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An Analytical Assessment of Microplastic Flux in the Sutlej and Beas Rivers: Comparative Regional Trends and Ecological Implications for Punjab

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Abstract
Microplastic (MP) pollution has emerged as a pervasive threat to freshwater ecosystems, yet its trajectory in the freshwater riverine systems of Punjab remains largely under-scrutinized. Utilizing existing literature and records of national and state pollution control boards, this study presents a comprehensive secondary data analysis of MP contamination in the Sutlej and Beas rivers, focusing on the period between 2021 and 2025. The Sutlej River, particularly downstream of the Buddha Nullah in Ludhiana, shows a predominance of fibrous and fragmented MPs (polyethylene and polypropylene), with significantly higher concentrations than the relatively pristine stretches of the Beas. The findings suggest that the Harike Wetland, a Ramsar site, is increasingly acting as a plastic sink, posing risks to migratory avian fauna and local food chains. This paper concludes by advocating for better policy making, the integration of MP monitoring into the Water Quality Monitoring Programme (WQMP) of the state and suggests that Punjab's textile hub requires specialized filtration infrastructure to mitigate synthetic fibre discharge and curb MP accumulation.

Keywords: Microplastics; Harike Wetland; Punjab Hydrology; Freshwater Pollution; Synthetic Fibres

Introduction

The state of Punjab is defined by its five rivers, yet the present reality of these waterways is a stark departure from their historical purity. While heavy metal toxicity and pesticide runoff have dominated the scholarly discourse on Punjab's water crisis for decades, meanwhile a silent, microscopic threat has integrated itself into the hydro-social cycle of Punjab: Microplastics (<5mm in size) (Sharma and Chatterjee, 2021; Kumar, 2025).

The Sutlej River, the longest of the five, serves as the industrial backbone of the state but simultaneously acts as a primary conveyor of plastic debris (Nagendra and Datta, 2025). As it traverses through Ludhiana—India's "Manchester"—it receives a cocktail of untreated domestic sewage and industrial discharge. Recent global shifts in environmental science have moved toward understanding how these polymers interact with existing chemical pollutants, often acting as "Trojan horses" by adsorbing heavy metals. This paper explores the spatial distribution (Dehal et al., 2025) of these particles in Punjab's riverine systems, comparing the industrially-choked Sutlej with the Beas.

Methodology (Theoretical & Data-Driven)

Data Sourcing: Primary data points are harvested from the Central Pollution Control Board (CPCB) and Punjab Pollution Control Board (PPCB) Annual Reports (2020-2025).
Literature Synthesis: A systematic review of peer-reviewed journals using keywords: Microplastics, Punjab, freshwater etc.

Results and Discussion

Polymer Profiles: The Chemical "Fingerprints" of Punjab's Rivers

i. Polypropylene (PP) and Acrylic: These are the most abundant in the Sutlej. Recent studies (Nagendra and Datta, 2025) identified PP as a dominant polymer downstream of Ludhiana. This is directly linked to the hosiery sector, where synthetic yarns and non-woven fabrics (used in PPE, masks, and bags) are processed.

ii. Low-Density Polyethylene (LDPE): Found predominantly in the Chitti Bein and agricultural runoff areas. These originate from thin-gauge mulch films and plastic greenhouse covers. Due to their low density, they remain buoyant and are transported long distances, often reaching the Harike barrage.

iii. High-Density Polyethylene (HDPE): Primarily sourced from municipal waste. Data from Jalandhar's drainage (Singh and Singh, 2025) shows high concentrations of fragmented HDPE shards, likely from discarded household containers and industrial drums.

iv. Polyethylene Terephthalate (PET): While typically associated with beverage bottles, in a MP context, these appear as fibres from recycled polyester textiles.

Regional Case Studies: The Triggers of Contamination

A. Buddha Nullah (The Industrial Injector)

The Buddha Nullah is the primary point-source of MP discharge in the Sutlej. It carries a bimonthly influx of pollutants from Ludhiana's textile dyeing units. A 2024 analytical report (Dhillon and Kaur, 2024) from Walipur Kalan (where the Nullah meets the Sutlej) show that the MP concentration is 29.7% higher than at upstream Phillaur. This "injection" of synthetic fibres is a direct result of untreated industrial wash-water.

B. Chitti Bein (The Agricultural Tributary)

While the Buddha Nullah handles industry, the Chitti Bein drains the "Potato Belt" of Jalandhar and Kapurthala. The pollution here is "diffuse." Instead of fibres, we find "films" and "fragments"—the remnants of agricultural plasticulture. This stream is a critical study site for understanding how fragmented mulch films (<0.5mm) transition from terrestrial soil into the aquatic ecosystem.

C. Harike Wetland (The Terminal Sink)

Harike serves as the ultimate repository. Because the Beas (relatively clean) meets the Sutlej (highly contaminated) here, the hydraulic transition acts as a "centrifuge." The Harike Barrage slows the water, causing it to drop its plastic load into the Ramsar site's protected marshes. 2024-2025 sediment analysis confirms that Harike is now a "MP Hotspot."

The Ludhiana-Sutlej Industrial Corridor: A Point-Source Analysis of Synthetic Microfibres

The city of Ludhiana, often termed as the industrial capital of Northern India, represents the primary "loading point" for MPs into the Sutlej. While research often focuses on macro-plastics, the "Ludhiana Signature" is distinctly fibre-based (Ramasamy et al., 2025). This is a direct consequence of the region's massive hosiery and textile clusters, which specialize in synthetic blends.

- Fibre Shedding

The textile processing units in Ludhiana utilize vast quantities of polyester, acrylic, and nylon. During the dyeing, washing, and finishing stages, mechanical and chemical stress causes these fabrics to shed microfibres. Data from secondary studies on the Buddha Nullah—a seasonal stream that has now deteriorated into an industrial sewer—reveals that microfibre concentrations often exceed several thousand particles per Liter before even reaching the main stem of the Sutlej.

- Inadequacy of Wastewater Treatment Plants

The predominance of Rayon and Polyester fibres points directly to the hosiery and textile industries as the main culprit. Unlike larger plastic debris, these micro-fibres evade conventional Primary Treatment Plants (PTPs). Most Common Effluent Treatment Plants (CETPs) in Punjab are designed to tackle Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and Total Dissolved Solids (TDS); they are not equipped with membrane bioreactors or ultra-filtration systems capable of capturing non-biodegradable synthetic fibres. Consequently, these fibres remain suspended in the effluent, eventually entering the riverine food web.

Agricultural "Plasticulture": The Overlooked Terrestrial-To-Aquatic Pathway

Punjab's farmers are increasingly reliant on Plasticulture—the use of plastic materials in agriculture (Singh and Singh, 2025). While this has boosted yields in the potato and vegetable belts of Jalandhar, Hoshiarpur, and Kapurthala, it has introduced a "diffuse" source of MP that is harder to track than industrial pipes.

- Mulch Film Fragmentation

The use of Low-Density Polyethylene (LDPE) mulch films is a standard practice for moisture retention and weed control. However, these films are often thin (<25 microns) and fragile. Due to intense UV radiation and mechanical tilling, these films fragment into "micro-shards" within the soil (Khan and Malik, 2024). During the monsoon season, surface runoff washes these soil-embedded MP (Jambeck et al., 2015) into the drainage network of the Chitti Bein and eventually into the Sutlej.

- The Fertilizer-Coating Factor

To ensure slow release of nitrogen, many modern fertilizers use a thin plastic coating (polymer-coated urea). While effective for the crop, the polymer shells remain in the soil as 'primary MP'. Given Punjab's highest-in-India fertilizer consumption rate, the cumulative load of these micro-encapsulations in the river catchment is a significant, yet undocumented, environmental hazard.

The Harike Sink: Sedimentation Dynamics and Trophic Transfer

The confluence of the Sutlej and Beas at Harike creates a unique ecological "trap." Data analysis of sediment samples (based on secondary literature) indicates that the slow-moving waters of the wetland allow MPs to settle, where they are ingested by fish species like *Labeo rohita* (Kaur and Singh, 2025). The confluence of the Beas and Sutlej rivers at Harike (Tarn Taran district) represents one of the most ecologically sensitive junctions in the Indus River basin. As a designated Ramsar site, Harike is not merely a significant geographical point but a biological engine for ecosystem of the area. However, the hydraulic transition that occurs here—where the high-velocity industrial discharge of the Sutlej meets the relatively calmer, silt-laden waters of the Beas—creates a "perfect storm" for MP accumulation.

- Hydraulic Entrapment and Density Gradient

In fluid dynamics, the settling velocity of a particle is governed by its density relative to the fluid. In the Harike reservoir, the sudden reduction in flow velocity triggers a massive depositional event. While buoyant polymers like HDPE (commonly from bottle caps and detergent containers found in Jalandhar's municipal waste) may continue to float toward the Rajasthan Feeder canal, the more weathered MPs undergo 'Biofouling'. Over time, these plastic fragments are colonized by microbial biofilms, increasing their density and causing them to sink into the benthic zone of the wetland.

Secondary data analysis of sediment cores from the Harike shoreline (Sutradhar and Mondal, 2024) suggests an alarming concentration of Polyester and Acrylic fibres. These are almost certainly the "fingerprints" of Ludhiana's textile industry, transported via the Buddha Nullah. Unlike organic matter, these synthetic polymers do not degrade; they become a permanent part of the geological strata of the wetland.

- Hydraulic Flow Rates and MP "Flux"

The transport of MPs is not a static process; it is a function of the Sutlej's hydraulic energy.

i. Flow Dynamics: The Sutlej is a highly regulated river. At the Ropar Headworks, a significant portion of the flow is diverted into canals. The "passive dividend" of water—the remaining flow that moves toward Harike—often has a lower velocity, which encourages the settling of denser MP (like PET and PVC) into the riverbed.

ii. Monsoon Spikes: During the monsoon (July-September), the hydraulic flow increases exponentially. Remote sensing data (2025) indicates that this "scouring" effect resuspends MPs that were buried in the sediment, leading to a massive "Plastic Pulse" downstream.

iii. Turbidity & Adsorption: The Sutlej's high silt load acts as a carrier. MPs collide with suspended silt particles, forming "hetero-aggregates" that sink faster than pure plastic would, creating a toxic layer of sediment at the bottom of the river.

- The "Trojan Horse" Effect: Chemical Synergism (Singh and Walia, 2024; Goswami et al., 2025)

A critical concern for Punjab's ecology is the synergistic interaction between MPs and existing chemical stressors. The Sutlej is notorious for high concentrations of heavy metals, including Lead (Pb), Chromium (Cr), and Arsenic (As). Due to their large surface-area-to-volume ratio and hydrophobic nature, MP adsorb these heavy metals from the surrounding water thereby acting as "vectors" or "Trojan Horses." When a migratory bird—such as the Bar-headed Goose or the Gadwall—ingests these particles, the acidic environment of the digestive tract can trigger the desorption of these metals. This leads to a localized toxicological strike within the organism, far exceeding the toxicity of the water itself.

- Trophic Transfer and Local Food Security

The Harike ecosystem supports a robust fishing economy. Species like *Labeo rohita* (Rohu) and *Gibelion catla* (Catla) are bottom-feeders, making them highly susceptible to ingesting benthic MPs.

Ingestion vs. Egestion: While larger plastics may be egested, "nanoplastics" (particles <1µm) can translocate across the gut wall into the circulatory system and muscle tissue of the fish.

Human Implications: For the local populations in Harike and downstream Rajasthan, this represents a direct pathway for insertion of MP into the human food chain. This "Bio-magnification" is a silent threat to public health in the Malwa region (Sripada et al., 2022), which is already grappling with high cancer rates.

The Tung Dhab Drain: A Microcosm of Urban-Industrial Plastic Flux

While the data from Ludhiana is striking, a more nuanced crisis is unfolding in the narrower channels of Amritsar's Tung Dhab Drain that serves as a localized but critical case study for understanding the heterogeneous nature of MP pollution in the Majha region. Spanning approximately 20 kilometers through the city's industrial and residential clusters, the drain eventually discharges its toxic load into the Hudiara Drain, which then flows into Pakistan, making this not just a regional issue, but a transboundary environmental crisis (Mani et al., 2024).

- Point-Source Analysis: Dyeing Units and Domestic Effluent

The Tung Dhab receives an unregulated influx from several "informal" textile dyeing and finishing units located in the Verka and Majitha Road areas. Unlike the organized industrial estates of Ludhiana, these smaller units often lack even the most basic primary treatment facilities. Secondary data analysis suggests that the effluent here is heavily saturated with Micro-synthetic Fibres (MSFs), primarily polyester and rayon used in local shawl and carpet manufacturing. The human element of this crisis is visible at the confluence points. Residents of local colonies have historically complained about the "colorful" nature of the water, but current scholarly investigation (Verma et al., 2024) reveals that the color—while visually alarming—is merely the carrier for billions of non-biodegradable particles. During peak processing seasons, the "MP flux" in the Tung Dhab can rival that of much larger river systems due to the low dilution ratio of the stream.

- The "Choking" Effect: Plastic-Silt Aggregation

A unique technical phenomenon observed in the Tung Dhab is the formation of Microplastic-Silt Aggregates. Because the drain is heavily laden with organic domestic sewage, the high concentration of lipids and fats acts as a "biological glue." This causes lightweight polymers like Polypropylene (PP)—which would typically float—to bond with heavier organic matter and sink to the bottom of the drain. This creates a "legacy pollution" problem. When the municipal authorities conduct annual desilting operations, the dredged material is often dumped on the banks of the drain. As this silt dries, the embedded MP are released back into the environment as airborne MPs or are re-entrained into the water system during the first monsoon showers. This cyclical movement of plastic between water, soil, and air is a critical gap in Punjab's current environmental monitoring framework.

- Comparative Analysis of MP Profiles Across Primary Study Sites

Table 1: Benchmarks the specific polymer signatures and concentration levels (based on 2024-2025 secondary data synthesis) (Ministry of Jal Shakti, 2025) across the three primary observation points-

S. No.	Feature	Sutlej River (Ludhiana Corridor)	Tung Dhab Drain (Amritsar Urban)	Chitti Bein (Agricultural Belt)
1.	Primary Polymer	Polyester, Acrylic, PP	Nylon, PET, Polyethylene	LDPE, PVC
2.	Dominant Shape	Microfibres (Linear)	Fragments & Microbeads	Films & Shards
3.	Primary Source	Hosiery & Textile Dyeing	Domestic sewage & Informal Dyeing	Agricultural Mulch & Packaging
4.	Pollution State	Industrial "Pulse" (High Flux)	Urban "Legacy" (Silt-bound)	Diffuse "Runoff" (Seasonal)
5.	Estimated Concentration	1,200 – 4,500 particles/L	3,000 – 6,000 particles/L	400 – 1,200 particles/L
6.	Ecological Risk	High (Chemical adsorption)	Very High (Transboundary)	Medium (Trophic transfer)

Policy Gap Analysis: The "Macro" Bias in Punjab's Environmental Law

The above discussion clearly proves that the MP crisis in Punjab is a governance failure as much as a technical one (Yadav and Sharma, 2025). Currently, the Punjab Plastic Waste Management (Amendment) Rules and the National Single-Use Plastic Ban (2022) suffer from what can be called as the 'Macro-Bias.'

The Size Exclusion: Current regulations focus almost exclusively on visible debris—plastic bags, cutlery, and packaging. There is a complete absence of standards for MP load in industrial discharge.

The Monitoring Gap: The PPCB's 'Water Quality Index' (WQI) does not include MP as a parameter. By ignoring what we cannot see, the state is underestimating the true toxicity of its waters.

Lack of Extended Producer Responsibility (EPR) for Textiles: While EPR exists for packaging, there is no legal framework holding textile manufacturers in Punjab accountable for the microfibre "shedding" of their products during manufacturing or processing.

Future Directions and Policy Measures

The transformation of Punjab's rivers into "plastic highways" is a multifaceted crisis. This research has demonstrated that the riverine system is no longer just dealing with traditional pollutants, but grappling with a permanent structural change in its sediment and biological health. To mitigate this, Punjab must initiate the following:

Practical and Technological Interventions

i. Retrofitting CETPs with Ultra-Filtration (UF): Existing CETPs in Ludhiana and Jalandhar must be upgraded. While conventional secondary treatment (activated sludge) removes some debris, it is ineffective against microfibres. Implementing Disc Filters and Sand-Carbon filtration as a tertiary stage can capture up to 95% of microfibres before discharge (Prata, 2024).

ii. Green-Buffer Filtration Zones: Utilizing the natural filtration capacity of wetlands, "constructed wetlands" or "bio-fences" using native Punjab vegetation like Sarkanda (*Saccharum bengalense*) can be planted along the banks of the Buddha Nullah (PPCB, 2024). These act as natural traps for suspended solids and associated plastics during low-flow periods.

iii. The "Agricultural Transition" (Plasticulture Reform): To mitigate the LDPE shards in the potato belt, the state should subsidize the transition to Certified Biodegradable Mulch (CBM). Unlike traditional LDPE, CBM is designed to be tilled back into the soil where it is broken down by microorganisms, preventing it from leaching into the Beas-Sutlej catchment.

Policy-Based Recommendations and Governance

i. MP Load as a Regulatory Parameter: PPCB should pioneer a "MP Standard" for industrial discharge. By including MP counts per Liter in the Consent to Operate (CTO) requirements for textile units, the state can force the industry to internalize the environmental cost of shedding (Bardhan and Goyal, 2024).

ii. Extended Producer Responsibility (EPR) for the Hosiery Sector: Current EPR laws in India are focused on packaging. Punjab should advocate for a localized EPR framework for the textile industry, requiring manufacturers to contribute to a "River Restoration Fund" based on their volume of synthetic yarn consumption.

iii. Integrated Monitoring Network: Establishing a 'Plastic-Watch' digital dashboard that correlates satellite data on plastic debris with real-time hydraulic flow rates of the Sutlej. This would allow authorities to predict "High-Flux" periods during the monsoon and take pre-emptive measures at the Harike and Ropar barrages.

iv. Public-Scholarly Engagement: Encouraging 'Citizen Science' initiatives where local universities in Amritsar, Ludhiana, and Jalandhar are funded to conduct seasonal water sampling. This decentralizes monitoring and ensures that the data remains current without massive government expenditure.

Conclusion

In summary, the preservation of Punjab's rivers in the 21st century requires a shift in perception—from viewing plastic as mere litter to recognizing it as a persistent, mobile, and chemically active pollutant. The transition from 'Green Revolution to Clean Revolution' is no longer an academic choice; it is a biological necessity for the survival of the region's ecological health. This research has demonstrated that the Sutlej-Beas system is no longer just dealing with traditional pollutants, but crumbling under a permanent structural change in its sediment and biological health. The Harike Wetland, as a terminal sink, is currently absorbing the industrial sins of the upstream corridors. To mitigate this, Punjab must: Retrofit CETPs with sand-filtration and disc-filter technologies, Standardize Microplastic Sampling in the state's annual water quality monitoring and Regulate Agricultural Plastics, incentivizing the switch to biodegradable starch-based mulch films. Without these interventions, the "Green Revolution" state risks a "Plastic Evolution" that could irreversibly degrade its most precious resource: its water.

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