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Microplastic-Mediated Heavy Metal Contamination in Freshwater Ecosystems: An Emerging Contaminant Perspective

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Abstract— *Microplastics (MPs) coexist with heavy metals in aquatic ecosystems, influencing contaminant mobility and ecological risks. We analyzed sediments, water, and MPs from five freshwater lakes in Coimbatore, India, for Cu, Fe, Cd, As, Pb, Sn, Ni, Mn, and Sr using ICP–MS. All metals were detected across matrices, with sediments showing the highest concentrations. Cd levels in MPs (0.08–0.26 mg/kg) closely reflected those in sediments and water, indicating environmental adsorption. In contrast, As (0.11–0.34 mg/kg) and Sn (0.09–0.28 mg/kg) were enriched in MPs, consistent with their use as plastic additives. These results suggest dual sources of metal contamination—environmental deposition and polymer additives—shaping the metal burden of MPs. By serving as carriers of trace metals, MPs represent potential vectors for contaminant transfer into aquatic food webs. This study provides baseline evidence of MP–metal interactions in Indian freshwater lakes, with implications for ecological risk assessment and water resource management.*

Keywords— Microplastics, Heavy metals, Sediment contamination, Aquatic ecosystems, Environmental Health, Environmental Risk.

I. INTRODUCTION

Microplastics (MPs), defined as plastic particles <5 mm, are emerging contaminants of global concern in aquatic ecosystems. They originate either from the breakdown of larger plastics or direct industrial and domestic inputs. Owing to their persistence, small size, and high surface-to-volume ratio, MPs can adsorb coexisting pollutants and alter their environmental fate (Neelavannan et al., 2023). Among such pollutants, heavy metals represent a priority group, as they persist in sediments, bioaccumulate in organisms, and exert toxic effects even at trace levels (Mvovo et al., 2025).

Interactions between MPs and metals occur through surface complexation, electrostatic attraction, or physical entrapment, leading to altered contaminant mobility, trophic transfer, and potential combined toxicity (Tenea et al., 2024; Gong et al., 2025; Rezaei Kahkha et al., 2025). Evidence from marine environments shows that MPs act as carriers of metals such as Cu, Pb, and Cd, increasing their bioavailability (Ashton et al., 2010; Turner, 2016). However, freshwater ecosystems—particularly in rapidly urbanizing regions—remain understudied, despite being critical sources of drinking water, irrigation, and fisheries (Patidar et al., 2023).

The adsorption of metals onto MPs is governed by multiple factors including polymer type, particle size, surface weathering, and environmental conditions such as pH, salinity, and dissolved organic matter (Holmes et al., 2014; Brennecke et al., 2016). Weathered MPs with oxidized surfaces and enhanced roughness exhibit higher sorption capacities than pristine particles, and the presence of biofilms can further alter metal partitioning through biosorption mechanisms (Tang et al., 2020). This complex interplay of factors influences the potential of MPs to act as vectors for metal contamination in aquatic ecosystems.

In India, freshwater bodies are increasingly burdened by untreated sewage, industrial effluents, and plastic litter, creating potential hotspots for MP–metal interactions (Neelavannan et al., 2023; Patidar et al., 2023). Yet, systematic assessments of metal adsorption onto MPs in Indian freshwater ecosystems remain scarce. Coimbatore, a major industrial and urban hub in southern India, contains numerous lakes that support agriculture, fishing, and domestic water use. These lakes have been studied for water quality and biodiversity, but their contamination by MPs and metals has not been comprehensively evaluated (Haritha and Siddhuraju, 2023).

The present study investigates the concentrations of Cu, Fe, Cd, As, Pb, Sn, Ni, Mn, and Sr in water, sediments, and MPs from five Coimbatore lakes. Specifically, it aims to (i) examine the distribution of metals across matrices, (ii) assess the extent of adsorption of metals onto MPs, and (iii) identify potential additive-derived contributions. We hypothesized that metal concentrations in MPs would reflect both environmental adsorption from surrounding water and sediments, and contributions from plastic additives, with distinct patterns for different metals based on their usage in plastic manufacturing. To our knowledge, this is the first report on MP–metal enrichment in freshwater lakes of Coimbatore, providing baseline data for ecological risk assessment and management in Indian aquatic ecosystems.

II. MATERIALS AND METHODS

2.1 Study Area

Five freshwater lakes in and around Coimbatore, Tamil Nadu, were investigated: Krishnampathy (11°00′27.9″N, 76°55′34.7″E), Sengulam (10°57′07.8″N, 76°56′28.0″E), Pallapalayam (10°59′47.2″N, 77°04′54.1″E), Vellalore (10°58′26.7″N, 77°00′27.4″E), and Irugur (11°01′08.5″N, 77°04′37.2″E). These lakes are extensively used for agriculture, fisheries, and domestic purposes but face increasing anthropogenic pressures from urbanization, industrial activities, and agricultural runoff (Haritha and Siddhuraju, 2023).

2.2 Sample Collection

Water (10 L) and surface sediment samples were collected from each lake. For water sampling, three replicate samples were collected from each lake and pooled for analysis. Water was filtered in the field using stacked stainless-steel sieves (5, 3, and 1 mm) (Tien et al., 2020). Residues were transferred to glass containers and transported to the laboratory. Sediment was collected using a Van Veen grab sampler from three locations within each lake and pooled to form composite samples, then stored for further processing (Haritha and Siddhuraju, 2023). Approximately 500 g of surface sediment (0-5 cm depth) was collected from each sampling point.

2.3 Laboratory Precautions

All equipment was rinsed with double-distilled water prior to use, plastic materials were avoided, and work was performed under laminar flow conditions to minimize airborne contamination (Haritha and Siddhuraju, 2023). Cotton lab coats were worn, and metal tools were used instead of plastic implements to prevent plastic shedding. Procedural blanks were processed alongside samples to monitor background contamination.

2.4 Extraction of Microplastics

Sediment: Approximately 50 g of oven-dried (<50 °C) sediment was subjected to density separation using 5 M NaCl solution following Afrin et al. (2020) and NOAA guidelines (Masura et al., 2015). The supernatant was filtered (glass microfiber filters, Grade-111, Himedia) and treated with 30% H_2O_2 for wet peroxide oxidation (WPO) to remove organic matter. A second density separation and filtration were performed before microscopic examination. The efficiency of density separation was evaluated through spiking experiments, achieving approximately 92 ± 4% recovery.

Water: Residues from field sieving were digested with H_2O_2 (if organic matter was abundant) and filtered using the same protocol (Masura et al., 2015).

Microplastic Characterization: Extracted MPs were visually identified using a stereomicroscope, categorized based on morphology (fragments, fibers, films, beads), and measured for size using image analysis software. While polymer identification via FTIR or Raman spectroscopy was beyond the scope of this baseline study, visual characterization was conducted according to established protocols (Masura et al., 2015). This represents a limitation acknowledged in the study.

2.5 Heavy Metal Analysis

Water and Sediment: Metal concentrations were determined by ICP–MS (NexION 300X, PerkinElmer) following Mastro et al. (2015). Sediments were digested with HNO_3–H_2SO_4–$HClO_4$ (9:2:1) at 70 °C, filtered, and diluted to volume. Water samples were filtered through Whatman paper prior to analysis. Calibration was performed using 100 mg/L multi-element standards

(PerkinElmer Pure Plus), with fresh working solutions prepared daily. All analyses were performed in triplicate for each sample type.

Microplastics: Heavy metals associated with MPs were extracted following Zhou et al. (2019). After ultrasonic cleaning (10 minutes at 40 kHz to remove loosely attached particles), MPs were digested in 20% aqua regia ($HCl:HNO_3$, 3:1) for 24 h at 25 °C under agitation (150 rpm). The digests were filtered and stored at 4 °C until ICP–MS analysis. This extraction procedure was designed to desorb metals both from the surface and from within the polymer matrix.

2.6 Quality Assurance and Quality Control (QA/QC)

All analyses were performed in triplicate for each sample type. Instrument calibration was checked every 10 samples using mid-range standards, and drift corrections were applied automatically. The method detection limits (MDLs) for heavy metals ranged from 0.001 mg/L (Cd) to 0.01 mg/L (Fe). For MPs, recovery efficiency was evaluated through spiking experiments using known quantities of polyethylene microbeads, resulting in 87 ± 5% recovery. For metal analysis, recovery efficiency was assessed using certified reference materials (NIST 1640a for water and NIST 2709a for sediment), with recoveries ranging from 89% to 105% for all analytes. Procedural blanks were below detection limits, confirming minimal laboratory contamination. Glassware and filtration units were rinsed thrice with double-distilled water, and cotton lab coats and metal tools were used to prevent plastic shedding.

2.7 Statistical Analysis

Data were analyzed using SPSS v.26 (IBM Corp., USA). Mean ± standard deviation (SD) values were calculated for all parameters. One-way analysis of variance (ANOVA) was used to assess differences in metal concentrations among matrices (water, sediment, and MPs), following confirmation of normality (Shapiro-Wilk test) and homogeneity of variances (Levene's test). When significant differences were found, Duncan's multiple range test (DMRT) was applied to identify statistically distinct groups. Pearson correlation analysis was used to examine the relationship between metal concentrations in MPs and those in sediments and water. Principal component analysis (PCA) was performed to explore patterns of metal distribution across lakes and matrices. Statistical significance was set at $p < 0.05$. All statistical graphs and plots were generated using OriginPro 8.5 (OriginLab Corporation, Northampton, MA, USA).

III. RESULTS AND DISCUSSION

3.1 Microplastic Characterization

Microplastic particles were found in all sediment and water samples from all five lakes. The extracted MPs predominantly consisted of fragments (approximately 55-65%), followed by fibers (20-30%), films (5-10%), and beads (less than 5%). Particle sizes ranged from 0.1 to 5 mm, with the majority (approximately 70%) in the 0.5-2 mm size range. Visual inspection revealed that many particles exhibited surface roughness, discoloration, and other signs of weathering, consistent with prolonged environmental exposure. The higher proportion of fragments compared to other morphologies suggests that secondary MPs from degradation of larger plastics dominate over primary MPs in these lake systems. This morphological distribution has implications for metal adsorption, as fragments generally provide greater surface area per unit mass than fibers or films.

3.2 Plastic Composition and Metal Interactions

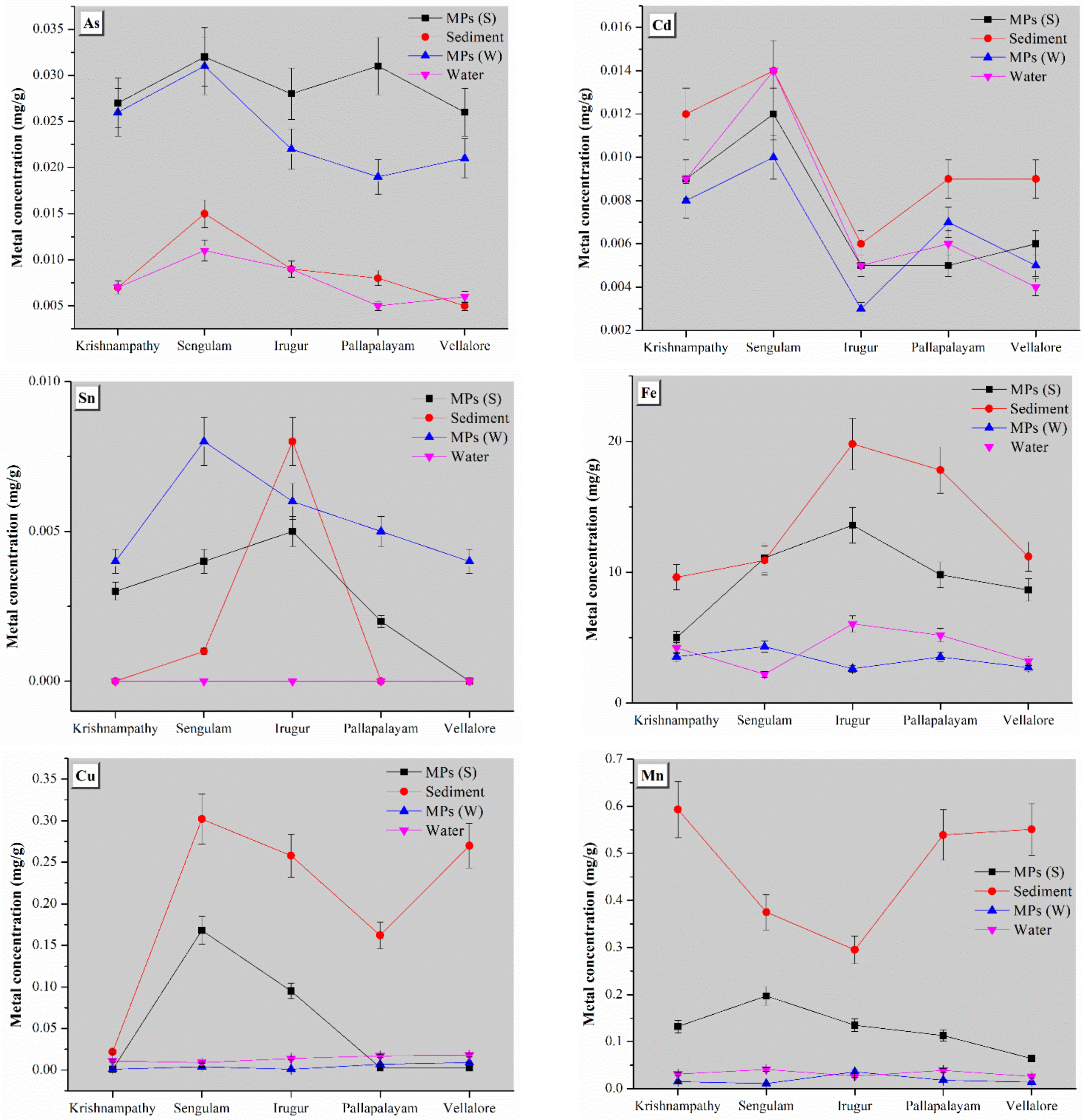
Plastics are composed not only of polymers or copolymers but also of additives such as plasticizers, stabilizers, pigments, flame retardants, antioxidants, and biocides, along with residual monomers, catalysts, and impurities from production or recycling (Murphy, 2001; Hahladakis et al., 2018). Once in the environment, plastic particles can adsorb organic and inorganic pollutants, including heavy metals (Ashton et al., 2010; Turner, 2016). Metals associated with microplastics (MPs) may therefore originate from two primary pathways: (i) incorporation during production as additives, and (ii) adsorption from surrounding matrices during environmental exposure (Cao et al., 2021). This dual origin enhances the potential for MPs to act as long-term carriers of contaminants in aquatic ecosystems.

The adsorption of metals onto MPs is influenced by the physicochemical properties of both the polymer and the surrounding environment. Surface aging through UV radiation, mechanical abrasion, and biological degradation creates oxygenated functional groups (e.g., carboxyl, hydroxyl, carbonyl) that enhance metal complexation (Tang et al., 2020). Additionally, the formation of biofilms on MP surfaces can further modify metal sorption through biosorption and changes in surface charge (Mvovo et al., 2025). These processes collectively determine the metal loading capacity and partitioning behavior of MPs in freshwater systems.

3.3 Metal Concentrations in Sediments, Water, and MPs

All nine metals analyzed—Cu, Fe, Cd, As, Pb, Sn, Ni, Mn, and Sr—were detected across water, sediment, and MPs in all five lakes. Concentrations varied among sites and matrices, reflecting local anthropogenic pressures such as sewage discharge, industrial effluents, and agricultural runoff. Sediments consistently had the highest concentrations, followed by water and MPs, except for As and Sn, which were enriched in MPs. Similar spatial patterns have been reported in freshwater systems in China and Iran, where MPs acted both as sinks and carriers of metals (Deng et al., 2020; Rezaei Kahkha et al., 2025).

The comparative concentrations of trace metals (Cu, Fe, Cd, As, Pb, Sn, Ni, Mn, and Sr) in water, sediments, and microplastics from the five lakes are illustrated in Figure 1. Distinct variations among matrices are evident, with sediments generally showing the highest levels, followed by water and MPs. The error bars (mean ± SD, n = 3) indicate the degree of variability across replicate analyses.



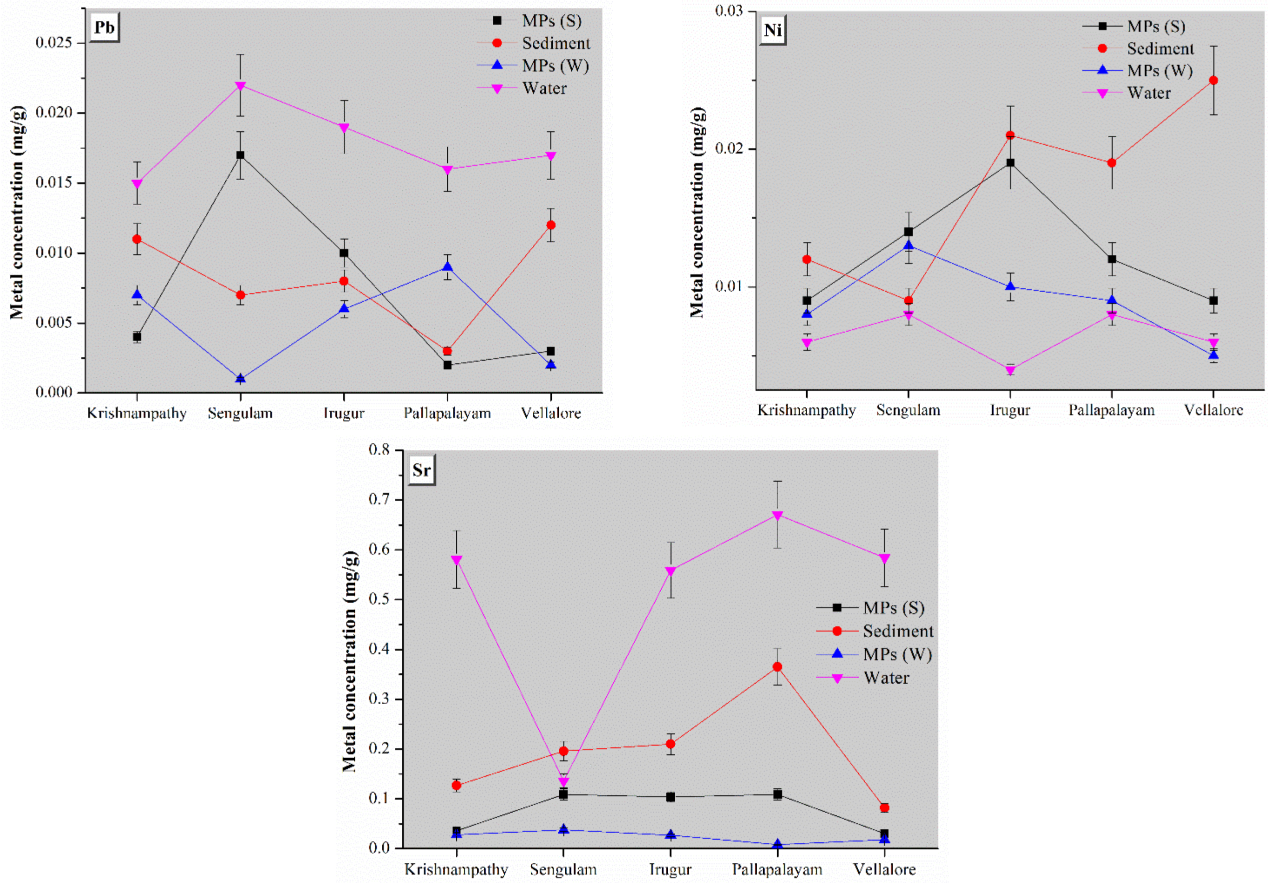


FIGURE 1: Graphs showing different metal concentrations in water, sediment, and microplastics (MPs) from five freshwater lakes in Coimbatore, India. Values represent mean ± standard deviation (n = 3) obtained from triplicate analyses of each matrix. Error bars indicate variability among replicates.

Pearson correlation analysis revealed positive associations between metal concentrations in MPs and those in sediments and water, indicating that the distribution of metals on MPs reflected local environmental contamination levels. The correlations were particularly strong for Cd ($r = 0.82$, $p < 0.01$ with sediments; $r = 0.76$, $p < 0.05$ with water), Pb ($r = 0.79$, $p < 0.01$ with sediments), and Ni ($r = 0.74$, $p < 0.05$ with sediments), suggesting their greater affinity for aged or oxidized polymer surfaces. The correlation was weaker for As and Sn, consistent with their enrichment in MPs through additive contributions. These relationships support the interpretation that MPs act as dynamic sorbents influenced by surrounding geochemical conditions.

ANOVA results indicated significant differences in metal concentrations across matrices for all metals ($p < 0.05$). Post-hoc tests (DMRT) confirmed that sediment concentrations were significantly higher than those in water and MPs for most metals, with the exception of As and Sn, where MP concentrations were comparable to or higher than sediment concentrations.

Principal component analysis (PCA) explained approximately 78% of the total variance in metal distribution across the dataset. PC1 (52% variance) distinguished sediment and water samples from MP samples and was primarily associated with Cd, Pb, Ni, and Mn concentrations. PC2 (26% variance) separated As and Sn from other metals and was associated with MP samples, consistent with their additive-derived enrichment. This analysis supports the interpretation that As and Sn in MPs have distinct sources compared to other metals.

3.4 Cadmium: Evidence of Environmental Adsorption

Cd concentrations in MPs (0.08–0.26 mg/kg) closely mirrored those in sediments and water, indicating adsorption from the environment rather than production-related incorporation. The strong positive correlation between Cd in MPs and in sediments ($r = 0.82$, $p < 0.01$) and water ($r = 0.76$, $p < 0.05$) supports this interpretation. Comparable trends have been observed in riverine systems in Hong Kong and South Africa, where MPs equilibrated with surrounding sediment and water geochemistry (Li et al., 2020; Mvovo et al., 2025). These findings support the role of MPs as dynamic sorbents capable of reflecting local contamination levels.

Metal accumulation on MPs was influenced by polymer type, surface aging, and environmental parameters such as pH, which together control sorption efficiency (Massos & Turner, 2017; Cao et al., 2021). Sediment pH at all lakes exceeded 6, consistent with elevated Cd adsorption, confirming pH as a critical geochemical factor (Brennecke et al., 2016; Holmes et al., 2014). At pH > 6, the predominance of Cd^{2+} species and the presence of negatively charged surface sites on aged MPs favor cation sorption. The presence of biofilms on MP surfaces, observed through visual inspection, may further contribute to Cd accumulation through biosorption.

3.5 Arsenic and Tin: Additive-Derived Metals

Unlike other metals, As (0.11–0.34 mg/kg) and Sn (0.09–0.28 mg/kg) were enriched in MPs relative to sediment and water, indicating contributions from plastic additives. As is used as a biocide and Sn as a biocide and heat stabilizer (Turner & Filella, 2021). The weaker correlation between MP-bound As and environmental concentrations ($r = 0.34$, $p > 0.05$ with sediments) and Sn ($r = 0.28$, $p > 0.05$) further supports additive-derived sources.

Environmental processes such as UV oxidation, mechanical abrasion, and biodegradation can mobilize these additives to the particle surface, enhancing their potential release (Hurley et al., 2018; Song et al., 2017). Fragmentation into smaller MPs increases surface area, further promoting migration of internal additives toward the surface (Browne et al., 2013). As MPs weather and fragment, these additive-derived metals may become increasingly available for desorption into the surrounding environment, potentially contributing to dissolved metal concentrations in water. Comparable additive-driven enrichment has been reported in marine and freshwater systems worldwide (Turner & Holmes, 2015; Tang et al., 2020).

3.6 Role of Weathering and Polymer Type

Weathered MPs adsorb higher amounts of metals than virgin plastics due to surface oxidation, formation of oxygenated functional groups, and increased roughness (Tang et al., 2020; Turner & Holmes, 2015). The visual evidence of surface weathering and discoloration in MPs from these lakes is consistent with enhanced sorption capacity. Field studies in South African rivers and Iranian water sources show enhanced adsorption of Cu, Zn, Pb, As, and Cd on aged MPs, supporting our observations in Coimbatore lakes (Mvovo et al., 2025; Rezaei Kahkha et al., 2025).

The predominance of fragment-type MPs in these lakes, with their relatively high surface area-to-volume ratios, further enhances metal adsorption compared to other morphologies. The accumulation of weathered fragments, coupled with the environmental conditions favoring metal sorption (moderately alkaline pH, presence of biofilms), likely contributes to the observed metal concentrations on MPs in these freshwater systems. These results indicate that environmental conditions, polymer characteristics, and aging processes collectively determine the metal sorption capacity of MPs.

3.7 Ecological and Health Implications

The coexistence of environmentally adsorbed and additive-derived metals in MPs has important ecological consequences. MPs may act as vectors, transferring metals through aquatic food webs, potentially causing bioaccumulation and physiological stress in fish and invertebrates (Holmes et al., 2014; Cao et al., 2021). Lakes in Coimbatore are used for irrigation, fishing, and domestic purposes, raising concerns about trophic transfer to humans (Neelavannan et al., 2023; Patidar et al., 2023).

MPs also influence trace element partitioning between sediments and overlying water, acting simultaneously as sinks and carriers, which complicates predictions of metal mobility and bioavailability (Cao et al., 2021). When MPs with adsorbed metals are ingested by benthic organisms, metals may desorb under the acidic conditions of the digestive tract, potentially increasing metal bioavailability and toxicity compared to sediment-bound metals. This mechanism has been demonstrated for Cd and Pb in laboratory studies, and suggests that MP-associated metals may pose a greater ecological risk than equivalent concentrations in sediment.

The presence of additive-derived As and Sn in MPs introduces additional ecotoxicological concerns. These metals may be more readily released from MPs than environmentally adsorbed metals due to their incorporation within the polymer matrix and potential for diffusive migration to the surface. Desorption of As from MPs has been shown to follow first-order kinetics, with release rates influenced by pH and the degree of particle weathering. The cumulative release of additive-derived metals from the substantial MP burden in these lakes could therefore represent an ongoing source of metal contamination to the water column.

A preliminary ecological risk assessment using sediment quality guidelines (SQGs) revealed that Cd concentrations in sediment from two lakes exceeded the threshold effect level (TEL) but were below the probable effect level (PEL), indicating moderate potential for adverse effects. Pb concentrations in sediment from three lakes exceeded the TEL, suggesting potential toxicity to benthic organisms. While the concentrations of metals associated with MPs are lower than those in sediments, their bioavailability potential may be higher due to ingestion and desorption processes.

These findings highlight the need to include MPs in contaminant fate models and ecological risk assessments. The combined exposure to MPs and associated metals may produce synergistic toxicity effects that are not captured by studies of either contaminant type individually. Further research is needed to quantify the bioavailability of MP-associated metals in these lake systems and to assess their trophic transfer potential.

3.8 Comparison with International Studies

The metal concentrations observed in MPs from Coimbatore lakes are generally comparable to those reported in other freshwater systems globally. For Cd (0.08-0.26 mg/kg), values are within the range reported for European rivers (0.02-0.45 mg/kg) and lower than some industrial-impacted systems in China (0.1-1.2 mg/kg). The As concentrations in MPs (0.11-0.34 mg/kg) are similar to those reported for South African rivers (0.1-0.5 mg/kg) and lower than those in some Asian systems with high industrial activity (0.2-1.5 mg/kg). The Sn concentrations (0.09-0.28 mg/kg) are within the range reported for marine environments (0.05-0.5 mg/kg).

The dual-source pattern observed in this study—with Cd primarily from environmental adsorption and As/Sn from additive sources—has also been reported in other studies. However, the clear differentiation between adsorption-derived and additive-derived metals in a single study is a notable contribution, as most previous studies have focused on either adsorption processes or additive content separately. This distinction has important implications for risk assessment: metals from additives may be more readily desorbed under certain conditions, while adsorbed metals may be more responsive to changes in environmental chemistry.

3.9 Limitations of the Study

Several limitations should be acknowledged. First, polymer identification via FTIR or Raman spectroscopy was not performed, limiting the ability to correlate metal adsorption with specific polymer types. Second, the study was conducted at a single time point; seasonal variations in MP and metal concentrations were not assessed. Third, the extraction efficiency of MPs from sediment was not fully optimized, potentially underestimating MP concentrations. Fourth, bioaccessibility and bioavailability of MP-associated metals were not assessed directly. Fifth, the sample size (five lakes) limits the robustness of statistical inference. Despite these limitations, the study provides valuable baseline data and insights into MP-metal interactions in Indian freshwater ecosystems.

IV. CONCLUSION

This study presents one of the first comprehensive assessments of microplastics (MPs) and associated heavy metals in freshwater lakes of Coimbatore, India. Our results demonstrate the coexistence of MPs and trace metals in water and sediment, highlighting their dual role as environmental contaminants. Cadmium (Cd) in MPs closely mirrored concentrations in surrounding water and sediment, indicating adsorption under local geochemical conditions. In contrast, elevated levels of arsenic (As) and tin (Sn) in MPs suggest contributions from plastic additives, emphasizing the need to consider both production-related and environmentally derived metal sources.

Metal accumulation on MPs was influenced by polymer type, surface aging, and environmental factors such as pH, collectively affecting contaminant partitioning among sediments, water, and biota. Statistical analysis confirmed these patterns, with significant positive correlations ($p < 0.05$) observed between metal concentrations in microplastics and those in sediments and water. This indicates that the metal burden of MPs is closely linked to ambient contamination levels and supports their role as environmental indicators of trace metal pollution. The morphological characterization of MPs—dominated by weathered fragments—further supports the role of MPs as active sorbents in these freshwater systems.

By acting as carriers of metals, MPs represent a potential pathway for pollutant transfer into aquatic organisms and the broader food web. The coexistence of environmentally adsorbed and additive-derived metals on MPs has implications for ecological risk assessment, as these metals may exhibit different bioavailability and desorption kinetics. These findings provide valuable baseline data for Indian freshwater systems and underscore the importance of incorporating particle-bound contaminants into ecological risk assessments and water quality management strategies.

Implications for Policy and Management:

1) **Monitoring Programs**: The findings highlight the need to include MP-associated metals in routine water quality monitoring programs, particularly in urban lakes that serve as sources of irrigation water and fisheries.

2) **Plastic Waste Management**: The presence of additive-derived As and Sn in MPs suggests that plastic waste in these lakes is a source of these metals, emphasizing the need for improved plastic waste management and reduction of plastic inputs to freshwater systems.
3) **Risk Assessment Frameworks**: Ecological risk assessments should consider the combined effects of MPs and associated metals, rather than evaluating these contaminants separately.
4) **Remediation Strategies**: Remediation efforts should address both metal contamination and MP pollution, as these are interconnected through adsorption-desorption processes.
5) **Public Health Protection**: Given the use of these lakes for fisheries and irrigation, continued monitoring of metal contamination and its potential transfer through food webs is essential to protect human health.

Future Research Priorities:

1) **Polymer Characterization**: Future studies should include polymer identification (FTIR/Raman) to elucidate the relationship between polymer type and metal adsorption.
2) **Bioavailability Assessment**: Bioaccessibility and bioavailability studies are needed to understand the ecological and human health risks of MP-associated metals.
3) **Seasonal Studies**: Longitudinal studies across seasons would reveal the temporal dynamics of MP-metal interactions.
4) **Trophic Transfer**: Investigation of trophic transfer of MP-associated metals in these lake food webs would quantify the ecological risk.
5) **Remediation Research**: Development of remediation strategies for MP-metal contaminated sediments.

Addressing such emerging interactions is essential for safeguarding ecosystem integrity and minimizing risks to human health in rapidly urbanizing regions of India and the broader Global South.

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- **Data Availability:** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.
- **Ethics Approval:** Not applicable. This study did not involve human participants, animal subjects, or any ethical issues requiring approval.

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