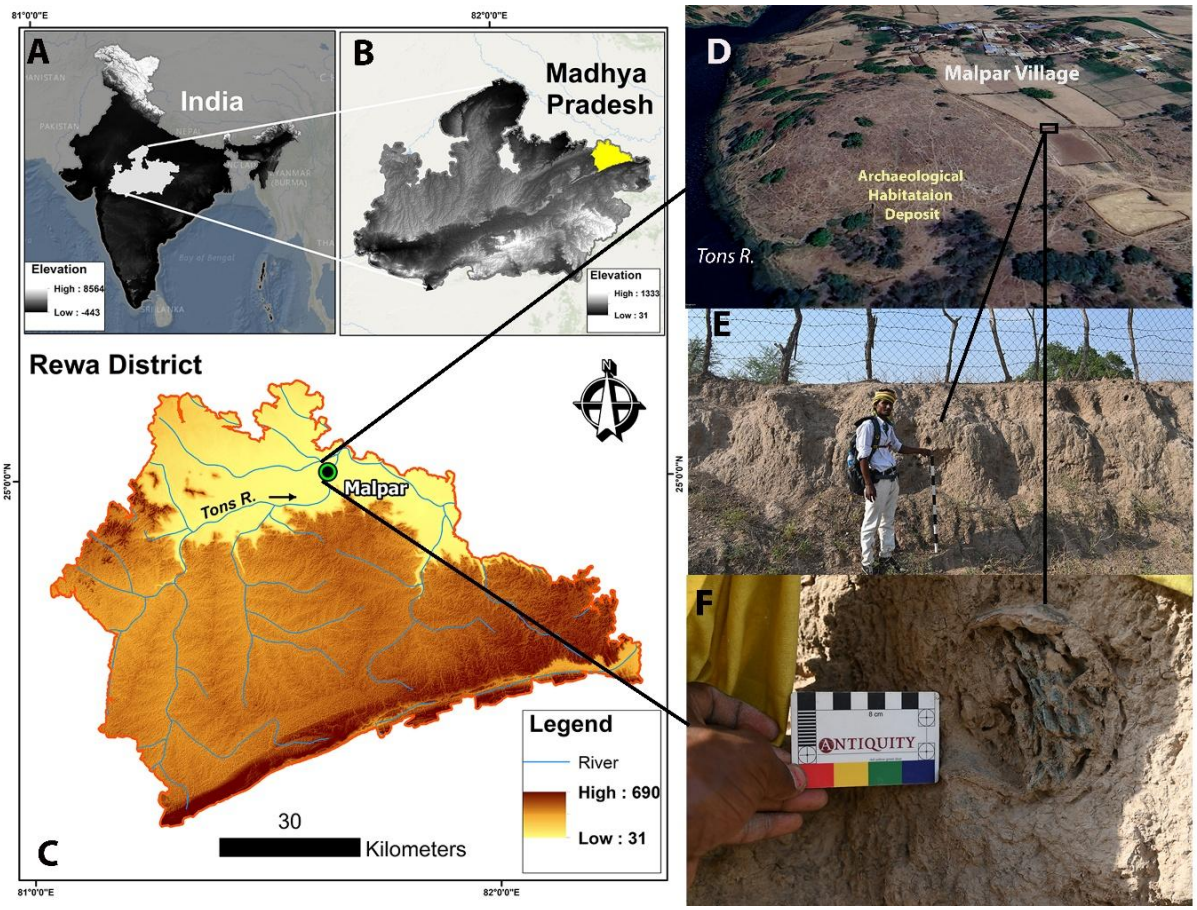


Fig. 1. Location and archaeological context of Malpar, Rewa District, Madhya Pradesh, India: (A) Map of India showing Madhya Pradesh; (B) Map of Madhya Pradesh showing Rewa District; (C) Map of Rewa District showing location of Malpar Archaeological Site; (D) Google Earth view of Malpar near the Tons River; (E) Section of the mound showing the coin hoard; (F) Close-up of the coin hoard inside the pot (Prepared by Dheeraj Sharma).

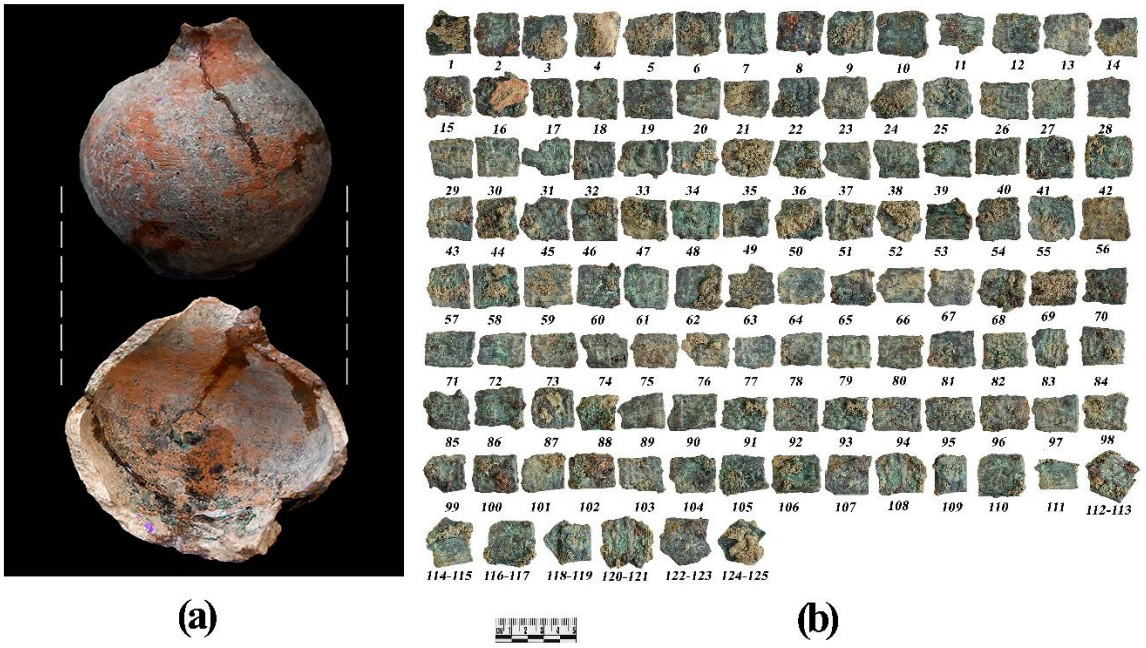


Fig. 2. Red ware pot and coin hoard from Malpar: (A) Photograph of the pot showing its complete profile and base; (B) The plate shows 125 coins arranged in sequence (Photo by Dheeraj Sharma & Virag Gopal Sontakke).

A range of cleaning techniques, including mechanical, chemical, electrochemical, and laser-based methods, have been employed in the conservation of archaeological metals. Mechanical cleaning is generally preferred as a preliminary step for coins because it removes surface deposits without introducing chemical agents [10–12]. However, its effectiveness is limited when dealing with dense or chemically stable corrosion layers. Chemical cleaning methods, on the other hand, can dissolve corrosion products and access micro-level features, but they must be carefully controlled to avoid excessive metal loss or alteration of the original surface [2,11–15]. Other advanced methods, such as electrochemical and laser cleaning [2,13–22], offer high efficiency and precision but may involve greater technical complexity, cost, or the risk of unintended surface modification.

Despite these available approaches, there remains a need for systematic, experimentally controlled evaluation of chemical cleaning processes, particularly regarding their effects on material loss and surface condition in copper-based artefacts. Previous studies have often focused on cleaning efficiency, while less attention appears to have been given to quantifying metal loss under varying chemical conditions and assessing its implications for conservation practice. In particular, experimentally controlled studies that quantify the relationship between

acid concentration, exposure time, and material loss in copper-based archaeological artefacts remain limited.

The present study is an exploratory evaluation of how hydrochloric acid concentration and exposure time relate to corrosion removal and material loss in five archaeological copper coins. The study integrates compositional characterisation, controlled chemical cleaning, and quantitative assessment of weight and metal loss. In addition, cleaning effectiveness is assessed by improvements in surface legibility and typological identification. The aim is to document the cleaning behaviour and measured material loss under controlled laboratory conditions, and to identify what a replicated study would need to test, rather than to establish a general conservation protocol.

Methods

The study was carried out in several steps, including sample selection, analysis, cleaning, stabilisation, and evaluation. The overall steps followed in the study are shown in Figure 3.

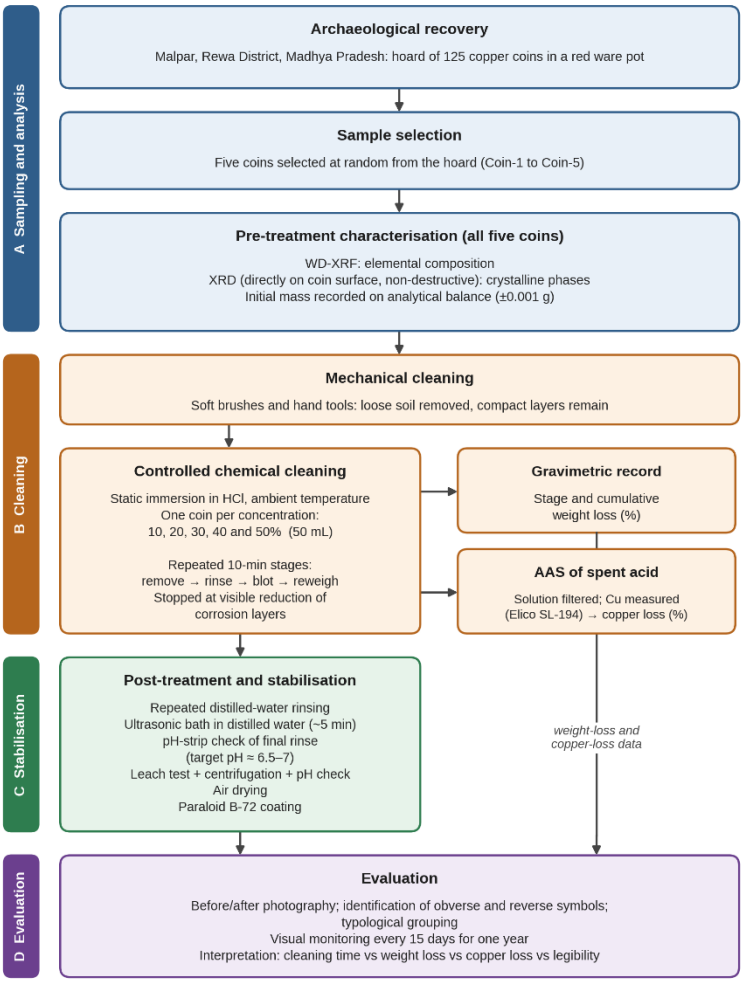


Fig. 3. Methodological workflow of the study.

Sample selection

A total of five coins were randomly selected from the Malpar hoard for the present study. These samples were chosen to represent the general condition and variability and were used for compositional analysis and controlled cleaning experiments. Coin-1 to Coin-5 were each treated in one HCl concentration (10–50%, respectively), so there was one coin per concentration and no replicates. The sample size was limited by cost constraints, conservation considerations and the need to minimise potential damage to archaeological material.

X-ray fluorescence (XRF)

The elemental composition of the selected coin samples was determined using Wavelength Dispersive X-ray Fluorescence (WD-XRF). The analysis was carried out on a Malvern Panalytical Zetium spectrometer at the Central Discovery Centre (CDC), Banaras Hindu University. WD-XRF is a non-destructive analytical technique that measures the characteristic X-ray wavelengths and intensities emitted by elements in the sample. This method enables both qualitative and quantitative determination of elemental composition. The analysis was performed prior to any cleaning treatment to identify the major metallic constituents and associated minor elements present in the coins. Because the measurements were made on uncleaned, corroded surfaces, the results (copper is reported as CuO) reflect surface corrosion products and adhered deposits as well as the metal, and should not be read as the bulk alloy composition.

X-ray diffraction (XRD)

X-ray diffraction (XRD) analysis was carried out on all selected coin samples to investigate their crystalline phases and corrosion products. The analysis was performed using a non-destructive approach, with measurements taken directly from the coin surfaces without sampling or material removal. Measurements were made before any cleaning. Diffraction patterns were recorded using a Rigaku Miniplex X-ray diffractometer with Cu Kα radiation (λ = 1.54 Å). The instrument was operated at 40 kV and 15 mA. Data were collected over a 2θ range of 20°–100° with a scan rate of 5°/min and a step size of 0.01°. The analysis was conducted at the Central Instrument Facility, Indian Institute of Technology (BHU), Varanasi. The obtained diffraction spectra were processed and interpreted using X'Pert Highscore software, and graphical representations were prepared using Origin software.

Mechanical cleaning

Initial cleaning of the coin surfaces was attempted using mechanical methods, including soft brushes and hand tools, to remove loosely adhered soil and deposits. While this approach was effective in removing superficial encrustations, it was insufficient to eliminate the compact, firmly bonded corrosion layers. As a result, further cleaning required a controlled chemical method.

Controlled chemical cleaning

Hydrochloric acid (HCl) was selected as the cleaning agent for its effectiveness in dissolving copper corrosion products, particularly oxides and chlorides. Analytical-grade HCl (Qualigens, acidimetric purity 35–37%) was used as the stock solution to prepare working solutions at concentrations of 10%, 20%, 30%, 40%, and 50% (v/v). Each working solution was prepared by diluting the specified volume of HCl stock solution with D_2O to a total volume of 50 mL (Table 1). Each coin was weighed prior to treatment on a digital analytical balance with a precision of ±0.001 g to establish a baseline mass. The coins were then fully immersed in the respective HCl solutions. Cleaning was carried out in controlled 10-minute stages. After each interval, the coins were removed, rinsed with heavy water, gently dried with blotting paper, and reweighed to monitor progressive material loss. The cleaning process was continued until a visible reduction in corrosion layers was observed. Stabilisation of weight between successive stages was evident only for the 10% and 20% treatments (Table 2); the 30%, 40%, and 50% treatments were stopped once a visible reduction in corrosion layers had been achieved, so the number of stages reflects this visual end point. Stage weight loss was calculated relative to the coin weight at the start of that stage, and cumulative weight loss relative to the initial weight. This stepwise approach allowed controlled interaction between the chemical solution and the coin surface. All experiments were conducted at ambient laboratory temperature, and the solutions were maintained under static conditions during treatment. Fixed time intervals and a constant solution volume were used to standardise the procedure; however, because each concentration was applied to a single coin, the design does not allow replication or statistical comparison between concentrations.

Table 1. Preparation of HCl working solutions used for controlled chemical cleaning.

Working solution (% v/v)	HCl stock solution (mL)	D_2O (mL)	Final volume (mL)
10%	5	45	50
20%	10	40	50

30%	15	35	50
40%	20	30	50
50%	25	25	50

Note: v/v = volume by volume*; D_2O = heavy water; mL* = millilitre

Post-treatment, neutralisation and pH verification

After chemical cleaning, the coins were immediately removed from the acid solution and thoroughly rinsed with heavy water to remove residual hydrochloric acid from the surface. The rinsing process was repeated multiple times to ensure effective dilution and removal of any remaining acidic residue.

To enhance removal of residual soluble contaminants, the cleaned coins were subjected to ultrasonic treatment in heavy water for approximately 5 minutes. This step facilitated removal of loosely bound corrosion products and residual ions from surface pores and micro-crevices. Completion of neutralisation was initially assessed by monitoring the pH of the final rinse water with pH indicator strips (range 2–7.5). Rinsing was continued until the pH reached a near-neutral value (pH ≈ 6.5–7), indicating removal of residual acidity from the coin surfaces.

To further verify the effectiveness of neutralisation, each cleaned coin sample was immersed in a known volume of heavy water for a fixed duration to allow any remaining soluble acidic species to leach into the solution. The samples were then centrifuged to obtain a clear supernatant. The pH of the extracted solution was measured using pH indicator strips against a calibrated colour scale. The measured pH values were near neutral (approximately pH 6.5–7), indicating the absence of significant residual acidity at the resolution of the indicator strips. After neutralisation and verification, the coins were carefully dried under ambient laboratory conditions. Excess moisture was removed with blotting paper, followed by air drying to avoid thermal or mechanical stress on the metal surface.

Surface stabilisation and protective coating

After drying, a thin protective coating of Paraloid B-72 was applied to the cleaned coin surfaces. The coating was applied in a controlled manner to form a uniform protective layer. This step was carried out to stabilise the surface, minimise exposure to environmental factors, and reduce the risk of further corrosion over time. The condition of the coated coins was monitored visually at 15-day intervals over a period of one year.

Metal loss analysis by atomic absorption spectroscopy (AAS)

The post-cleaning solutions from each experiment were collected, filtered, and analysed using an Elico SL-194 atomic absorption spectrophotometer. The analysis quantified the concentration of copper ions released into the solution during cleaning. The measured copper concentration was used to estimate the percentage of metal loss and to evaluate the effect of different acid concentrations on the integrity of the coins. All measurements were conducted under controlled laboratory conditions. The weighing precision was ±0.001 g, and instrumental uncertainties associated with AAS analysis were taken into account during data interpretation.

Visual documentation and typological identification

Surface condition was assessed by visual examination and photographic documentation before treatment and after successive treatments. Symbols were identified on the cleaned surfaces, compared with published descriptions of EUCCC, and used to group the coins typologically by the number and arrangement of symbols on each face.

Results

Elemental and phase composition

X-ray fluorescence (XRF) analysis of the selected coin samples (n = 5) indicated that copper was the predominant element in all cases. The copper content, expressed as CuO in oxide form, ranged from 64.89% to 87.08%, consistent with the copper-based nature of the coins. In addition to copper, minor amounts of SiO_2, Al_2O_3, Fe_2O_3, SnO_2, TiO_2, and trace elements such as Pb, Ni, and Zn were detected (Fig. 4). A relatively high proportion of silica (SiO_2) was recorded, particularly in some samples, suggesting the presence of siliceous encrustations and adhered soil particles on the coin surfaces [8,23]. Similarly, iron oxide (Fe_2O_3) and other minor oxides are likely derived from the burial environment and corrosion processes rather than representing intentional alloying components. The presence of chlorine (Cl) in all samples indicates chloride-related corrosion, which is commonly associated with prolonged burial in soil environments. The observed variation in minor elemental composition among samples reflects heterogeneity in corrosion behaviour and depositional conditions.

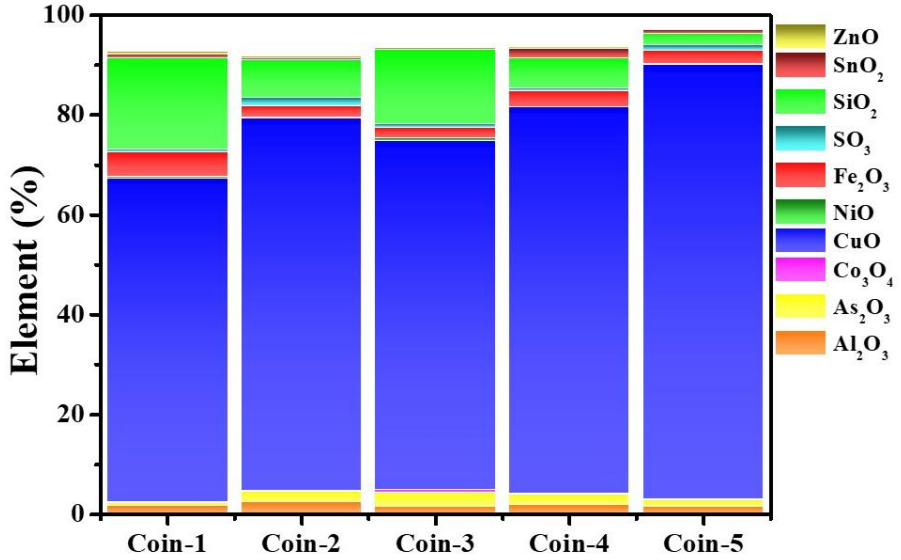


Fig. 4. Elemental composition of the selected coin samples based on the results of X-ray fluorescence (XRF) (Prepared by Ankur Yadav).

X-ray diffraction (XRD) patterns from all five samples show similar diffraction features, indicating comparable phase compositions across the coins (Fig. 5). Prominent diffraction peaks occur at approximately $2\theta \approx 43°$, 50°, and 74°, corresponding to the (111), (200), and (220) crystallographic planes of metallic copper (Cu), respectively. The high intensity of these peaks indicates that metallic copper was the dominant phase detected in all samples. In addition to metallic copper, weak diffraction peaks appear at $2\theta \approx 36–38°$ and around 61°, corresponding to the (111) and (220) planes of cuprous oxide (Cu_2O). The relatively low intensity of these peaks suggests that crystalline Cu_2O is a minor phase in the analysed surface volume. Only Cu and Cu_2O were assigned in the patterns; the chlorine and silica detected by XRF were not assigned to crystalline phases.

Based on XRF and XRD results, it is postulated that the coins predominantly contained metallic copper, with minor surface oxidation and adhered environmental deposits. This compositional and phase information provides context for the coins' corrosion behaviour and for the application of controlled chemical cleaning for surface recovery.

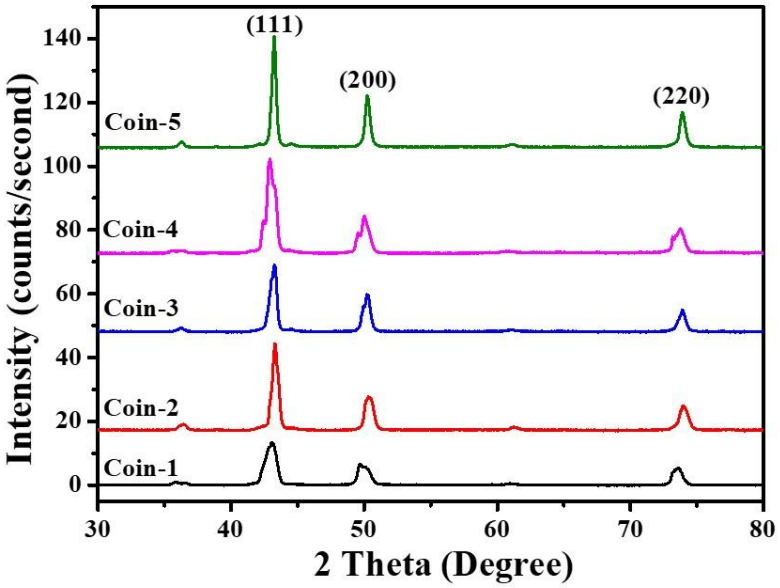


Fig. 5. Overlay of XRD spectra of selected coin samples from Malpar (Prepared by Ankur Yadav and Sayantan Mukherjee).

Weight loss during chemical cleaning

The weight parameters recorded during the chemical cleaning process show that total weight loss differed between the five treatments, which differed in HCl concentration, treatment time and the coin treated. When cleaned with different concentrations of HCl solution, the total weight loss among the samples ranged from 5.75% to 12.61% (Fig. 6). Stage losses in Table 2 are expressed relative to the coin weight at the start of that stage, whereas cumulative values are relative to the initial weight. For the sample treated with 10% HCl, the cleaning process was carried out in five stages of 10 minutes each, for a total treatment time of 50 minutes (Table 2). The total weight loss recorded was 0.181 g (6.20%). Weight loss occurred gradually at each stage, with higher loss in the initial stages and smaller changes in later stages, showing a progressive reduction in weight across successive intervals. In the case of 20% HCl, the cleaning was completed in four stages (40 minutes total). The total weight loss was 0.457 g (10.98%). A large portion of the weight loss occurred during the first three stages, after which the rate of loss decreased significantly.

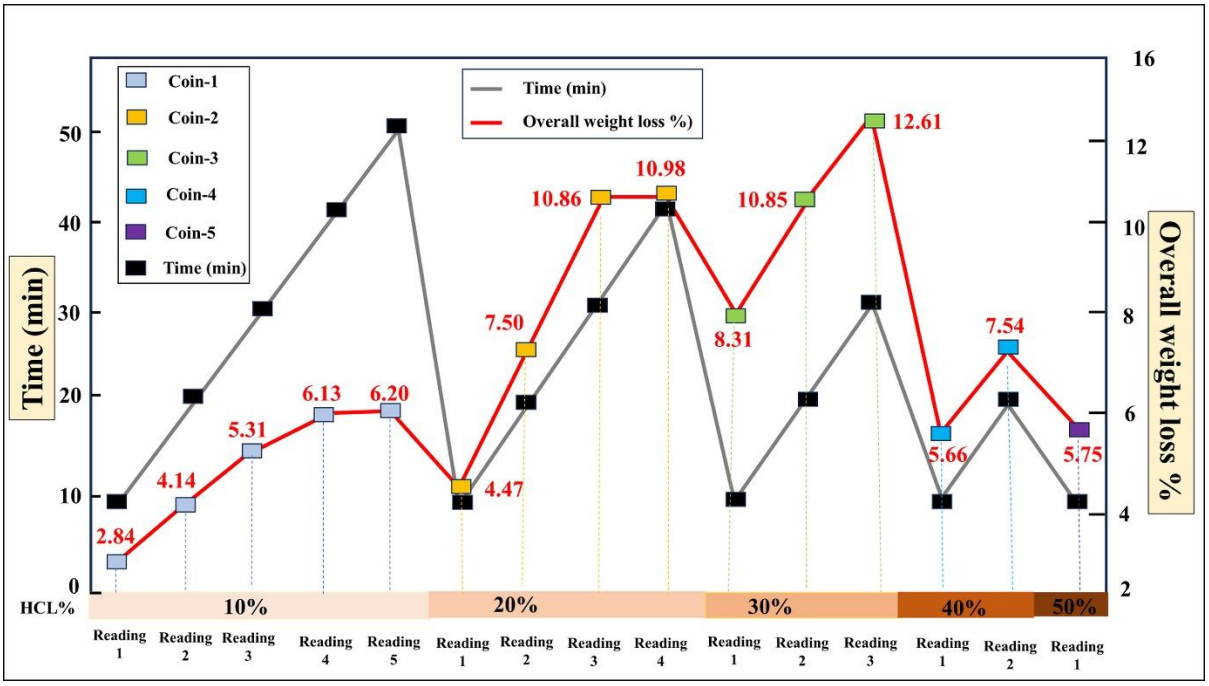


Fig. 6. Weight loss at different treatment times with different strength of HCl solution (Prepared by Sayantan Mukherjee and Dheeraj Sharma).

The sample treated with 30% HCl showed the highest weight loss among all samples. Cleaning was completed in three stages (30 minutes), with a total weight loss of 0.522 g (12.61%). Most of the material loss occurred in the first stage, followed by smaller losses in the later stages. For 40% HCl, the cleaning process required only two stages (20 minutes total). The total weight loss recorded was 0.257 g (7.54%). The majority of the weight loss occurred during the first stage, with minimal change in the second stage. The sample treated with 50% HCl required only one stage of 10 minutes to complete the cleaning process. The total weight loss was 0.223 g (5.75%). Despite the higher acid concentration, the total weight loss was lower compared to the samples treated with intermediate concentrations. After the first 10-minute stage, cumulative weight loss was 2.84%, 4.47%, 8.31%, 5.66% and 5.75% for 10%, 20%, 30%, 40% and 50% HCl, respectively, so the highest first-stage loss also occurred at 30% HCl. Overall, the number of stages required decreased as concentration increased (five stages at 10% HCl to one stage at 50% HCl), whereas total weight loss did not vary monotonically with concentration.

Table 2. Progressive weight loss of coins during cleaning, showing interval and cumulative weight loss (%). Stage weight loss (%) is relative to the weight at the start of that stage; cumulative weight loss (%) is relative to the initial weight.

Coin-1	Reading	Time (min)	Starting Weight (g)	Final Weight (g)	Weight Loss (g)	Weight loss (%)	Overall weight loss (%)
	1	10	2.921	2.838	0.083	2.84%	2.84%

	2	10	2.838	2.800	0.038	1.34%	4.14%
	3	10	2.800	2.766	0.034	1.21%	5.31%
	4	10	2.766	2.742	0.024	0.87%	6.13%
	5	10	2.742	2.740	0.002	0.07%	6.20%
Coin-2	1	10	4.162	3.976	0.186	4.47%	4.47%
	2	10	3.976	3.850	0.126	3.17%	7.50%
	3	10	3.850	3.710	0.140	3.64%	10.86%
	4	10	3.710	3.705	0.005	0.13%	10.98%
Coin-3	1	10	4.140	3.796	0.344	8.31%	8.31%
	2	10	3.796	3.691	0.105	2.77%	10.85%
	3	10	3.691	3.618	0.073	1.98%	12.61%
Coin-4	1	10	3.410	3.217	0.193	5.66%	5.66%
	2	10	3.217	3.153	0.064	1.99%	7.54%
Coin-5	1	10	3.876	3.653	0.223	5.75%	5.75%

Note: *min* = minutes; *g* = gram

Copper loss from AAS analysis

Atomic absorption spectroscopy (AAS) analysis of the post-cleaning solutions was conducted to determine the percentage of copper dissolved during chemical cleaning at varying hydrochloric acid concentrations. The results show a clear variation in copper loss with acid concentration (Fig. 7). At 10% HCl, the copper loss was 2.82%, increasing to 4.21% at 20% HCl. The maximum copper loss was observed at 30% HCl, reaching 6.89%, indicating the highest level of metal dissolution among all samples. At higher concentrations, the copper loss decreased. For 40% HCl, the copper loss was reduced to 3.21%. The minimum copper loss was recorded at 50% HCl, with a value of 2.43%, despite the higher acid concentration. Each value corresponds to one coin and one post-cleaning solution. Copper loss was numerically lower than the corresponding total weight loss in every treatment (Figs. 6 and 7). Overall, the results show that copper dissolution varied between treatments, with maximum loss at an intermediate concentration (30% HCl) and minimum loss at a higher concentration (50% HCl).

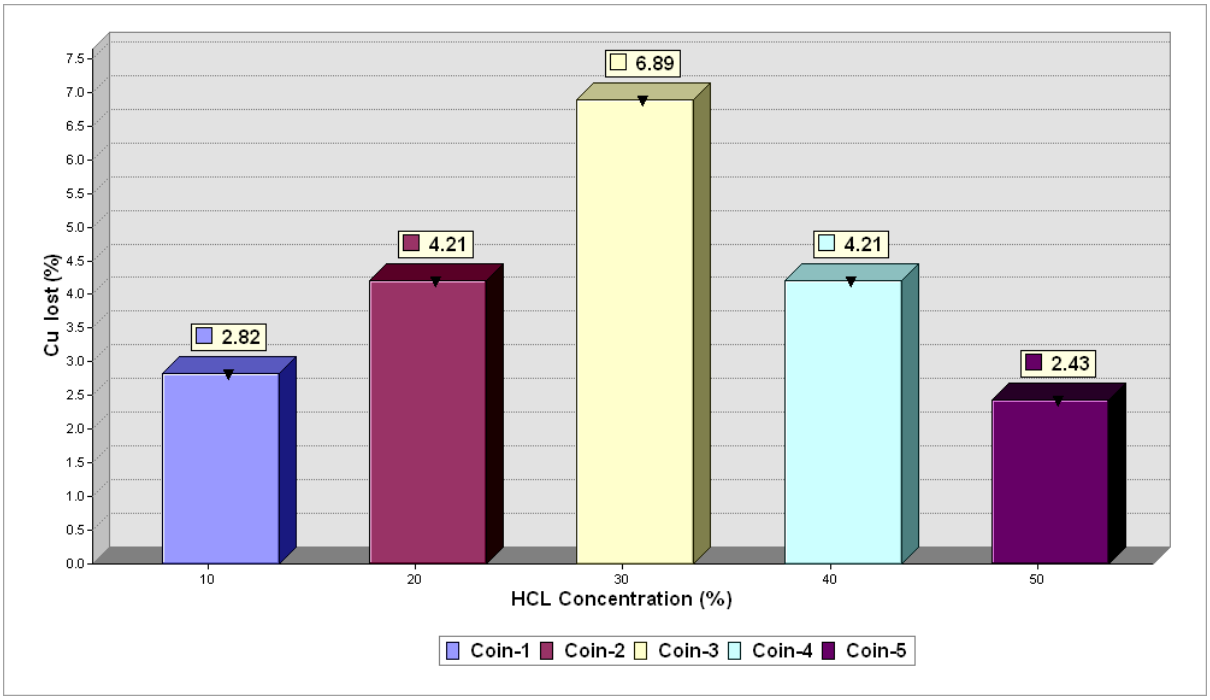


Fig. 7. Cu lost in the solution at different concentrations of HCl determined by atomic absorption spectroscopy (AAS) (Prepared by Sayantan Mukherjee).

Surface observation and coin identification

No visible macroscopic damage was observed after the cleaning process by visual examination and photographic documentation. The overall morphology of the coins remained intact, and the treatment enhanced legibility without visibly affecting the surface features. Visual examination of the coin surfaces before and after cleaning revealed a marked reduction in corrosion layers and encrustations (Fig. 8a & b). Prior to treatment, the surfaces of the coins were covered with thick deposits, which obscured symbols and surface features, making identification difficult. After controlled chemical cleaning, the removal of corrosion layers resulted in a clear improvement in surface visibility. The symbols present on both the obverse and reverse sides became distinctly visible, allowing for identification and typological classification of the coins.

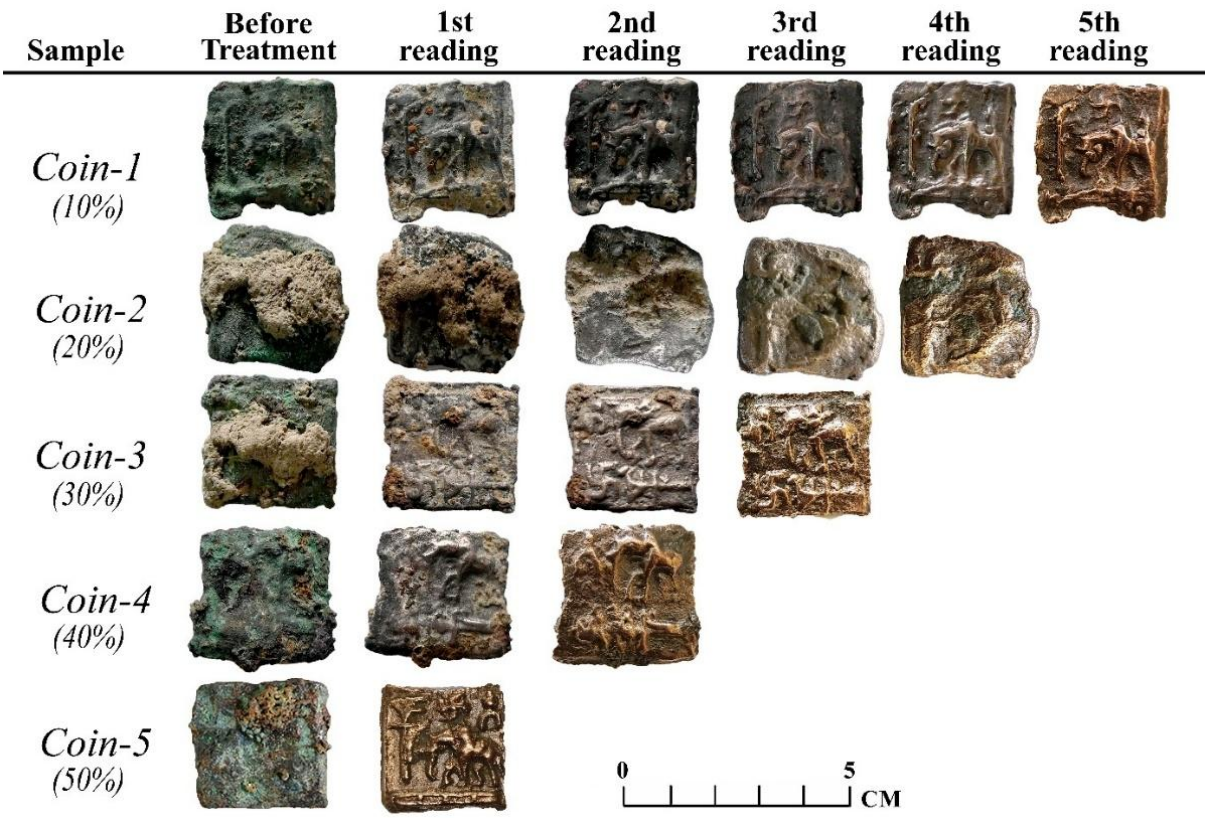


Fig. 8 (a). Obverse of each coin before treatment and after successive treatments, revealing the gradual removal of corrosion layers and improved surface legibility (Photo by Dheeraj Sharma).

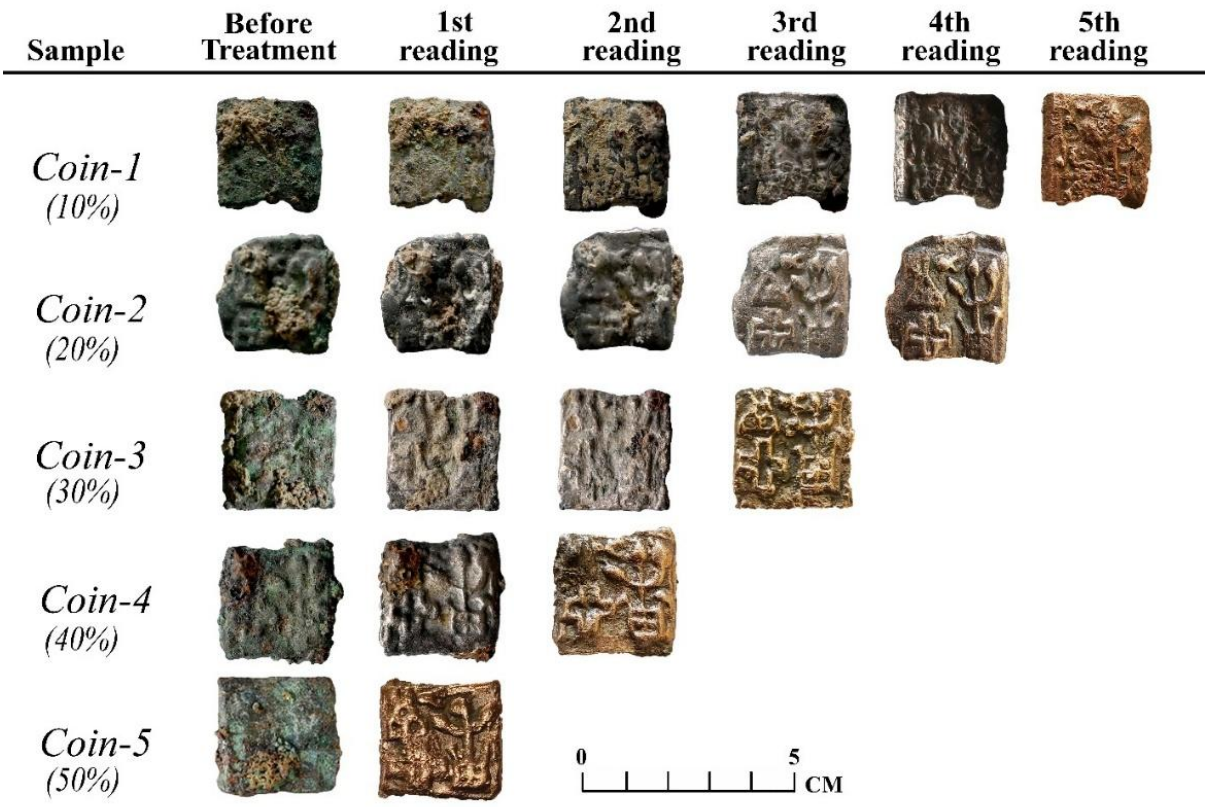


Fig. 8 (b). Reverse of each coin before treatment and after successive treatments, revealing the gradual removal of corrosion layers and improved surface legibility (Photo by Dheeraj Sharma).

Careful examination of the cleaned coin surfaces revealed a set of characteristic symbols commonly associated with uninscribed copper cast coins, a type of early Indian coinage. These include symbols such as the *swastika*, taurine, elephant (facing left), *Indra-dhvaja*, tree-in-railing, hollow cross, three-arched hill with crescent, and ladder motif. The presence and arrangement of these symbols enabled typological classification of the coins into two distinct groups (Fig. 9). Type-1 coins are characterised by the presence of five symbols on the obverse, including *swastika*, taurine, elephant, ladder, and *Indra-dhvaja*, and four symbols on the reverse, including tree-in-railing, hollow cross, three-arched hill with crescent, and taurine.

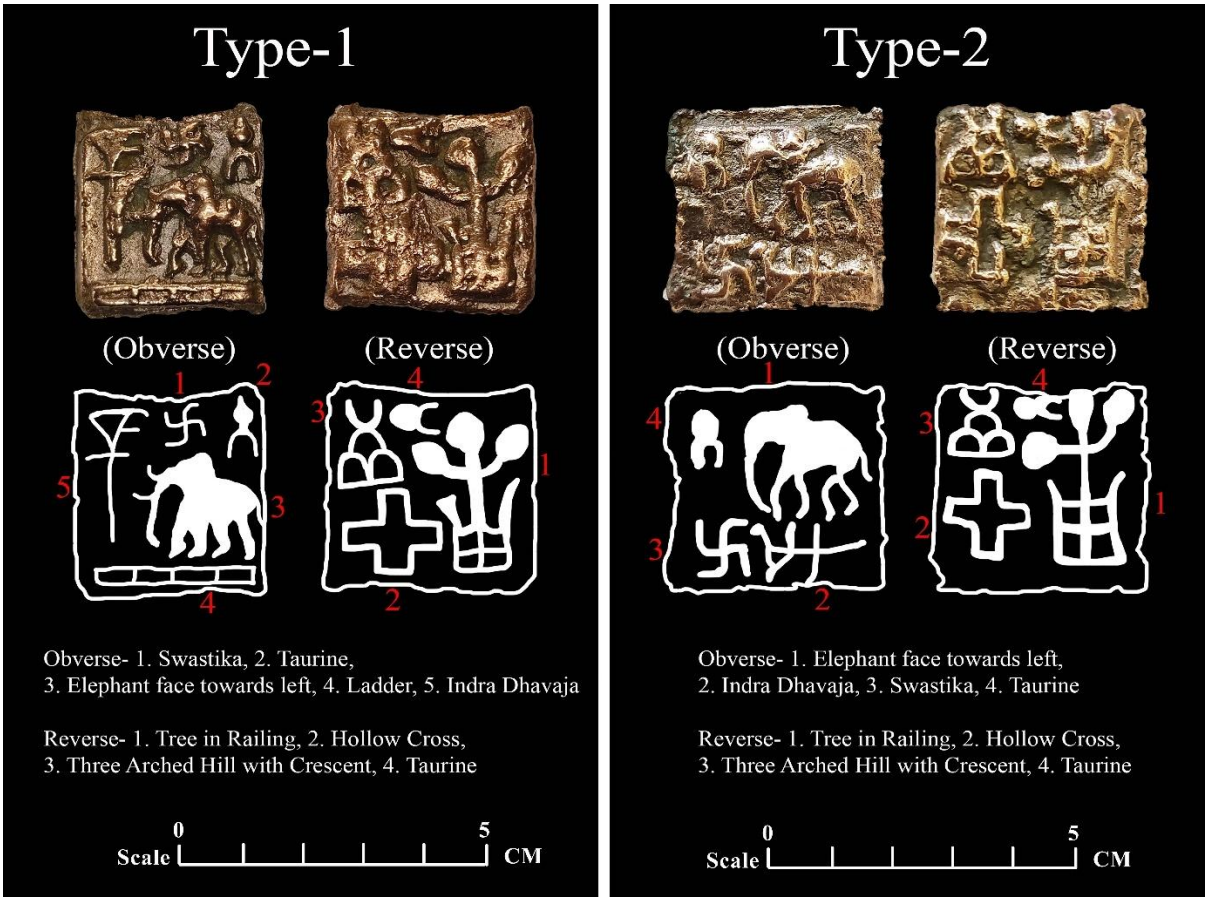


Fig. 9. Symbol typology of cleaned EUCCC from Malpar Hoard (Photo by Dheeraj Sharma).

Type-2 coins display four symbols on both the obverse and the reverse, including elephant, *Indra-dhvaja*, *swastika*, and taurine on the obverse, and tree-in-railing, hollow cross, three-arched hill with crescent, and taurine on the reverse. The identification of these symbols and their arrangement is consistent with the category of Early Uninscribed Copper Cast Coins (EUCCC), which represent one of the earliest forms of coinage in ancient India.

Neutralisation and stabilisation

The pH of the extracted solutions after immersion and centrifugation was measured and found to be near neutral (pH ~6.5–7) for all samples, indicating that residual acidity had been removed to within the resolution of the indicator strips. Following coin cleaning and neutralisation, a protective coating of Paraloid B-72 was applied to the fully dried surfaces of all five coins. The coated surfaces appeared stable and uniform under visual inspection, with no immediate changes to surface features or symbols. The stability of these coated coins was further monitored at 15-day intervals over a period of one year. No visible changes in colour, weight, or surface condition were observed during this period.

Discussion

This study examined how hydrochloric acid concentration and exposure time relate to corrosion removal and material loss in five archaeological copper coins from Malpar. In this small data set, the number of 10-minute stages needed to reach the visual end point fell from five at 10% HCl to one at 50% HCl, while total weight loss (5.75–12.61%) and copper loss in solution (2.43–6.89%) were both highest at 30% HCl and lowest at 50% HCl. These trends are descriptive: because each concentration was applied to a different coin, without replicates, the effects of acid concentration, exposure time and coin-specific condition (such as initial mass and corrosion thickness) cannot be separated.

A kinetic explanation is plausible [2,13]. At intermediate concentrations, the dissolution rate may be high enough to remove corrosion products while the longer exposure allows continued interaction between the solution and the underlying metallic substrate [12,15], so that both corrosion layers and portions of the base metal are dissolved, leading to higher cumulative loss. At 50% HCl, the rapid removal of surface corrosion layers shortens the duration of acid–metal interaction and may limit deeper penetration into the metallic core [11,14]. Prolonged interaction can also lead to greater cumulative loss at lower acid strengths [2,12]. However, this explanation is not fully supported by the present data. The highest first-stage weight loss was also recorded at 30% HCl (8.31%, compared with 5.66% at 40% and 5.75% at 50% for the same 10-minute exposure), which points to coin-specific factors, such as the thickness and composition of the corrosion crust, as a likely contributor. The number of stages also reflects the visual end point chosen for each coin rather than an independently measured dissolution rate.

Compositional and phase analyses from XRF and XRD provide context for these results [6,24]. The predominance of metallic copper, together with cuprous oxide (Cu_2O) and siliceous encrustations, suggests that both corrosion products and adhered burial deposits contribute to the weight lost during cleaning. Copper in the post-cleaning solutions was numerically lower than the corresponding weight loss in every treatment, consistent with part of the weight loss consisting of non-copper encrustation, although the two percentages may not share the same basis. AAS also cannot distinguish copper released from corrosion products from copper dissolved from the metallic core, so the copper-loss values should not be read as loss of original metal alone. Dissolving corrosion layers is necessary for surface recovery; however, excessive removal can compromise the artefact's integrity if not carefully controlled [6,8,25].

Rinsing and ultrasonic treatment brought the extracts to near-neutral conditions (pH ~6.5–7), indicating that residual acidity was largely removed. Indicator strips have limited resolution

and chloride was not measured directly, so residual chloride ions, which are known to promote active corrosion in copper-based materials [8], cannot be excluded. Paraloid B-72 has been used as a protective coating [26–28], and it forms a transparent barrier that reduces exposure to environmental factors without obscuring surface features [28]. Visual monitoring over one year showed no observable change in colour, weight or surface condition; this is a limited period and method of observation and does not replace longer-term or accelerated ageing tests.

In this data set, the 50% HCl treatment reached the visual end point in a single 10-minute stage with the lowest weight loss and copper loss, whereas the 30% treatment produced the highest losses. These results suggest that short, closely monitored exposures merit further testing, but they do not establish an optimal concentration. The importance of controlled exposure conditions in chemical cleaning has been noted in previous studies [2,13], emphasising the need for carefully optimised treatment protocols in archaeological conservation.

The cleaning process substantially improved the visibility of surface features, enabling detailed identification of motifs on the coins. The observed symbols include the *swastika*, taurine symbol, elephant, *Indra-dhvaja*, tree-in-railing, hollow cross, three-arched hill with crescent, and ladder motif. The arrangement and combination of these symbols enabled classification of the coins into two distinct types based on their distribution on the obverse and reverse surfaces. The identified features are consistent with the category of Early Uninscribed Copper Cast Coins (EUCCC), which represent one of the earliest forms of coinage in ancient India [29]. These coins are characterised by the absence of inscriptions and the use of symbolic representations, typically produced through casting techniques. As per Tye and Mitchiner, “these coins were certainly intended as more than one denomination, but weight standards appear to have been poorly adhered to, especially amongst the smaller coins” [30,31]. Buddhist and Brahmanical literature also refer to different types of copper coins in various multiples, such as *Vimisatika, Ardha and Pada Vimisatika, Kārsapana, Māsa, Kākini and Ardh Kakini,* based on their weight [32]. Since the final (cleaned) weights of the five coins taken up for the current study range between 2.740 g and 3.705 g (Table 2), they could be identified as ancient *Karshapan* (Prof. O. N. Singh, *personal communication*). It was also noticed that a few symbols on the cleaned copper cast coins from this study, such as tree-in-railing, three-arched hill with crescent, and hollow cross, were also present on the Mauryan punch-marked coins. Continuity of these motifs across time may be associated with authority, authenticity, or acceptance, or with a weight standard [29]. Thus, the symbolic motifs on these coins likely served functional and

communicative purposes. In this sense, the symbols can be understood as a visual system conveying information related to value and trust in early monetary practices.

Comparable coins with the same motif typology as cleaned coins type 1 and 2 have been reported from a wide geographical area across the Indian subcontinent, including sites such as Kaushambi [33], Hastinapur [34], Rajghat [35], Pataliputra [36], Nalanda [29], Maheshwar [37], Navadatoli [37], Chandraketugarh and Sisupalgarh [38]. This wide distribution suggests that such coins circulated widely and played a significant role in early economic and exchange systems. The location of Malpar right on the ancient route connecting Kaushambi and Ujjain suggests that it was closely associated with trade activities. This raises the possibility that these coins were minted in Eran in Vidisha and Kaushambi, as both have been identified as copper-cast coin-minting centres [39,40].

Archaeological evidence from stratified contexts indicates that EUCCC were used over a long period and often coexisted with punch-marked coins. Comparative analysis of similar finds from dated sites allows the coins in the present study to be tentatively assigned to an approximate period between 600 BCE and 100 BCE [29,33–36,41–45]; this attribution rests on typological comparison rather than independent dating of the Malpar hoard. In this case, chemical cleaning enabled the identification and classification of the coins, illustrating how conservation and archaeological interpretation depend on one another.

The conclusions of this study are limited by its design. Each HCl concentration was applied to a single coin, so concentration, exposure time and coin-specific condition are confounded, and no statistical comparison was possible. Weight loss includes encrustation and corrosion products as well as metal, and AAS cannot separate copper from corrosion products from copper from the metallic core. The basis of the percentage copper loss, the stopping rule (a visual end point) and the intervals between weighings further limit comparison between treatments. XRF and XRD were performed on corroded surfaces and do not give the bulk alloy composition, and no post-treatment surface characterisation (for example microscopy or elemental mapping) was undertaken, so “no macroscopic damage” refers only to visual examination. Chloride removal was not measured, pH was read with indicator strips, and the one-year monitoring was visual. Alternative cleaning methods were not compared.

In conclusion, in this exploratory study of five EUCCC coins from Malpar, HCl cleaning in 10-minute stages improved the legibility of symbols and allowed typological classification, with total weight loss of 5.75–12.61% and copper loss of 2.43–6.89% across the 10–50%

treatments, and with the highest losses at 30% HCl. Neutralisation to near-neutral pH and Paraloid B-72 coating were followed by no visible deterioration over one year. These findings are preliminary. A replicated design, with several coins of comparable condition per concentration, a defined end-point criterion, direct chloride testing and microscopic or elemental examination before and after cleaning, is needed before any concentration or exposure time can be recommended for archaeological copper coins.

Data availability

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

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Competing interests

The authors declare no competing interests.

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