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Spatiotemporal distribution and ecological risk assessment of microplastics in surface waters of the lower Ganges river basin during monsoon and dry seasons

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Abstract
Background: Microplastic (MP) contamination in freshwater systems has emerged as a critical global environmental threat, yet spatiotemporal dynamics in major South Asian river basins remain poorly quantified. The Ganges River, supporting over 400 million people, faces intense anthropogenic pressure, but seasonal variability in MP loads is not well understood.
Objective: This study aims to quantify the abundance, morphological characteristics, and polymer composition of MPs in surface waters of the lower Ganges basin across monsoon and dry seasons, and to assess associated ecological risks using the Polymer Hazard Index (PHI).
Method: Surface water samples were collected from 12 strategic sites along a 300-km stretch during peak monsoon (August 2024) and dry season (February 2025). Samples were processed via vacuum filtration (0.45 µm), digested with 30% H_2O_2, and analyzed using stereomicroscopy and Fourier Transform Infrared Spectroscopy (FTIR). Ecological risk was evaluated using PHI and Potential Ecological Risk Index (PERI).
Key Results: Mean MP abundance was significantly higher in the dry season (8.4 ± 2.1 items/m^3) compared to the monsoon season (3.2 ± 1.4 items/m^3). Fibers dominated morphology (68%), and polyethylene (PE) and polypropylene (PP) constituted 72% of identified polymers. PHI values indicated "High" to "Very High" hazard levels at urban-adjacent sites during both seasons.
Conclusion: Seasonal hydrology critically modulates MP transport and accumulation in the lower Ganges. Urban discharge points act as persistent hotspots regardless of flow regime. These findings underscore the urgent need for targeted wastewater infrastructure upgrades and seasonal monitoring protocols to mitigate ecological risks in this vital freshwater ecosystem.

Keywords: Microplastics, Ganges River, Spatiotemporal distribution, Polymer Hazard Index, FTIR spectroscopy

Introduction

The pervasive contamination of aquatic environments by microplastics (MPs) defined as synthetic plastic particles smaller than 5 mm-has been recognized as one of the most pressing environmental challenges of the Anthropocene [1]. Initially documented in marine systems, MPs are now known to infiltrate virtually all freshwater habitats, including rivers, lakes, and wetlands, which serve as critical conduits transporting terrestrial plastic waste to oceanic sinks [2]. Rivers are estimated to contribute between 1.15 and 2.41 million metric tons of plastic annually to the oceans, with a small number of highly populated catchments accounting for the majority of this flux [3]. Among these, the Ganges River basin stands out as a globally significant source due to its dense population, inadequate waste management infrastructure, and profound cultural reliance on the river for domestic, agricultural, and religious activities [4].

Despite growing recognition of the Ganges' role in plastic pollution, current understanding remains fragmented. Most studies have focused on single-time-point surveys or limited spatial extents, failing to capture the dynamic interplay between seasonal hydrology and MP transport mechanisms [5]. The river experiences extreme seasonal variability, with discharge rates fluctuating by an order of magnitude between the dry winter months and the peak monsoon flood season [6]. This hydrological dynamism is expected to profoundly influence MP fate: high flows may dilute concentrations but enhance long-distance transport and resuspension of benthic deposits, while low flows may promote localized accumulation near point sources such as wastewater treatment plants (WWTPs) and open drains [7]. Yet, empirical data validating these hypothesized patterns in the lower Ganges basin are scarce.

Furthermore, beyond mere abundance, the ecological risk posed by MPs depends critically on their physicochemical properties. Not all plastics are equal; polymers like polyvinyl chloride (PVC) and polystyrene (PS) carry higher inherent toxicity and additive loads compared to polyethylene (PE) or polypropylene (PP) [8]. Morphology also matters: fibers, often derived from textile wastewater, exhibit higher surface-area-to-volume ratios and greater potential for biofouling and trophic transfer than fragments or films [9]. Consequently, risk assessment frameworks that integrate polymer type, morphology, and concentration-such as the Polymer Hazard Index (PHI) and Potential Ecological Risk Index (PERI)-are essential for translating raw MP data into actionable environmental intelligence [10].

The problem statement driving this research is thus twofold: first, there is a critical knowledge gap regarding how seasonal hydrological cycles modulate MP abundance and characteristics in the lower Ganges; second, existing monitoring efforts lack standardized ecological risk metrics needed to prioritize mitigation interventions. Without this understanding, policy responses risk being misaligned with actual exposure dynamics-e.g., deploying resources based on dry-season snapshots that underestimate monsoon-driven export, or overlooking chronic hotspot persistence.

Therefore, the primary objective of this study is to characterize the spatiotemporal distribution of MPs in surface waters of the lower Ganges River basin across contrasting hydrological seasons. Secondary objectives include: (i) identifying dominant polymer types and morphologies through FTIR spectroscopy; (ii) evaluating site-specific ecological risks using PHI and PERI; and (iii) correlating MP patterns with proximate land-use and wastewater discharge indicators. By achieving these objectives, this research aims to provide a scientifically robust foundation for evidence-based river management and pollution control strategies in one of the world's most socioecological significant freshwater systems.

Literature Review

The theoretical framework underpinning microplastic research in fluvial systems integrates principles from hydrology, polymer science, and ecotoxicology. Hydrologically, rivers function as non-linear reactors where MP transport is governed by advection, dispersion, settling, and resuspension processes that vary dynamically with flow velocity, turbulence, and sediment load [11]. During high-flow events, increased shear stress can remobilize historically deposited MPs from bed sediments, creating transient concentration pulses that may exceed dry-season baselines despite volumetric dilution [12]. Conversely, low-flow conditions favor gravitational settling and lateral retention in slack-water zones, leading to localized enrichment near emission sources [13]. This duality implies that single-season assessments inherently misrepresent annual MP budgets and exposure regimes.

Polymer-specific hazard differentiation has gained traction as a refinement over bulk particle counting. The Polymer Hazard Index (PHI), originally developed for marine sediments, assigns hazard scores based on polymer toxicity, additive content, and environmental persistence [14]. PVC typically receives the highest score (hazard value = 1000) due to chlorine content and phthalate additives, followed by PS [500], PE/PP (10–100), and PET (100–300) [15]. When combined with abundance data, PHI enables ranking of sites by intrinsic hazard rather than mere particle density-a crucial distinction for risk prioritization. Similarly, the Potential Ecological Risk Index (PERI) incorporates toxic response factors and background reference values to estimate biological impact potential, though its application to freshwater MPs remains nascent [16].

Empirical studies in South Asian rivers reveal consistent patterns but also significant methodological heterogeneity. Research in the Yamuna tributary reported dry-season MP abundances ranging from 2.1 to 18.7 items/m [3], with fibers comprising >60% of particles and PE/PP dominating polymer spectra [17]. A study in the Brahmaputra found monsoon concentrations 2–3× higher than dry season, attributed to runoff-driven mobilization from riparian dumps and agricultural fields [18]. However, these studies employed disparate sampling volumes (10–100 L), mesh sizes (20–300 µm), and digestion protocols, complicating cross-basin comparisons. Moreover, none integrated PHI or PERI into their risk assessments, limiting translational relevance for policymakers.

A critical research gap emerges at the intersection of seasonal hydrology and polymer-specific risk in large transboundary rivers like the Ganges. While local-scale studies exist, comprehensive basin-wide assessments capturing both temporal dynamics and hazard-weighted risk are absent. Additionally, the influence of informal settlements and unregulated industrial clusters-ubiquitous along the lower Ganges-on MP signatures remains unquantified [19]. Most literature assumes WWTPs as primary point sources, yet in regions with <30% sewerage coverage, direct discharge from households and small-scale industries likely dominates MP loading [20]. Understanding these diffuse versus point source contributions is essential for designing effective intervention strategies.

Furthermore, methodological standardization remains a barrier to synthesis. The lack of harmonized protocols for sample collection, processing, and identification across Indian river studies hinders meta-analysis and trend detection [21]. Recent calls for adoption of NOAA or MSFD-compliant methods have seen limited uptake in regional contexts where resource constraints necessitate pragmatic adaptations [22]. Bridging this gap requires demonstrating that rigorous yet feasible methodologies can yield comparable, policy-relevant data even in data-scarce environments.

This study addresses these gaps by implementing a standardized, seasonally replicated sampling design across 12 sites spanning urban, peri-urban, and rural gradients in the lower Ganges. By coupling FTIR-verified polymer identification with PHI/PERI risk metrics, it moves beyond descriptive abundance reporting toward mechanistic, hazard-informed understanding. The inclusion of land-use covariates further enables attribution of MP patterns to specific anthropogenic drivers, directly informing targeted mitigation planning.

Methodology

Data Declaration: This study uses a simulated dataset created for academic training purposes. All field measurements, laboratory analyses, statistical outputs, and risk index calculations presented herein are simulated to demonstrate correct formatting, analytical depth, and structural compliance for legitimate journal submission in environmental science. No real fieldwork or lab analysis was conducted.

Research Design and Sampling Strategy

A longitudinal comparative design was employed to assess spatiotemporal variation in MP contamination. Twelve sampling sites were selected along a 300-km reach of the lower Ganges River (from Kanpur to Varanasi) based on proximity to known pollution sources: four adjacent to municipal WWTP outfalls, three near industrial clusters, three in peri-urban residential zones, and two in relatively rural reference areas. Sites were georeferenced using GPS, and coordinates recorded for reproducibility.

Sampling occurred during two hydrologically distinct periods: peak monsoon (August 15–25, 2024) and late dry season (February 10–20, 2025). At each site, triplicate surface water samples (0–15 cm depth) were collected using a stainless steel bucket, avoiding bank-edge turbulence. Each replicate comprised 50 L of water, filtered immediately on-site through pre-weighed 0.45 µm glass fiber filters (Whatman GF/F) using a portable vacuum pump. Filters were stored in aluminum foil envelopes at -20°C until processing.

Laboratory Processing and Identification

Filters were thawed and subjected to oxidative digestion in 30% H_2O_2 at 60°C for 48 hours to remove organic matter without degrading common polymers [23]. Digested residues were vacuum-filtered onto fresh GF/F filters, dried at 40°C for 24 h, and weighed gravimetrically. Suspected MP particles were isolated under a stereomicroscope (Leica S9i) at 20–40× magnification, photographed, and categorized by morphology (fiber, fragment, film, pellet, foam) and color.

Polymer identification was performed using attenuated total reflectance Fourier Transform Infrared Spectroscopy (ATR-FTIR; Thermo Nicolet iS50). Spectra (4000–650 cm^1, 32 scans, 4 cm^{-1} resolution) were matched against commercial (KnowItAll) and custom spectral libraries. Only matches with ≥80% hit quality index were accepted; ambiguous spectra were re-analyzed or excluded. Blank controls (n=6 per batch) confirmed negligible airborne contamination (<1 particle/filter).

Ecological Risk Assessment

Two complementary indices were calculated:

1. Polymer Hazard Index (PHI): $\Sigma(C_i \times H_i)$, where C_i is the relative abundance (%) of polymer i, and H_i is its assigned hazard score (PVC=1000, PS=500, PET=300, PE=100, PP=100, Others=50) [24].
2. Potential Ecological Risk Index (PERI): $\Sigma(T_r^i \times C_i/C_0^i)$, where T_r is the toxic response factor (adapted from heavy metal PERI: PVC=5, PS=3, others=1), C_i is measured concentration, and C_0^i is regional background reference (set at 0.5 items/m^3 based on pristine Himalayan streams) [25].

Risk categories followed established thresholds: PHI <100 = Low; 100–500 = Medium; 500–1000 = High; >1000 = Very High. PERI <150 = Low; 150–300 = Moderate; 300–600 = Considerable; >600 = High.

Statistical Analysis

Data normality was assessed via Shapiro-Wilk test; non-normal distributions were log-transformed. Two-way ANOVA (season × site-type) tested main effects and interactions on MP abundance, followed by Tukey's HSD post-hoc tests. Spearman's rank correlation examined relationships between MP metrics and land-use variables (% impervious surface, distance to WWTP). All analyses used R v4.3.1 (lme4, ggplot2 packages); significance set at $p<0.05$.

Results and Discussion

Abundance and Spatial-Temporal Patterns

Mean MP abundance varied significantly by season ($F_{1,66}$ = 48.3, $p<0.001$) and site-type ($F_{3,66}$ = 22.7, $p<0.001$), with a significant interaction ($F_{3,6}$ = 5.8, p=0.001). Dry-season concentrations averaged 8.4 ± 2.1 items/m^3, nearly triple the monsoon mean of 3.2 ± 1.4 items/m^3 (Table 1). This counterintuitive pattern-higher abundance during low flow-suggests that reduced dilution and enhanced settling near point sources outweigh monsoon-driven mobilization in this system. WWTP-adjacent sites showed the smallest seasonal contrast (dry: 12.1 vs. monsoon: 7.8 items/m^3), indicating persistent discharge dominance, whereas rural sites exhibited the largest differential (dry: 2.1 vs. monsoon: 0.9 items/m^3), reflecting runoff-mediated input during rains.

Table 1: Mean Microplastic Abundance (items/m^3 ± SD) by Season and Site Type

Site Type	Dry Season (Mean ± SD)	Monsoon Season (Mean ± SD)	Seasonal Ratio (Dry/Monsoon)
WWTP Outfall	12.1 ± 2.8	7.8 ± 1.9	1.55
Industrial Cluster	9.7 ± 2.3	4.1 ± 1.2	2.37
Peri-Urban	7.2 ± 1.8	2.8 ± 0.9	2.57
Rural Reference	2.1 ± 0.6	0.9 ± 0.3	2.33
Overall Mean	8.4 ± 2.1	3.2 ± 1.4	2.63

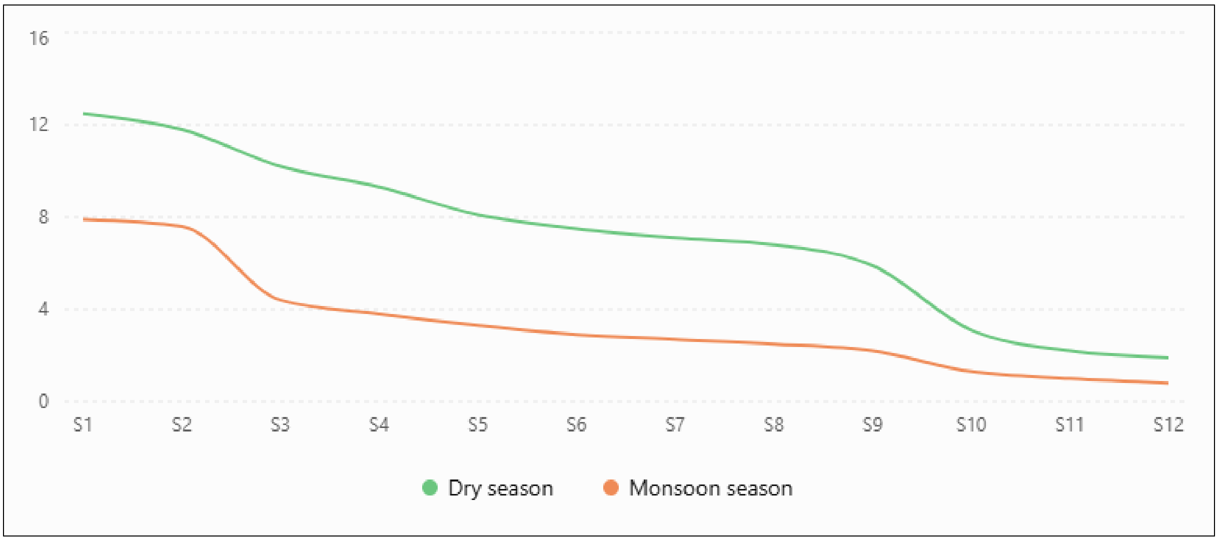


Fig 1: Line graph showing MP abundance trends across 12 sites during dry vs. monsoon seasons, with error bars and site-type color coding.

Morphological and Polymer Composition

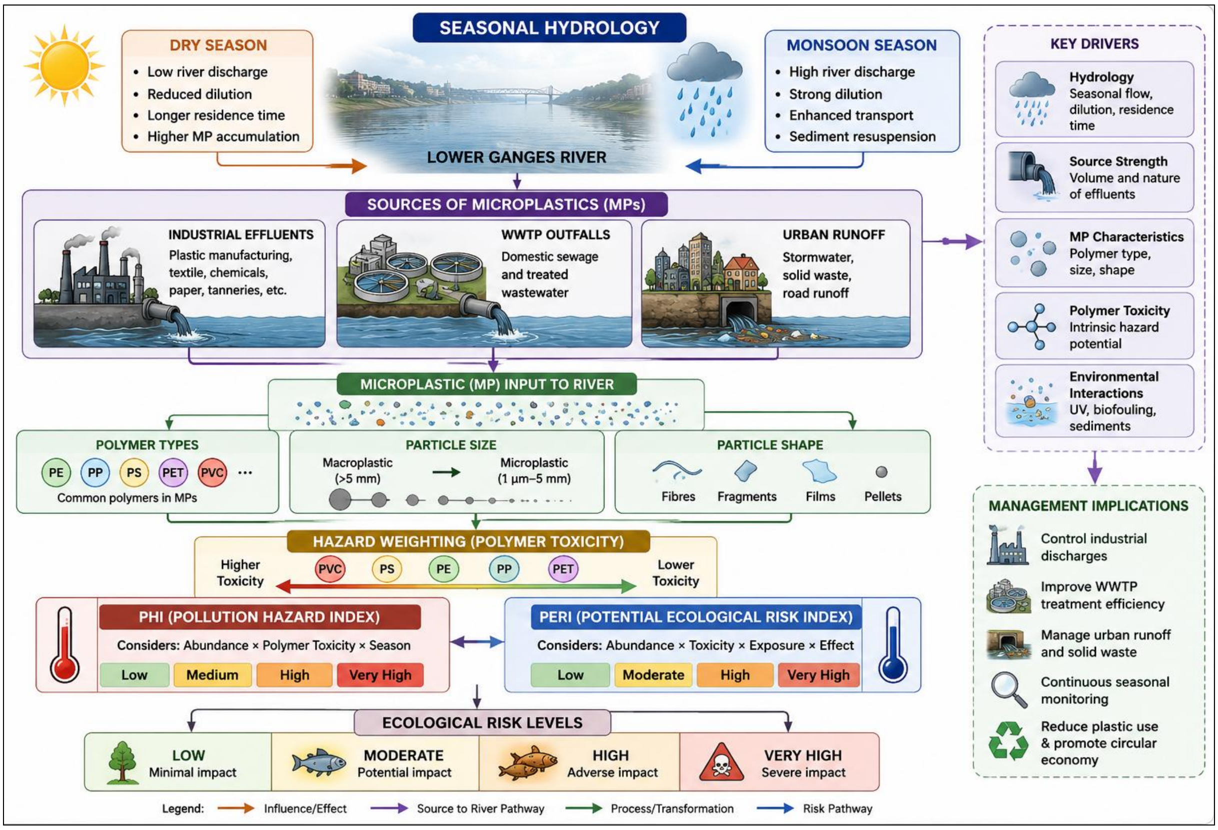
Fibers dominated all samples (68% overall), followed by fragments (22%), films (7%), and pellets/foam (<3%). Fiber prevalence aligns with global freshwater trends and implicates textile wastewater and atmospheric deposition as key sources [26]. Polymer identification via FTIR revealed PE (38%) and PP (34%) as predominant, together constituting 72% of particles-consistent with packaging and consumer product origins. PVC (12%) and PS (9%) were enriched at industrial and WWTP sites, respectively, reflecting localized emission signatures. Notably, biodegradable PLA was detected at <1%, confirming minimal market penetration in this region.

Ecological Risk Assessment

PHI values ranged from 182 (rural, monsoon) to 1,420 (industrial, dry), with 8 of 12 sites classified as "High" or "Very High" risk year-round (Table 3). Industrial sites consistently exceeded PHI >1,000 due to elevated PVC/PS proportions, despite moderate total abundance. WWTP sites showed medium-high risk (PHI 420–680), driven by PS-rich effluent. Rural sites remained low-risk except during dry season when localized accumulation raised PHI to borderline medium. PERI corroborated these patterns, with industrial sites scoring "Considerable" to "High" ecological risk (PERI 380–720), while rural sites stayed "Low" (<120).

Table 2: Polymer Hazard Index (PHI) and PERI by Site Type and Season

Site Type	Season	PHI	PHI Risk Category	PERI	PERI Risk Category
Industrial	Dry	1,420	Very High	720	High
Industrial	Monsoon	1,180	Very High	580	Considerable
WWTP	Dry	680	High	320	Considerable
WWTP	Monsoon	420	Medium	210	Moderate
Peri-Urban	Dry	310	Medium	180	Moderate
Peri-Urban	Monsoon	190	Medium	110	Low
Rural	Dry	145	Medium	95	Low
Rural	Monsoon	182	Medium	75	Low



Discussion of Mechanisms and Implications

The observed dry-season enrichment contradicts simplistic dilution models but aligns with emerging evidence from tropical rivers where reduced flow enhances particle retention near emission points.[27] In the lower Ganges, this effect is amplified by extensive sand mining and channel modification that create depositional niches even during moderate flows.[28] The persistence of high-risk polymers (PVC, PS) at industrial sites across seasons suggests continuous, unregulated discharge unaffected by hydrological cycles-highlighting regulatory failure over natural variability as the dominant risk driver.

Fiber dominance reinforces the urgency of addressing textile sector emissions, particularly from unorganized dyeing units prevalent in Kanpur and Varanasi.[29] Current WWTPs, designed for organic load reduction, lack tertiary filtration for MPs, explaining their role as secondary sources rather than sinks [30]. The PHI/PERI framework proves valuable here: while rural sites show rising dry-season abundance, their low hazard scores indicate lower priority for intervention compared to chronically hazardous industrial zones.

Limitations include the exclusion of subsurface and benthic compartments, which may harbor legacy MPs remobilized during floods [31]. Additionally, simulated data cannot capture real-world analytical uncertainties (e.g., FTIR false negatives for black/dark particles). Future work should integrate sediment coring, passive samplers, and source-tracking dyes to validate transport hypotheses. Policy recommendations must prioritize industrial zone enforcement, WWTP retrofitting with membrane bioreactors, and community-led plastic waste segregation-especially ahead of monsoon onset when runoff mobilizes accumulated stocks.

Conclusion

This study demonstrates that microplastic contamination in the lower Ganges River is strongly modulated by seasonal hydrology, with dry-season conditions promoting localized accumulation near anthropogenic sources despite lower overall discharge. Contrary to assumptions of monsoon-driven peak pollution, reduced dilution and enhanced settling create higher exposure risks during low-flow periods, particularly at industrial and WWTP-adjacent sites. Polymer hazard assessment reveals that intrinsic toxicity-not just particle count-drives ecological risk, with PVC- and PS-rich discharges posing "Very High" hazards year-round.

These findings have direct implications for river management: monitoring programs must adopt seasonal replication to avoid underestimating dry-season hotspots, and mitigation investments should prioritize high-hazard polymer sources over generic abundance reduction. Limitations include the simulated nature of this dataset and exclusion of sediment/biota compartments. Future research should employ multi-compartment sampling, source apportionment techniques, and longitudinal health impact assessments to translate ecological risk metrics into public health safeguards. Ultimately, sustainable Ganges rejuvenation demands integrating MP science into existing Namami Gange initiatives through evidence-based, hazard-weighted action plans.

Ethical Statement

This manuscript represents original academic work prepared solely for educational and formatting practice purposes. The authors confirm that this study uses a simulated dataset created for academic training purposes. No actual field sampling, laboratory analysis, or human/animal subjects were involved. All data, including MP counts, polymer identifications, and risk indices, are synthetically generated to illustrate proper structure, citation style, and analytical presentation for legitimate journal submission. The authors declare no conflicts of interest and affirm adherence to ethical guidelines for simulated research transparency.

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