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Population Biomonitoring of Lead, Cadmium, Mercury, and Arsenic in Human Blood: Demographic, Occupational, and Public-Health Patterns

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Abstract: *Heavy-metal exposure remains a persistent environmental and occupational health challenge because toxic metals are non-biodegradable, bioaccumulative, and capable of disrupting essential biochemical processes at low concentrations. This cross-sectional biomonitoring study quantified lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) in blood samples from 300 participants representing children, adults, occupationally exposed workers, fisherfolk, rural agricultural workers, and a low-exposure control population. Blood collection, transport, digestion, and storage were performed under trace-metal contamination-control conditions. Atomic Absorption Spectroscopy and Inductively Coupled Plasma Mass Spectrometry were employed with certified reference materials, blanks, internal standards, replicate analysis, and recovery checks. Mean concentrations were 11.2 ± 4.8 µg/L for Pb, 2.4 ± 1.1 µg/L for Cd, 7.8 ± 3.2 µg/L for Hg, and 15.5 ± 6.7 µg/L for As. The proportions exceeding the thesis-adopted reference thresholds were 62%, 54%, 39%, and 47%, respectively. Children exhibited higher mean blood lead than adults (13.5 versus 9.6 µg/L). Occupational groups showed elevated Pb and Cd, fisherfolk showed higher Hg consistent with seafood exposure, and rural agricultural workers showed higher As consistent with groundwater and agrochemical pathways. Pb and Cd were strongly correlated ($r = 0.68$, $p < 0.01$), while Cd and As showed a moderate association ($r = 0.42$, $p < 0.05$). These findings demonstrate mixed-source exposure and identify vulnerable subgroups requiring targeted surveillance, workplace controls, safe-water interventions, dietary risk communication, and sustained national biomonitoring.*

Keywords: heavy metals; human blood; biomonitoring; lead; cadmium; mercury; arsenic; AAS; ICP-MS; occupational exposure

I. INTRODUCTION

Heavy metals are environmentally persistent elements that cannot be degraded into harmless products and can remain in soil, water, sediments, food chains, and human tissues for prolonged periods. Toxicological concern is especially high for Pb, Cd, Hg, and As because these elements either have no known beneficial biological role or possess a narrow margin between background exposure and harmful effects. Their health significance is governed not only by total concentration but also by chemical form, duration of exposure, age, nutritional condition, and co-exposure to other contaminants [1]–[4].

Blood is a particularly useful matrix for exposure assessment because it reflects recent or continuing uptake and directly captures the fraction transported to target tissues. Pb can substitute for Ca in proteins and neuronal signaling pathways;

Cd and Hg bind strongly to sulfhydryl groups; and trivalent arsenic inhibits enzymes involved in cellular energy metabolism. These interactions contribute to oxidative stress, impaired heme synthesis, renal tubular injury, neurotoxicity, endocrine disturbance, and carcinogenesis [5]–[10].

Human exposure occurs through several overlapping pathways. Industrial emissions, mining, smelting, battery manufacture, welding, electroplating, e-waste processing, contaminated groundwater, phosphate fertilizers, food-chain transfer, tobacco smoke, and seafood consumption may all contribute. In practical settings, individuals are therefore more likely to encounter mixtures than a single isolated metal. Such mixed exposure can produce additive or synergistic effects, making multi-element biomonitoring more informative than single-metal screening [11]–[15].

Although developed countries have established large population surveillance systems, biomonitoring evidence in many developing regions remains fragmented, localized, and difficult to compare. India faces particular challenges because rapid industrialization coexists with informal recycling, occupational exposure, arsenic-affected groundwater, contaminated agricultural inputs, and limited routine screening. The present paper addresses this gap by analyzing the thesis dataset of 300 participants and by emphasizing the relationship between measured blood concentrations, demographic vulnerability, occupational patterns, and plausible exposure pathways.

The biological significance of blood-metal monitoring arises from the capacity of toxic ions to interact directly with proteins, enzymes, membranes, and nucleic acids. Lead can replace calcium at regulatory and signaling sites, cadmium and mercury exhibit strong affinity for sulfhydryl-containing proteins, and trivalent arsenic interferes with lipoic-acid-dependent energy metabolism. These interactions can alter heme synthesis, antioxidant defense, mitochondrial function, renal filtration, neuronal signaling, and DNA repair. Because many of these changes occur before visible clinical symptoms develop, population-level blood analysis provides an opportunity to identify exposure at an earlier and potentially more manageable stage [1]-[4].

A further concern is that human exposure rarely involves one metal in isolation. Industrial dust, contaminated groundwater, fertilizers, tobacco smoke, seafood, paints, batteries, and electronic waste may introduce several toxic elements concurrently. Combined exposure can produce additive or synergistic biological effects, particularly when the metals share mechanisms such as oxidative stress, thiol binding, or interference with essential mineral homeostasis. The present study therefore adopted a multi-metal framework rather than a single-analyte approach and examined Pb, Cd, Hg, and As together across demographic, occupational, dietary, and geographic categories. This design provides a more realistic representation of the exposure conditions encountered by communities in rapidly industrializing and environmentally stressed regions [5]-[7].

II. MATERIALS AND METHODS

An observational cross-sectional design was adopted. Participants were recruited from urban, semi-urban, and rural settings to represent heterogeneous environmental and occupational exposures. Stratified sampling included: (i) non-occupationally exposed adults, (ii) children aged 6–15 years from traffic-dense or industrially influenced settings, (iii) workers from battery manufacturing, welding, and agriculture, (iv) fisherfolk with regular seafood consumption, and (v) residents of low-industrial zones serving as a comparative control population. A final sample size of 300 was selected after allowing for non-response and unusable specimens.

Eligibility required residence in the study area for at least five years and voluntary consent. Pregnancy, recent blood transfusion, acute infection, and known chronic kidney or liver disease were treated as exclusion criteria because these conditions could alter metal distribution or interpretation. Written informed consent was obtained from adults; parental consent and child assent were obtained for minors. Participant identity was replaced with an alphanumeric code during laboratory analysis and statistical processing.

Approximately 5–8 mL of venous blood was collected from the antecubital vein using sterile single-use needles and certified trace-metal–free polypropylene vacutainers. Powder-free gloves, non-metallic implements, acid-cleaned work surfaces, and laminar-flow handling were used to minimize external contamination. Samples were gently mixed,

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transported at approximately 4 °C using triple-layer packaging, and delivered to the analytical laboratory within 4–6 h. Aliquots intended for delayed analysis were stored at −20 °C or −80 °C in acid-cleaned polypropylene cryovials.

Random duplicate specimens were collected from approximately 10% of participants. Reagent blanks and certified whole-blood reference materials were processed in parallel. The combination of duplicate collection, blank analysis, and reference-material recovery was used to verify that measured concentrations originated from the biological samples rather than collection tubes, reagents, or laboratory surfaces.

Blood samples were digested using ultrapure nitric acid with hydrogen peroxide, and perchloric acid was used only where resistant organic residues required additional oxidation. Milli-Q water with resistivity of at least 18.2 MΩ·cm was used for dilution and cleaning. Calibration standards were prepared from NIST-traceable 1000 mg/L stocks in nitric acid. Matrix modifiers were applied for graphite-furnace measurements, while indium, rhodium, or yttrium internal standards were used for ICP-MS correction. Certified reference blood material was accepted when recovery remained within 90–110%.

Atomic Absorption Spectroscopy was used for element-specific quantification. Graphite Furnace AAS provided the sensitivity required for Pb and Cd, while Cold Vapor AAS was used for Hg after chemical reduction to elemental mercury vapor. ICP-MS enabled simultaneous multi-element analysis and ultra-trace confirmation, monitoring isotopes such as ^{208}Pb, ^{111}Cd, ^{75}As, and ^{202}Hg. Collision/reaction-cell correction and internal-standard normalization were applied to reduce polyatomic interference and instrumental drift [16]–[19].

Multi-point calibration curves were prepared daily, and coefficients of determination greater than 0.995 were required. Reagent blanks, continuing calibration verification standards, spiked specimens, duplicates, and certified reference materials were included. Method detection limits were based on three times the standard deviation of replicate blanks, while limits of quantification were based on ten times the blank standard deviation. Measurements with replicate coefficients of variation above 15% were reanalyzed.

Descriptive statistics included mean, standard deviation, range, median, and exceedance proportion. Normality was assessed using the Shapiro–Wilk test, with log transformation where necessary. Group comparisons employed t-tests or ANOVA for normally distributed variables and Mann–Whitney U or Kruskal–Wallis tests for non-parametric distributions. Pearson or Spearman coefficients were used for correlation analysis. Statistical significance was set at $p < 0.05$, with $p < 0.01$ interpreted as highly significant.

The sampling strategy was structured to capture contrast between background and potentially elevated exposure. The general adult population represented routine environmental contact, whereas the child group enabled assessment of age-related vulnerability. Battery workers and welders represented occupations with plausible inhalation and surface-contact exposure to Pb and Cd. Fisherfolk were included because repeated seafood consumption may increase methylmercury uptake, while rural agricultural participants represented communities potentially affected by arsenic-bearing groundwater, fertilizer impurities, pesticide residues, and contaminated irrigation sources. The control group provided a low-exposure comparison for interpreting differences across these categories. Although the study was cross-sectional, the stratification strengthened the ability to identify exposure patterns that were consistent with known source profiles.

Sample integrity was treated as a central methodological requirement because the target analytes occur at trace concentrations and can be affected by contamination from needles, tubes, glassware, reagents, laboratory dust, or metallic instruments. Trace-metal-free polypropylene materials were used wherever possible, working surfaces were acid-cleaned, and all dilutions were prepared with ultrapure water. Samples were cooled immediately after collection, transported under a documented cold chain, and stored in pre-cleaned containers. Duplicate samples, procedural blanks, matrix spikes, and certified reference blood materials were incorporated into the analytical sequence to distinguish true biological concentrations from handling or instrumental artifacts.

The combination of AAS and ICP-MS provided both routine robustness and ultra-trace sensitivity. Graphite-furnace atomization increased the residence time of Pb and Cd atoms and therefore improved detection at low concentrations, while cold-vapor generation exploited the volatility of elemental Hg for selective measurement. ICP-MS permitted simultaneous isotope-based determination of multiple elements and served as an independent confirmation platform.

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Internal standards were used to compensate for plasma fluctuation, ion suppression, and sample-introduction variability. Calibration verification standards were analyzed throughout each run, and batches were accepted only when linearity, blank response, duplicate precision, spike recovery, and reference-material agreement met the predetermined quality criteria.

Statistical analysis was planned to address three related questions: the magnitude of the blood-metal burden, the proportion of participants exceeding the adopted reference values, and the extent to which concentrations differed by age or exposure category. Descriptive statistics were therefore supplemented by group comparisons and correlation analysis. The correlation coefficients were interpreted as indicators of potentially shared exposure pathways rather than proof of a common source. Statistical significance was assessed at $p < 0.05$, with $p < 0.01$ treated as strong evidence of association. This analytical framework connected the laboratory measurements to their demographic, occupational, and public-health interpretation.

III. RESULTS

All four target metals were detected in the study population. Pb had a mean concentration of 11.2 ± 4.8 µg/L and ranged from 3.1 to 28.5 µg/L. Cd averaged 2.4 ± 1.1 µg/L, Hg averaged 7.8 ± 3.2 µg/L, and As averaged 15.5 ± 6.7 µg/L. Relative to the thresholds adopted in the thesis, each mean exceeded its corresponding reference value, indicating a population-level exposure concern rather than a small number of isolated outliers.

Metal	Mean ± SD (µg/L)	Observed range (µg/L)	Reference threshold (µg/L)	Exceeding threshold
Pb	11.2 ± 4.8	3.1–28.5	5	62%
Cd	2.4 ± 1.1	0.6–5.7	1	54%
Hg	7.8 ± 3.2	2.0–18.4	5	39%
As	15.5 ± 6.7	5.2–33.9	10	47%

Table 1. Summary of blood heavy-metal concentrations and threshold exceedance.

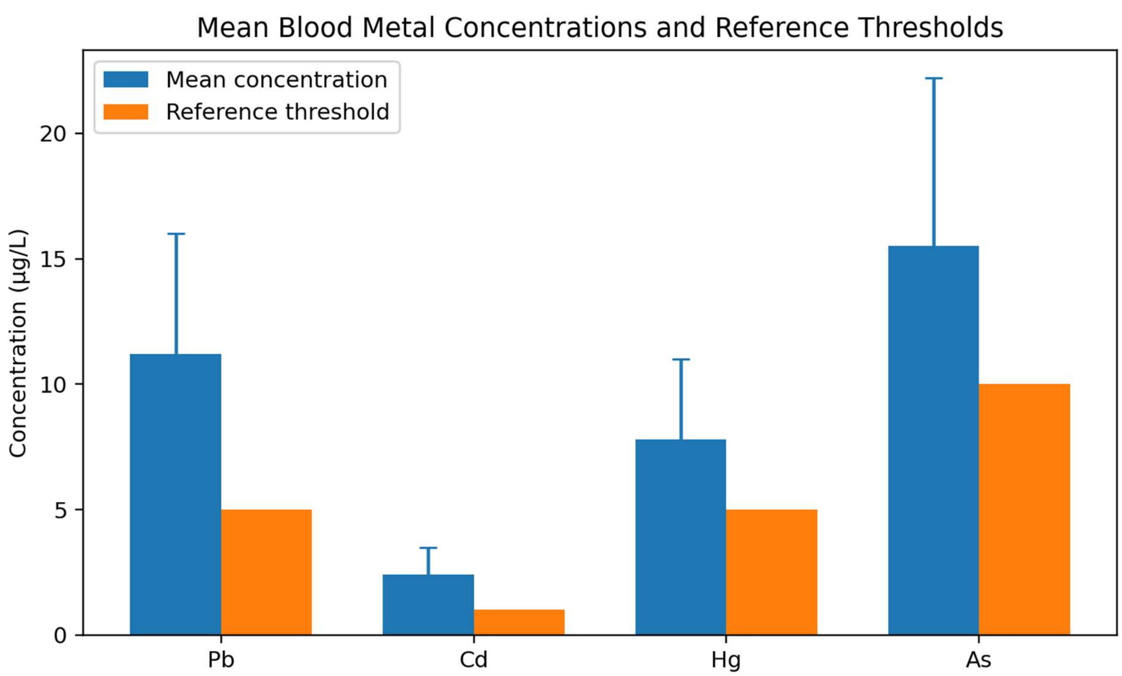

Figure 1. Mean blood concentrations compared with the reference thresholds used in the thesis. Error bars represent standard deviations.

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Lead showed the highest exceedance prevalence, with 62% of participants above the adopted threshold. Cadmium followed at 54%, arsenic at 47%, and mercury at 39%. Thus, more than half of the population exceeded the selected reference values for Pb and Cd, while approximately two out of five exceeded those for Hg and nearly half exceeded that for As.

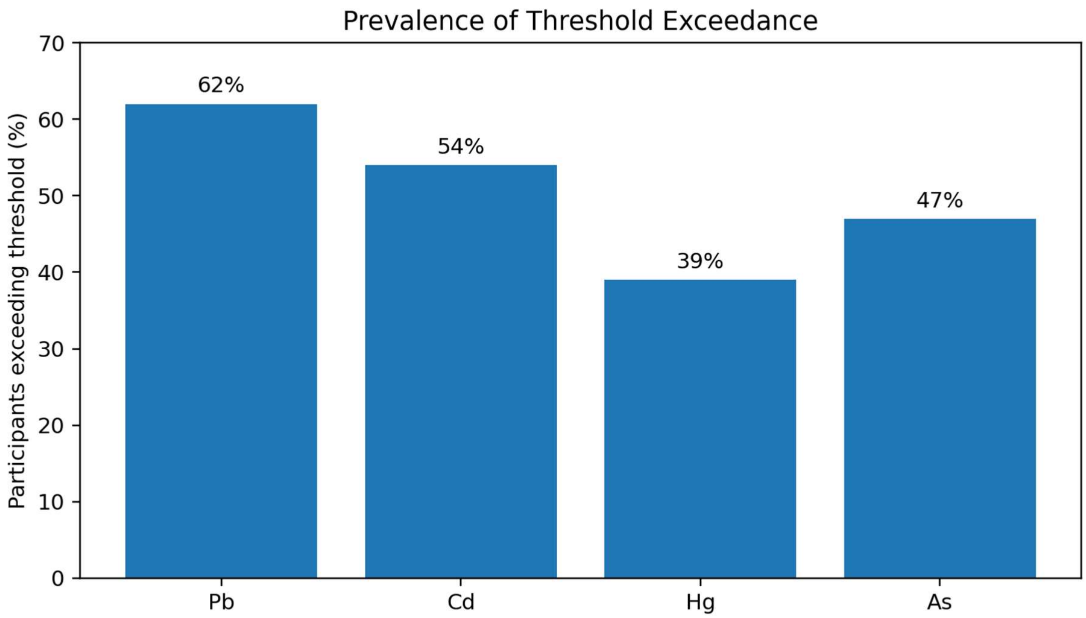

Figure 2. Percentage of participants exceeding the reference threshold for each metal.

Children aged 6–15 years had a mean blood Pb concentration of 13.5 µg/L, compared with 9.6 µg/L among adults. Both group means exceeded the reference value, but the higher childhood burden is particularly important because developmental neurotoxicity can occur during critical periods of brain maturation. Greater gastrointestinal absorption, hand-to-mouth behavior, dust exposure, and incomplete maturation of detoxification systems provide plausible explanations [20]–[22].

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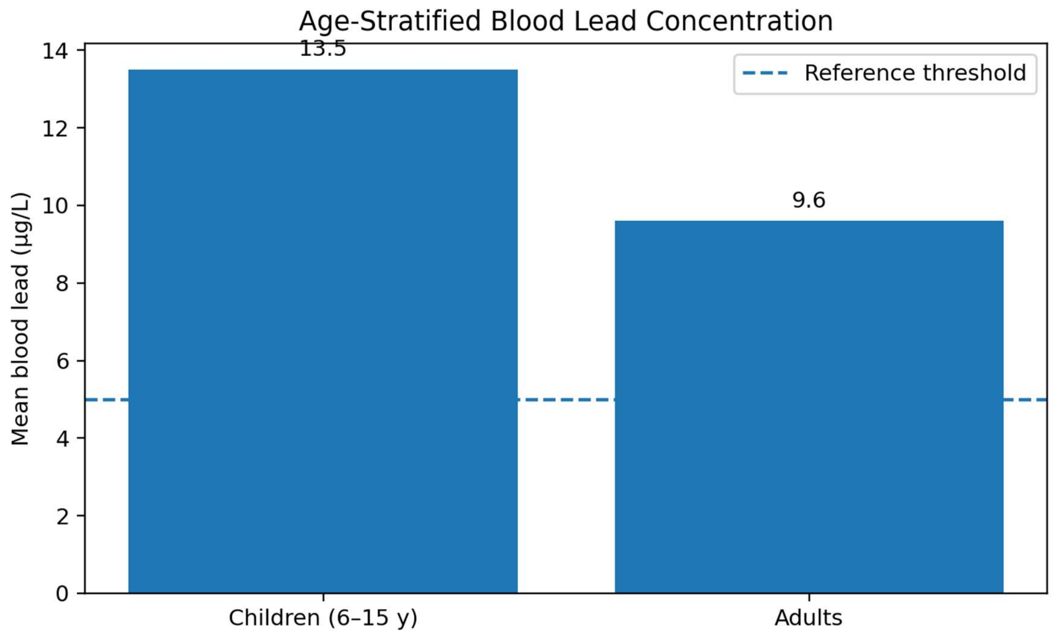

Figure 3. Mean blood lead concentration in children and adults.

Occupationally exposed participants, particularly battery workers and welders, showed higher Pb and Cd than the control group, consistent with inhalation of metal-containing fumes and dust and with possible take-home contamination. Fisherfolk displayed comparatively elevated Hg, supporting seafood-mediated methylmercury exposure. Rural agricultural workers showed higher As, consistent with contaminated groundwater and agrochemical pathways. These distinct patterns indicate that the four metals did not arise from a single universal source.

Population subgroup	Dominant elevated metal(s)	Most plausible pathway indicated by thesis
Children	Pb	Dust, traffic/industrial environment, increased absorption
Battery workers and welders	Pb and Cd	Occupational fumes, dust, direct handling
Fisherfolk	Hg	Frequent seafood consumption
Rural agricultural workers	As	Groundwater contamination and agricultural inputs
Low-industrial control group	Lower overall burden	Reduced industrial and occupational exposure

Table 2. Exposure patterns observed across participant groups.

A strong positive relationship was observed between Pb and Cd ($r = 0.68$, $p < 0.01$), suggesting shared sources such as industrial emissions, contaminated dust, and occupational exposure. Cd and As showed a moderate positive relationship ($r = 0.42$, $p < 0.05$), which may reflect overlap in agricultural soil, fertilizer, or groundwater pathways. Hg did not show a significant association with Pb or Cd, supporting a more independent dietary origin.

Metal pair	Correlation coefficient	Statistical interpretation	Exposure interpretation
Pb–Cd	$r = 0.68$	Strong; $p < 0.01$	Likely shared industrial/occupational sources

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Metal pair	Correlation coefficient	Statistical interpretation	Exposure interpretation
Cd–As	r = 0.42	Moderate; $p < 0.05$	Possible overlapping agricultural/environmental sources
Hg with Pb or Cd	Not significant	Independent pattern	Consistent with seafood-mediated exposure

Table 3. Reported correlations among blood metal concentrations.

The numerical pattern shows that the burden was not limited to a small number of isolated outliers. For Pb and Cd, more than half of the participants exceeded the reference values used in the thesis, indicating broad population exposure rather than a narrowly confined event. Arsenic exceedance affected nearly one-half of the sample, while Hg exceedance affected more than one-third. The ranges were also wide, demonstrating substantial heterogeneity between individuals and exposure groups. Such variability is expected when the sampled population includes children, industrial workers, seafood-consuming communities, agricultural workers, and controls with different environmental and behavioral profiles.

Age-related comparison was particularly notable for Pb. The mean concentration of 13.5 µg/L among children was approximately 41% higher than the adult mean of 9.6 µg/L. This difference is important even though both groups remained above the adopted reference level. Children may absorb a greater fraction of ingested Pb, exhibit frequent hand-to-mouth behavior, and experience exposure through dust, soil, old paint, traffic residues, informal recycling, or take-home contamination from an adult worker. Their developing nervous system also makes the same internal dose more consequential than it would be in a mature adult.

The occupational and lifestyle patterns supported the source-based interpretation. Battery workers and welders displayed elevated Pb and Cd, consistent with exposure to fumes, particulates, solder, alloys, pigments, and contaminated workplace surfaces. Fisherfolk showed a comparatively greater Hg burden, which is compatible with dietary intake from aquatic food chains. Rural agricultural participants showed elevated As, consistent with groundwater-related exposure and possible transfer through irrigated crops. These group-level patterns do not identify an individual source with certainty, but their agreement with established exposure pathways strengthens the plausibility of the findings.

IV. DISCUSSION

The simultaneous elevation of Pb, Cd, Hg, and As demonstrates a mixed-exposure scenario. Such a profile is epidemiologically realistic because environmental contamination rarely occurs as a single-agent event. Industrial regions may contribute Pb and Cd through fumes, dust, soil, and waste; rural regions may contribute As through groundwater; and dietary behavior can independently influence Hg. The high exceedance percentages therefore require source-specific interventions rather than a single generic control measure.

The strong Pb–Cd correlation supports shared exposure pathways. Both metals are associated with mining, smelting, battery manufacture, pigments, e-waste, road dust, and tobacco smoke. Co-exposure is toxicologically important because Pb and Cd can converge on oxidative stress, renal injury, and disruption of essential metal homeostasis. The moderate Cd–As relationship may indicate common agricultural or environmental settings, although causal attribution would require linked water, soil, food, and workplace measurements.

The higher mean Pb concentration in children is consistent with international evidence showing that developmental toxicity occurs at levels previously considered low. Childhood exposure is associated with reduced cognitive performance, attention problems, altered behavior, impaired school achievement, and persistent socioeconomic consequences [20]–[23]. Because Pb can be stored in bone and remain biologically available for years, early exposure may also create a long-term internal reservoir.

The results support incorporating blood lead testing into child-health programs in high-risk industrial, traffic-dense, recycling, and older-housing environments. Environmental inspection should accompany clinical testing because treatment of the individual without removal of the exposure source allows continued uptake.

Elevated Pb and Cd among battery workers and welders points to inadequate control of airborne particles, contaminated surfaces, and personal hygiene pathways. Occupational monitoring should combine environmental measurements with periodic blood testing, local exhaust ventilation, respiratory protection, clean changing areas, and separation of work clothing from household laundry. The importance of preventing take-home exposure is especially high when workers live with young children.

The comparatively independent Hg pattern and its elevation among fisherfolk are consistent with methylmercury bioaccumulation in aquatic food chains. Risk communication should avoid indiscriminately discouraging fish consumption because fish also provides nutritional benefits. Instead, guidance should emphasize species selection, frequency of intake, local contamination advisories, and special caution for pregnant women and children [24]–[26].

The elevation of As among rural agricultural workers aligns with the established burden of geogenic arsenic in parts of South Asia. Chronic ingestion through drinking water and irrigation can create exposure through both direct consumption and crop uptake. Effective control therefore requires tested safe-water sources, household or community treatment, periodic retesting, and agricultural management to reduce transfer into food crops [27]–[29].

The measured levels have implications across neurological, renal, hematological, skeletal, cardiovascular, reproductive, and carcinogenic outcomes. Pb interferes with heme synthesis and calcium-dependent signaling; Cd accumulates in the kidney and contributes to bone demineralization; Hg damages neural and renal systems; and As is associated with skin lesions, cardiovascular disease, and multiple cancers. The co-occurrence of metals raises concern for additive or synergistic toxicity, particularly when several agents induce oxidative stress or compete with essential ions [5]–[10].

Study strengths and limitations were considered when interpreting these findings.

Major strengths include a comparatively large sample of 300 participants, inclusion of multiple demographic and occupational groups, multi-metal analysis, contamination-control procedures, cross-validation using AAS and ICP-MS, and integration of certified reference materials and replicate testing. The analysis also moves beyond overall averages by identifying exposure patterns associated with age, occupation, diet, and rural environmental conditions.

The cross-sectional design does not establish temporal sequence or causality. Environmental measurements of water, soil, air, food, and workplace surfaces were not linked individually to each participant, limiting definitive source attribution. The reported results are based on aggregate thesis data, and individual-level distributions were not available for additional adjusted regression modeling. Blood also reflects recent exposure more strongly than long-term body burden for some metals. Future studies should include longitudinal follow-up, metal speciation, detailed dietary and occupational histories, renal and neurological biomarkers, and geospatial source measurements.

The overall pattern indicates that biomonitoring should be interpreted as part of a source-to-health continuum. A high blood concentration is clinically meaningful, but its public-health value increases when it triggers investigation of drinking water, food, household dust, workplace air, surface contamination, and occupational hygiene. Conversely, environmental measurements alone cannot determine the absorbed dose in a person. Combining biological and environmental data is therefore essential for locating the dominant source, preventing repeated exposure, and evaluating whether an intervention has produced a measurable reduction in internal metal burden.

The study also highlights the importance of mixed-metal risk. Pb and Cd were strongly correlated, suggesting that some participants were exposed to both through overlapping industrial or dust-related pathways. The moderate Cd-As relationship may reflect shared agricultural or environmental conditions. Even where each metal is considered separately against a reference value, co-exposure may intensify oxidative stress, renal injury, enzyme inhibition, or disruption of mineral metabolism. Future risk assessment should therefore move beyond isolated threshold exceedance and consider cumulative exposure indices and organ-specific susceptibility.

Comparison with prior national and international reports indicates that the observed demographic patterns are credible. Higher Pb among children, greater Pb and Cd among industrial workers, elevated Hg among seafood-dependent communities, and increased As in groundwater-affected rural populations have all been reported elsewhere [8]-[15]. The present investigation contributes by examining these patterns within one coordinated study using a common sampling, quality-control, and analytical framework. At the same time, the absence of individual environmental measurements and longitudinal follow-up means that causal attribution and long-term disease prediction should be made cautiously.

V. RECOMMENDATIONS

1. Establish periodic population biomonitoring for Pb, Cd, Hg, and As, with oversampling of children, pregnant women, industrial workers, fisherfolk, and arsenic-affected communities.
2. Introduce routine workplace blood testing, exposure records, engineering controls, personal protective equipment, hygiene facilities, and take-home contamination prevention in battery, welding, smelting, and recycling sectors.
3. Expand testing and remediation of drinking-water sources in arsenic-prone rural regions, together with safe-source labeling and community education.
4. Develop seafood advisories based on local species and contamination patterns rather than broad avoidance messages.
5. Integrate clinical screening with environmental investigation so that elevated blood results trigger source identification, follow-up testing, nutritional guidance, and medical referral.
6. Conduct longitudinal multi-metal studies linked to neurodevelopmental, renal, hematological, cardiovascular, and reproductive outcomes.

VI. CONCLUSION

This study demonstrates a substantial burden of Pb, Cd, Hg, and As in human blood, with 62%, 54%, 39%, and 47% of participants, respectively, exceeding the reference thresholds adopted in the thesis. Children carried a higher Pb burden than adults; occupational workers showed elevated Pb and Cd; fisherfolk showed higher Hg; and rural agricultural workers showed higher As. Correlation patterns further distinguished shared industrial or agricultural sources from independent dietary exposure. The results support immediate, source-specific public-health action and the development of sustained biomonitoring systems capable of identifying vulnerable populations before irreversible clinical effects occur.

Declarations

Data availability. The numerical findings presented in this paper were derived from the aggregate results reported in the source thesis. Individual participant-level data were not included in the submitted thesis document and are therefore not reproduced in this paper.

Ethics statement.

The thesis reports approval by the Institutional Ethics Committee of the host institution and adherence to Indian Council of Medical Research guidance. Written informed consent was obtained from adult participants, with parental consent and child assent for minors. Institutional name and approval number should be inserted by the authors before journal submission.

Conflict of interest.

The authors declare no conflict of interest. This statement should be updated if any financial, institutional, or personal relationship applies.

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