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RESEARCH ARTICLE

REINTERPRETATION OF ELEMENTAL SIGNATURES IN INDO-PACIFIC GLASS BEADS: INSIGHTS INTO ANCIENT TECHNOLOGIES, TRADE NETWORKS, AND ANTHROPOGENIC FINGERPRINTS FROM THE SUNGAI MAS ARCHAEOLOGICAL SITE

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ABSTRACT

This study presents a reinterpretation of elemental data from Indo-Pacific glass beads excavated from the Sungai Mas archaeological site in the Bujang Valley, Malaysia. The published analytical data gathered from literature are used to quote the elemental concentrations, specifically those of copper (Cu), zinc (Zn), iron (Fe), manganese (Mn), chromium (Cr), and arsenic (As). High-precision multi-elemental quantification was done using Instrumental Neutron Activation Analysis (INAA). Reassessment of these data reveals deliberate inclusion of metal oxides to achieve specific colour properties, such as high Cu and Zn in blue and orange beads, and Fe and Mn in black and yellow varieties. Elevated levels of arsenic and antimony further suggest the use of refining and opacifying agents, reflecting advanced glassmaking knowledge and material control. In addition to technological implications, the dataset reflects early anthropogenic fingerprints, possibly linked to recycling of metallurgical by-products. These findings support the role of Sungai Mas as an important production or redistribution center along the Indo-Pacific maritime trade routes. The study highlights how compositional analysis of archaeological materials can inform interpretations of ancient technologies, socio-economic networks, and early environmental interactions.

KEYWORDS

Indo-Pacific beads, Sungai Mas, elemental analysis, ancient glass technology

1. INTRODUCTION

Indo-Pacific glass beads are among the most widespread and chronologically persistent artifacts in early Southeast Asian archaeology, serving not only as ornamental items but also as indicators of trade, technology, and cultural exchange. Their presence across maritime Asia, from India to the Malay Peninsula and beyond, points to an extensive interaction network linking early societies in a shared sphere of technological innovation. In Malaysia, the Bujang Valley—particularly the Sungai Mas site—has yielded a rich assemblage of such beads, making it one of the most significant archaeological locales for studying ancient material culture in the region. These beads offer vital clues not only about aesthetic preferences but also about the technological capabilities and raw material choices of ancient craftspeople (Rahman et al., 2008; Bertini et al., 2011; dos Santos et al., 2013).

Compositional analysis of glass beads provides essential insights into the materials and processes used in their production. Elements such as copper (Cu), iron (Fe), zinc (Zn), manganese (Mn), chromium (Cr), and arsenic (As) play critical roles in glass colouration, opacity, and stability. Studies employing analytical techniques like Instrumental Neutron Activation Analysis (INAA) and Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS) have successfully uncovered multi-elemental profiles of these artifacts (Rahman et al., 2008; Kozmenko et al., 2025; Park et al., 2016). This study, conducted a comprehensive elemental analysis of Sungai Mas beads using INAA, producing high-quality data on the presence of major, minor, and trace elements (Notably et al., 2008). Their work laid the foundation for further interpretation of the beads' production technology and provenance, while complementary studies have applied similar techniques to glass beads from other contexts to assess toxic metal content, opacifiers, and production recipes (Sandhu et al., 2013; Nakayama et al., 2005; Kon et al., 2011).

While previous studies have emphasized classification and typology, there remains a need for more critical reinterpretation of elemental signatures to better understand the broader technological and environmental implications of ancient glassmaking. The concentrations of heavy metals such as Cu, Fe, and Cr not only reflect chromophoric and functional roles but may also carry anthropogenic signatures—traces of early recycling practices, exposure to proto-industrial pollutants, and use of metallurgical residues (Sandhu et al., 2013; Burghardt et al., 2022). Studies on modern industrial glass beads have demonstrated how hazardous elements can

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leach from materials used in road markings and other applications, suggesting similar environmental risks may have existed historically, even if unrecognized at the time (Tang et al., 2019; Orihashi et al., 2003).

This paper aims to reinterpret the elemental dataset by focusing on the functional, technological, and environmental implications of selected heavy metals in Indo-Pacific beads from Sungai Mas (Rahman et al., 2008). Special attention is given to the roles of Cu, Zn, Fe, Mn, Cr, and As, which are examined in relation to bead colour, technological sophistication, and potential anthropogenic inputs.

2. Methodology

The elemental data used in this study are cited (Rahman et al., 2008). The study conducted forms the primary source of quantitative data for trace elements including copper (Cu), zinc (Zn), iron (Fe), arsenic (As), manganese (Mn), chromium (Cr), which are reinterpreted in the present work to explore their archaeological and environmental significance (Rahman et al., 2008).

Briefly, this study obtained glass bead samples from the Department of Museum Malaysia, representing a variety of colours, shapes, and sizes (Rahman et al., 2008). The samples were cleaned ultrasonically to remove surface contaminants and dried at room temperature. Subsamples weighing 20–50 mg were prepared and sealed in clean polyethylene vials. Instrumental Neutron Activation Analysis (INAA) was performed at the Malaysian Nuclear Agency using the TRIGA MARK II research reactor, operating at a thermal neutron flux of approximately 1×10^{12} cm^{-2} s^{-1}. Gamma-ray spectrometry was employed post-irradiation to quantify elemental concentrations. Analytical reliability was validated using the IAEA-certified reference material SL-1, ensuring the accuracy and reproducibility of the results.

3. Results

Concentrations of heavy metals in Indo-Pacific glass beads from Sungai Mas, Bujang Valley, Malaysia is shown in table 1. Copper (Cu) concentrations among the Indo-Pacific beads demonstrated considerable variability, reflecting diverse manufacturing practices and intentional inclusion for colour properties. The most prominent Cu enrichment was observed in sample 331 A (Blue) with a remarkably high value of 6390.00 ± 575.00 ppm, suggesting the deliberate use of Cu to produce blue colouration. Other samples with moderate Cu values include 331 Hb (Orange opq; 43.1 ± 3.9 ppm) and 90 G (Blue; 29.5 ± 2.7 ppm), while Cu levels in samples like 331 I (White; <0.1 ppm) and several green beads (e.g., 1239 C, Db) were notably low, indicating the absence of copper-based additives.

Zinc (Zn) levels ranged broadly, with 331 A (Blue) again standing out at 6390 ± 575 ppm, aligning with its intense blue hue possibly enhanced by ZnO-based compounds. Elevated Zn values were also found in 331 Hb (Orange opq; 43.1 ± 3.9 ppm) and 1239 B (Red opq; 43.1 ± 3.9 ppm), which may serve as both opacifiers and fluxing agents. In contrast, several greenish or yellowish samples such as 1239 F (Green-blue; 18.1 ± 1.6 ppm) and 331 E (Green opq; 138.0 ± 12.3 ppm) contained relatively low Zn, suggesting limited use or exclusion of Zn additives in these colour groups.

Iron (Fe) contents were notably variable across the samples. The highest Fe percentage was detected in 331 F (Black) at 15.2 ± 1.7%, consistent with its deep black appearance and reinforcing Fe's role as a black colourant. Other red and black beads, such as 1239 B (Red opq; 1.87 ± 0.20%) and 331 B (Red opq; 1.77 ± 0.18%), showed similarly elevated Fe content. By contrast, 331 I (White; 0.19 ± 0.02%) and 331 J (Blue opq; 0.44 ± 0.06%) had the lowest Fe percentages, in line with their light or translucent appearances.

As concentrations varied significantly, with maximum levels in 331 B (Red opq; 21.1 ± 2.1 ppm) and 90 G (Blue; 12.6 ± 1.3 ppm), possibly linked to its use as a fining or opacifying agent in glass production. Several samples showed intermediate values between 5–10 ppm, such as 1239 A (Black; 5.34 ± 0.52 ppm) and 1239 C (Green opq; 8.81 ± 0.87 ppm). On the lower end, 331 A (Blue) and 331 Ha (Orange + Black opq) recorded levels below 1 ppm, indicating minimal or no arsenic input.

Manganese (Mn) displayed a broad spectrum across the beads. The highest Mn concentration was reported in 331 D (Yellow opq) with 9600 ± 768 ppm, highlighting its probable function as a glass decolourizer or yellow/purple tinting agent. Other high Mn values were found in 331 A (Blue; 789 ± 68 ppm) and 1239 F (Green-blue; 675 ± 54 ppm). In contrast, relatively lower Mn content was observed in samples like 331 Hb (Orange opq; 620 ± 31 ppm)

Chromium (Cr) was another key element exhibiting significant variation. The highest Cr level was observed in 1239 A (Black) at 54.6 ± 4.9 ppm, possibly contributing to black or dark green hues through Cr^3+ ion incorporation. Elevated levels were also recorded in 331 B (Red opq; 49.8 ± 4.5 ppm) and 331 C (Orange opq; 49.5 ± 4.5 ppm), aligning with the known use of Cr compounds in red-orange colouration. The lowest Cr concentrations (<30 ppm) were found in green and yellowish samples like 1239 F (Green-blue; 25.2 ± 2.3 ppm) and 331 I (White; 21.4 ± 2.0 ppm), where Cr-based pigments are unlikely to have been employed.

Table 1: Concentrations of heavy metals in Indo-Pacific glass beads from Sungai Mas, Bujang Valley, Malaysia.

Sample ID	Colour	Fe, %	Mn, ppm	Zn, ppm	Co, ppm	Cr, ppm	As, ppm
1239 A	Black	1.87	488	39.4	7.24	54.6	5.34
1239 B	Red (opq)	1.87	534	43.1	12.4	46	9.16
1239 C	Green (opq)	1.23	510	26.6	0.5	30.5	8.81
1239 Da	Green-blue	1.05	483	33.9	7.61	29.3	13.4
1239 Db	Green	1.47	471	34.1	9.33	31.5	9.86
1239 E	Yellow (opq)	1.24	482	27.1	5.87	34.1	3.65
1239 F	Green-blue	0.94	675	18.1	4.4	25.2	1.12
331 A	Blue	0.97	789	6390	28.1	60.5	<0.1
331 B	Red (opq)	1.77	442	37.5	9.33	49.8	21.1
331 C	Orange (opq)	1.72	503	28.2	3.77	49.5	3.43
331 D	Yellow (opq)	0.95	9600	27.8	6.87	37.2	5.87
331 E	Green (opq)	1.36	1060	138	9.19	41.9	580
331 F	Black	15.2	3140	110	4.12	42.3	6.45
331 G	Dark blue	0.36	5430	32.5	4.34	37.6	24
331 Ha	Orange + black (opq)	1.04	426	28.4	4.87	32.1	<0.1
331 Hb	Orange (opq)	1	456	43.1	5.22	31.5	5.88
331 I	White	0.19	1280	<0.1	0.2	21.4	1.16
331 J	Blue (opq)	0.44	2350	508	3.15	35.1	18.4
90 A	Green	2.4	302	41.3	8.83	41.4	1.25
90 B	Red (opq)	1.71	556	41.8	8.63	36.3	2.44
90 D	Brown	1.55	725	35.1	3.24	25.7	1.02

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Table 1 (cont): Concentrations of heavy metals in Indo-Pacific glass beads from Sungai Mas, Bujang Valley, Malaysia.

90 E	Yellow (opq)	1.6	474	35.4	2.61	31.6	6.97
90 F	Green-blue	1.24	523	36.5	3.65	31.6	13.6
90 G	Blue	1.18	2620	29.5	11.7	26.5	12.6

Source: Rahman et al., 2008

4. DISCUSSION

4.1 Technological Implications of High Cu and Fe Contents

The high Cu and Fe concentrations in beads like sample 331 A (Blue) and 331 F (Black) suggest their intended employment as chromophores in ancient glassmaking. Copper values above 6000 ppm in blue beads indicate the employment of Cu^{2+} ions for deep blue coloration, a procedure found in Indo-Pacific and Mediterranean glassmaking traditions (Koleini et al., 2019; Rahman et al., 2008). Redox manipulation during burning probably produces rich, opaque tones from iron oxides in black beads with Fe concentrations of 15% (Gratuze, 2013). These findings show that ancient Southeast Asian artists were skilled pyrotechnologists who could adjust furnace conditions to stabilize oxidation states and purposely add metal additions. The constituent profiles match global early glass production trends, demonstrating Sungai Mas glassmakers' technological proficiency.

Figure 1 show the overall importance of heavy metal compositions of ancient glass beads.

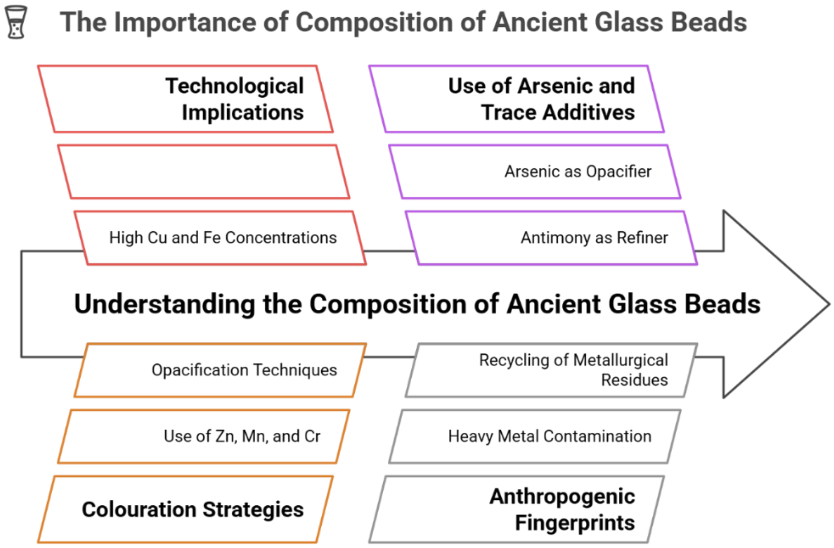

Figure 1: The overall importance of heavy metal compositions of ancient glass beads.

4.2 Colouration Strategies Using Zn, Mn, and Cr Oxides

Sungai Mas beads use Zn, Mn, and Cr for color modification and opacification. Sample 331 A's high Zn concentration (6390 ppm) supports its dual role as a flux and opacity enhancer, stabilizing the glass matrix and maybe adding brightness (Bertini et al., 2011). Mn, present at 9600 ppm in yellow and blue beads, presumably served as a decolorizer, hiding Fe's greenish hue, and chromophore, producing pink to purple tints based on Mn^{2+}/Mn^{3+} ratio (Shugar et al., 2012). Cr, abundant in black, red, and orange beads (up to 54.6 ppm), contributes to green and dark tones through thermally stable Cr^{3+} complexes under reducing circumstances (Kozmenko et al., 2025). Local glassmakers used indigenous minerals to create a range of durable and bright colors using advanced empirical knowledge of raw ingredients and regulated kiln settings.

4.3 Use of Arsenic and Trace Additives as Opacifiers and Refiners

As at 21.1 ppm (331 B) and 12.6 ppm (90 G) in red, orange, and blue beads suggests arsenates were added to improve opacity and refine the glass melt. Historical literature and experimental archaeology show that as compounds were used to eliminate gas bubbles and create a smooth, translucent surface, which is supported by the presence of antimony (Sb) in various samples (Sandhu et al., 2013; Rahman, 2008). The variety of As and Sb levels in the bead assemblage suggests recipe specialization in ancient glass studios based on aesthetic aims and material availability. Such careful use of trace chemicals shows pre-industrial crafts people's nuanced awareness of glass refining processes, balancing useful material science and beautiful skill.

4.4 Regional Exchange and Provenance Inferences from Elemental Signatures

The Indo-Pacific beads from Sungai Mas may have come from multiple technological traditions or raw material sources according to elemental profile variance, especially Cr, Mn, Zn, and Cu. Samples 331 A (high in Cu, Zn, Mn) and 331 F (high in Fe, Cr) may have been produced in different glassmaking centers or used different mineral resources, possibly due to trade routes that supplied different silicate sands and metallurgical residues. This geochemical diversity suggests that Sungai Mas was part of a broad Indo-Pacific commerce and manufacturing network that included technology transfers from South Asia, West Asia, and maybe the eastern Mediterranean (Ali et al., 2024). The beads are both artifacts of local workmanship and material proxies for reconstructing trans-regional cultural interactions and high-value raw material flows throughout the early maritime Silk Road. The Bujang Valley's vital location in historic economic and technological landscapes is highlighted by local production and imported technologies.

4.5 Possible Anthropogenic Fingerprints Reflected by Heavy Metals

This study found that Indo-Pacific glass beads from Sungai Mas contain six heavy elements that reflect proto-industrial anthropogenic imprints as well as technological use. Extremely high levels of Cu (up to 6390 ppm), Mn (up to 9600 ppm), and Cr (up to 54.6 ppm) may result from intentional chromophore use and sourcing from contaminated ores, recycled metallurgical slag, or industrial by-products, which were increasingly available in developing urban centers. Arsenic (up to 21.1 ppm) and antimony (Sb) support the idea that ancient artisans used semi-refined or recycled compounds from early copper-smelting residues, which is consistent with pre-modern metallurgy recycling (Sandhu et al., 2013).

Anthropogenic signatures match socio-economic development in the Bujang Valley, where early settlement expansion and trading networks allowed the acquisition of diverse raw materials, including metallurgical derivatives from external production hubs (Ali et al., 2024). The continuous use of non-essential and potentially dangerous ingredients—especially in red and black beads—raises questions about early exposure to hazardous compounds. No direct evidence suggests awareness of their toxicological hazards, but empirical control of their physical and chemical alterations during high-temperature processing reveals a smart, ecologically oblivious material science.

A deeper historical continuum of human-induced elemental dispersion suggests that heavy metal contamination may have predated the industrial revolution. Over ages, replicating such glassmaking methods may have contaminated soils and aquatic systems, especially around workshop areas. Thus, these beads serve as chemical proxies for assessing early human impacts on the geochemical landscape, emphasizing the need to view environmental degradation in a longue durée perspective that includes pre-industrial and artisanal industries as major contributors to historical ecological change.

5. Conclusion

The elemental analysis of Indo-Pacific glass beads from the Sungai Mas archaeological site shows that ancient glassmakers carefully used heavy metals including Cu, Zn, Fe, Mn, Cr, and As. The wide concentration ranges and significant colour-element correlations suggest metallic oxides were used to give blue, red, black, and yellow hues. Ancient Southeast Asian artisans' advanced pyrotechnology and redox chemistry skills are shown by high Cu and Fe levels in blue and black beads. Mn and Cr indicate sophisticated colour-stabilising and decolourising, whereas mild As and Sb levels indicate the employment of fining and opacifying chemicals to improve glass quality and appearance. These compositional fingerprints may indicate proto-industrial waste and metallurgical byproduct recycling in early anthropogenic activities. The data suggest that Sungai Mas was a major trans-Asian commerce hub with imported materials and regional glass technologies. Isotopic analysis and geochemical fingerprinting could help explain Southeast Asia's early technological and cultural contacts by revealing these items' provenance and production origins.

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