



CHEMICAL BEHAVIOUR AND ENVIRONMENTAL TRANSFORMATION OF HEAVY METALS GENERATED FROM MARBLE PROCESSING ACTIVITIES IN THE JABALPUR DIVISION, CENTRAL INDIA

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Abstract: Marble processing industries generate substantial quantities of slurry and fine particulate matter during cutting, grinding, and polishing operations. These wastes are often regarded as chemically inert; however, growing evidence indicates that they actively influence the geochemical behaviour and environmental mobility of heavy metals. The present study evaluates the chemical behaviour, transformation mechanisms, and environmental fate of key heavy metals — chromium (Cr), lead (Pb), cadmium (Cd), nickel (Ni), arsenic (As), and mercury (Hg) — associated with marble processing activities in the Jabalpur Division, Central India.

A comprehensive environmental assessment was conducted through systematic sampling of marble slurry, airborne particulate matter (PM₁₀ and PM_{2.5}), soil, and groundwater from major processing zones. Heavy metal concentrations were determined using Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) following standard acid digestion protocols. The geochemical framework of the study area is dominated by carbonate-rich systems, where dissolution of calcium carbonate (CaCO₃) produces alkaline conditions (pH 8.2–9.5). These alkaline environments significantly influence metal speciation, solubility, adsorption–desorption equilibria, and redox transformations.

The results reveal that chromium exhibits high mobility under alkaline conditions due to the predominance of hexavalent chromium [Cr(VI)] in the form of soluble chromate ions, posing a significant risk to groundwater quality. In contrast, lead and cadmium are largely immobilized through the formation of stable carbonate and hydroxide precipitates, although periodic changes in pH and redox conditions may trigger their remobilisation. Nickel shows a strong association with fine airborne particulates, indicating that atmospheric transport is a major pathway for its dispersion and human exposure. Arsenic and mercury demonstrate complex redox-dependent transformations, with mercury undergoing potential methylation and arsenic exhibiting variable mobility depending on oxidation state.

The study further highlights the role of marble slurry as a reactive geochemical medium that regulates heavy metal distribution through buffering capacity, mineral precipitation, surface complexation, and redox interactions. These findings challenge the conventional perception of marble waste as inert and emphasize its active role in contaminant dynamics. The research underscores the need for effective waste management strategies, continuous environmental monitoring, and regulatory interventions to mitigate long-term ecological and human health risks associated with marble processing activities.

1. INTRODUCTION

Marble processing is widely recognized as a predominantly mechanical activity; however, significant geochemical interactions occur during cutting, grinding, and polishing operations. The industry generates large volumes of slurry and fine particulate matter, which are commonly disposed of without adequate environmental management. These waste materials are often assumed to be chemically inert, yet recent studies indicate that they actively influence the geochemical behaviour and environmental mobility of heavy metals.

Marble is primarily composed of calcium carbonate (CaCO_3), which plays a crucial role in regulating environmental chemistry through carbonate buffering reactions. When exposed to atmospheric carbon dioxide and water, CaCO_3 participates in dissolution processes that generate alkaline conditions in surrounding soil and water systems. Such alkaline environments significantly affect metal speciation, solubility, adsorption–desorption equilibria, and redox transformations, thereby controlling the fate and transport of contaminants.

Marble processing has a long industrial history and represents one of the major sectors in the dimension stone industry worldwide. India is among the leading producers of marble, with extensive processing activities concentrated in states such as Rajasthan and Madhya Pradesh. Over the past few decades, rapid industrialization and increasing demand for decorative stone have significantly expanded marble processing operations, resulting in the generation of large quantities of slurry waste. It is estimated that nearly 20–30% of processed marble is converted into slurry during cutting and polishing processes, posing serious disposal and environmental challenges.

In the Jabalpur Division of Central India, marble processing activities are concentrated in regions such as Katni, Sleemanabad, Baboriband, and Jabalpur. Field observations indicate that marble slurry is frequently dumped on open land or near drainage channels without engineered containment systems. This practice promotes direct interaction between slurry, soil, and groundwater systems, facilitating the release and migration of heavy metals into environmental compartments. Additionally, airborne particulate matter generated during processing contributes to atmospheric dispersion, creating multiple exposure pathways for both ecosystems and human populations.

Previous studies have demonstrated that marble slurry can alter soil properties, including porosity, permeability, and pH, thereby affecting contaminant transport processes. Researchers have also reported that alkaline conditions generated by carbonate dissolution influence the speciation and mobility of heavy metals in aquatic and terrestrial environments. Studies on industrial waste systems indicate that metals such as chromium, lead, and cadmium exhibit distinct geochemical behaviour depending on pH, redox potential, and mineral interactions. Furthermore, airborne particulate matter generated from stone processing has been identified as a significant source of trace metal exposure in industrial regions.

Heavy metals associated with marble processing originate from various sources, including mineral impurities within the parent rock, abrasion of cutting tools, corrosion of machinery, and the use of polishing chemicals. Once released, these metals undergo a range of physicochemical transformations, including precipitation, adsorption onto mineral surfaces, complexation with carbonate and hydroxide ions, and redox reactions. These processes collectively determine metal mobility, bioavailability, and toxicity in environmental systems.

Among the metals of concern, chromium exhibits variable oxidation states with distinct mobility characteristics, while lead and cadmium tend to form relatively stable mineral phases under alkaline conditions. Nickel is often associated with fine particulate matter, indicating atmospheric transport, whereas arsenic and mercury demonstrate complex redox-controlled behaviour with significant implications for environmental persistence and human health risks.

Despite these findings, limited research has focused on the integrated assessment of heavy metal behaviour in marble processing environments, particularly in carbonate-dominated systems of Central India. Most existing studies have either addressed soil contamination or air pollution independently, without considering the coupled interactions between slurry, soil, air, and groundwater

systems. Additionally, the role of carbonate buffering in controlling metal transformation pathways under field conditions remains insufficiently explored.

The present study provides a comprehensive geochemical evaluation of heavy metal behaviour across multiple environmental compartments, emphasizing the role of carbonate buffering and hydrogeochemical interactions in regulating metal mobility and environmental risk. The specific objectives of this study are: (i) to assess the concentration and distribution of heavy metals in slurry, soil, air, and groundwater; (ii) to evaluate the role of carbonate buffering in controlling metal speciation and mobility; and (iii) to identify environmental transport pathways and associated risks to human health and ecosystems.

2. MATERIALS AND METHODS

2.1 STUDY AREA

The present study was carried out in major marble processing regions of the Jabalpur Division, Central India, including Jabalpur, Katni, Sleemanabad, and Bahoriband. These areas are characterized by intensive marble quarrying and processing activities, with a high density of small- to medium-scale industrial units.

Geologically, the region is dominated by carbonate formations, primarily composed of calcium carbonate (CaCO_3), along with minor silicate and trace mineral phases. These lithological characteristics significantly influence the hydrogeochemical behaviour of the area. The climate is subtropical, with average annual rainfall ranging from 1100 to 1400 mm, mainly during the monsoon season, which plays a crucial role in leaching and transport of contaminants.

The unregulated disposal of marble slurry in open areas, agricultural land, and drainage systems has led to its direct interaction with soil and groundwater, making the region an ideal site for investigating heavy metal transformation processes.

2.2 SAMPLING STRATEGY AND SAMPLE COLLECTION

A systematic sampling strategy was adopted to ensure representative coverage of different environmental compartments. Sampling locations were selected based on proximity to marble processing units, waste disposal sites, and residential areas. The following sample types were collected from multiple sites to capture spatial variability across the study region:

- Marble slurry samples directly from processing discharge points
- Airborne particulate matter (PM_{10} and $\text{PM}_{2.5}$) using high-volume air samplers
- Soil samples collected from surface (0–15 cm) and sub-surface (15–30 cm) layers
- Groundwater samples collected from hand pumps and bore wells

All samples were collected using pre-cleaned, acid-washed polyethylene containers to minimize contamination. Groundwater samples were preserved by acidifying with ultrapure nitric acid (HNO_3) to $\text{pH} < 2$, following standard preservation protocols. Soil and slurry samples were sealed, labeled, and transported to the laboratory under controlled conditions.

2.3 SAMPLE PREPARATION AND DIGESTION

Soil and slurry samples were air-dried at room temperature, homogenized, and sieved through a 2 mm mesh to remove coarse particles. The fine fraction was used for chemical analysis. Acid digestion was performed using a mixture of nitric acid (HNO_3) and hydrochloric acid (HCl), following standard digestion procedures for environmental samples. In selected cases, perchloric acid (HClO_4) was used to ensure complete digestion of resistant mineral phases.

Water samples were filtered through 0.45 μm membrane filters and acidified prior to analysis. All glassware was thoroughly cleaned and rinsed with deionized water to avoid cross-contamination.

2.4 ANALYTICAL TECHNIQUES

Heavy metal concentrations of Cr, Pb, Cd, Ni, As, and Hg were determined using two primary analytical techniques: Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS). These techniques provide high sensitivity and accuracy for trace metal analysis in environmental samples.

Additionally, Fourier Transform Infrared Spectroscopy (FTIR) was employed to identify functional groups and mineral phases responsible for metal adsorption and binding in marble slurry. Physicochemical parameters such as pH, electrical conductivity (EC), and total dissolved solids (TDS) were measured using standard analytical procedures.

2.5 QUALITY ASSURANCE AND QUALITY CONTROL (QA/QC)

Strict quality control measures were implemented to ensure the accuracy and reliability of analytical results. These included: use of analytical-grade reagents and ultrapure water; calibration using certified standard solutions; analysis of procedural blanks to detect contamination; duplicate sample analysis to assess precision; use of standard reference materials (SRMs) for validation; and periodic calibration of analytical instruments. The relative standard deviation (RSD) for replicate analyses was maintained within $\pm 5\%$, indicating acceptable analytical precision.

2.6 GEOCHEMICAL AND STATISTICAL ANALYSIS

The analytical data were evaluated using statistical and geochemical approaches to understand the distribution and behaviour of heavy metals. Correlation analysis was performed to identify relationships among different metals and environmental parameters. Comparative analysis was conducted across different sample matrices — soil, water, air, and slurry. Geochemical interpretations were based on pH conditions, carbonate equilibrium, and known metal speciation behaviour.

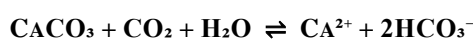
2.7 HYDROGEOCHEMICAL CONSIDERATIONS

The study emphasized carbonate buffering as the dominant geochemical process controlling heavy metal behaviour. The interaction between CaCO_3 , CO_2 , and water generates alkaline conditions that influence precipitation, dissolution, and complexation reactions. Variations in pH and redox conditions were considered critical factors governing the mobility, transformation, and environmental fate of heavy metals in soil and groundwater systems.

3. RESULTS AND DISCUSSION

3.1 CARBONATE BUFFERING AND GEOCHEMICAL CONTROL

The dissolution of calcium carbonate (CaCO_3) establishes a carbonate buffering system that maintains alkaline conditions (pH 8.2–9.5) in the study area. This buffering system exerts primary control on metal speciation, solubility equilibria, and precipitation–dissolution kinetics. The governing reaction is as follows:



Elevated pH conditions increase the availability of carbonate (CO_3^{2-}) and hydroxide (OH^-) ions, promoting the formation of stable metal complexes and precipitates. Consequently, the free ionic activity of metals is reduced, influencing their thermodynamic stability and environmental mobility. The carbonate system thus acts as a geochemical regulator, determining both the speciation and transport potential of heavy metals across all environmental compartments studied.

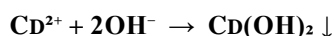
3.2 CHROMIUM (CR): REDOX SPECIATION AND MOBILITY DYNAMICS

Chromium occurs in two major oxidation states, Cr(III) and Cr(VI), with fundamentally distinct environmental behaviours. Under alkaline and oxidizing conditions prevalent in the study area, Cr(VI) predominates as chromate (CrO_4^{2-}), a highly soluble and mobile species. Due to its weak adsorption onto mineral surfaces at high pH, chromate exhibits enhanced leaching potential into groundwater systems.

Additionally, the oxidation of Cr(III) to Cr(VI) may be facilitated by manganese oxides present in soil matrices, further increasing chromium mobility. Thermodynamically, Cr(VI) remains stable under alkaline conditions, whereas reduction to Cr(III) may occur under reducing environments. Elevated chromium levels measured in groundwater samples from the study area confirm active leaching and limited natural attenuation, presenting a significant long-term risk to potable water quality.

3.3 LEAD (Pb) AND CADMIUM (Cd): PRECIPITATION–DISSOLUTION EQUILIBRIA

Lead and cadmium demonstrate strong affinity for carbonate and hydroxide ions, resulting in the formation of sparingly soluble precipitates. The relevant precipitation reactions are:



These reactions significantly reduce metal mobility under the prevailing alkaline conditions. In addition to precipitation, Pb and Cd are adsorbed onto mineral surfaces, including clay minerals and iron oxides, through surface complexation processes. However, changes in environmental conditions — such as decreased pH or increased complexation with organic ligands — may lead to dissolution and remobilisation of these metals. Seasonal variations in rainfall and evaporation may periodically destabilize these precipitates, creating dynamic cycles of immobilization and release.

3.4 NICKEL (Ni): ATMOSPHERIC TRANSPORT AND SURFACE INTERACTION

Nickel is predominantly associated with fine particulate matter (PM_{2.5} and PM₁₀), generated through mechanical abrasion during marble cutting, grinding, and polishing operations. Atmospheric transport is identified as a major pathway for its environmental dispersion and human exposure. Due to their high surface area, fine particulates act as efficient carriers of nickel, enabling both short- and long-range transport.

Upon deposition, nickel may undergo adsorption onto soil particles or dissolution under favourable geochemical conditions. Continuous emission and deposition cycles contribute to dynamic distribution patterns across environmental compartments. Occupational exposure through inhalation represents a significant health risk for workers in marble processing units, given the respiratory toxicity associated with prolonged nickel exposure.

3.5 ARSENIC (As) AND MERCURY (Hg): REDOX TRANSFORMATION AND TOXICITY

Arsenic and mercury exhibit complex behaviour governed by redox reactions and microbial processes. Arsenic exists primarily as arsenite [As(III)] and arsenate [As(V)], with As(III) being more mobile and toxic under reducing conditions. The oxidation state of arsenic determines its solubility, adsorption affinity, and biological availability, making redox potential a critical factor in its environmental fate.

Mercury undergoes microbial methylation to form methylmercury (CH₃Hg⁺), a highly toxic and bioaccumulative compound. This transformation significantly enhances its ecological risk and potential for biomagnification in food chains, particularly in aquatic ecosystems receiving contaminated runoff from marble processing areas. The environmental fate of both arsenic and mercury is strongly influenced by redox conditions, microbial activity, and interactions with organic matter in soils and sediments.

3.6 MULTI-COMPARTMENT DISTRIBUTION AND TRANSPORT PATHWAYS

Heavy metals exhibit distinct distribution patterns across the four environmental compartments investigated in this study:

- Slurry — Acts as the primary source of contamination, providing a continuous supply of metals to adjoining environmental media.
- Soil — Functions as a geochemical sink through adsorption onto clay minerals, iron-manganese oxides, and organic matter, as well as through carbonate and hydroxide precipitation.
- Groundwater — Dominated by mobile species such as Cr(VI), representing the major long-distance transport medium for dissolved metals.

- Air — Facilitates transport of metal-bearing fine particulates (especially Ni), contributing to atmospheric deposition across wider areas.

These compartments are interconnected through processes such as leaching, surface runoff, atmospheric deposition, and infiltration, forming an integrated environmental system. The interconnected nature of these pathways underscores the importance of multi-compartment monitoring for comprehensive risk assessment in marble processing regions.

3.7 HYDROGEOCHEMICAL MODELLING PERSPECTIVE

The geochemical behaviour of metals in the study area can be interpreted using hydrogeochemical modelling frameworks, where carbonate equilibrium governs metal speciation and saturation states. Chromium remains highly mobile due to its soluble anionic form under alkaline conditions, while lead and cadmium tend to precipitate and accumulate in the solid phase. Nickel exhibits dynamic partitioning between atmospheric and solid phases, while arsenic and mercury are fundamentally controlled by redox equilibrium processes and microbial transformation pathways.

Application of geochemical modelling tools such as PHREEQC would be beneficial in future investigations to simulate metal speciation indices, mineral saturation states, and the thermodynamic stability of metal phases under varying environmental conditions. Such models can provide predictive insights into the long-term behaviour of contaminants under changing land-use and climatic conditions.

3.8 ENVIRONMENTAL AND HUMAN HEALTH RISK ASSESSMENT

The presence and mobility of heavy metals in the Jabalpur Division study area pose significant environmental and public health concerns. A summary of the major health effects associated with each metal is provided below:

- Chromium Cr(VI) — Classified as a known human carcinogen; long-term exposure through contaminated drinking water significantly elevates cancer risk.
- Lead (Pb) — Neurotoxic metal causing developmental impairment in children and cardiovascular effects in adults.
- Cadmium (Cd) — Primarily targets the kidneys; chronic exposure leads to Itai-Itai disease and renal tubular dysfunction.
- Nickel (Ni) — Inhalation of nickel-bearing dust causes respiratory toxicity and is associated with lung and nasal cancers.
- Arsenic (As) — Chronic exposure through contaminated water is associated with skin, lung, and bladder cancers.
- Mercury (Hg) — Methylmercury primarily targets the nervous system, causing neurological damage, especially in developing fetuses and young children.

Occupational exposure among marble processing workers is significantly elevated due to continuous inhalation of dust particles and direct dermal contact with slurry. Additionally, groundwater contamination presents a long-term risk to nearby residential populations who depend on bore wells and hand pumps as primary drinking water sources.

4. CONCLUSION

The present study provides a comprehensive evaluation of the chemical behaviour and environmental transformation of heavy metals associated with marble processing activities in the Jabalpur Division, Central India. The findings clearly demonstrate that marble slurry is not an inert industrial by-product, but a chemically active system that significantly influences the geochemical dynamics of surrounding environments.

The dissolution of calcium carbonate (CaCO_3) establishes a carbonate buffering system, resulting in alkaline conditions (pH 8.2–9.5), which play a crucial role in controlling metal speciation, solubility, and mobility. Among the studied metals, chromium exhibited high mobility under alkaline conditions due to the formation of soluble Cr(VI) species, posing a significant risk to groundwater quality. In contrast, lead and cadmium were largely immobilized through precipitation as carbonate and hydroxide phases, although their stability remains sensitive to environmental changes such as pH fluctuations.

Nickel was predominantly associated with airborne particulate matter, indicating that atmospheric transport is a key pathway for its dispersion and human exposure. Arsenic and mercury displayed complex redox-dependent transformations, with mercury undergoing methylation and arsenic exhibiting variable mobility depending on oxidation state, thereby increasing their environmental persistence and toxicity.

The study highlights the interconnected nature of environmental compartments, where slurry acts as a primary source, soil serves as a sink, groundwater functions as a transport medium, and air facilitates dispersion. These interactions collectively determine the distribution, transformation, and risk profile of heavy metals across the study area.

From an environmental management perspective, the findings emphasize the need for improved waste management practices, including controlled disposal and recycling of marble slurry, implementation of dust suppression systems in processing units, and regular monitoring of groundwater quality. Stricter regulatory frameworks governing marble waste disposal are essential to mitigate long-term environmental and human health risks. Future research should incorporate geochemical modelling, isotopic tracing, and GIS-based spatial analysis to further advance understanding of metal transformation pathways in carbonate-dominated industrial regions.

Overall, this study contributes to a better scientific understanding of carbonate-controlled geochemical systems and provides an evidence-based foundation for developing sustainable management strategies for marble processing waste in the Jabalpur Division and similar industrial regions of Central India.

5. FUTURE RESEARCH DIRECTIONS AND RECOMMENDATIONS

Beyond the present investigation, there is a growing need to integrate advanced analytical and modelling approaches to better understand the long-term environmental behaviour of heavy metals in marble processing regions. A number of key directions are recommended for future research:

5.1 GEOCHEMICAL MODELLING

Future research should focus on the application of geochemical modelling tools such as PHREEQC to simulate metal speciation, saturation indices, and mineral stability under varying environmental conditions. These models can provide quantitative predictions of metal behaviour under scenarios of changing pH, redox potential, and ionic strength, supporting both risk assessment and remediation planning.

5.2 ISOTOPIC TRACING

Isotopic tracing techniques, particularly stable isotope ratio analysis of lead, chromium, and mercury, may provide deeper insights into the sources and transformation pathways of heavy metal contamination. This approach can help distinguish between geogenic background concentrations and anthropogenic contributions from marble processing activities.

5.3 REMOTE SENSING AND GIS ANALYSIS

The incorporation of remote sensing data and Geographic Information System (GIS)-based spatial analysis can significantly enhance the assessment of contamination spread and risk zonation in industrial regions. Satellite-derived indices combined with field measurements can enable continuous, large-scale monitoring of surface contamination patterns and changes over time.

5.4 LONG-TERM ENVIRONMENTAL MONITORING

Long-term monitoring studies are essential to evaluate seasonal variations in metal mobility and their cumulative impacts on soil and groundwater systems. Data collected over multiple years would allow for the detection of temporal trends in contamination levels and the assessment of remediation effectiveness.

5.5 SUSTAINABLE WASTE MANAGEMENT TECHNOLOGIES

From a technological perspective, future studies should explore sustainable waste management strategies, including the reuse of marble slurry in construction materials such as cement and tiles, soil stabilization applications, and environmental remediation. The development of cost-effective treatment technologies, such as adsorption using natural materials, phytoremediation, and biogeochemical stabilization, could significantly reduce environmental risks while providing economic benefits to the marble processing industry.

5.6 REGULATORY FRAMEWORKS

There is a critical need to establish region-specific environmental guidelines and regulatory frameworks for the safe disposal and utilization of marble processing waste. Integrating scientific findings from studies such as the present investigation with environmental policy-making will be crucial for achieving sustainable industrial development while minimizing ecological and human health impacts in the Jabalpur Division and across Central India.

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