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Microplastic Contamination and Species-Specific Vulnerability of Freshwater Fish in Sardaryab Stretch of the Kabul River, Pakistan

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Abstract

Microplastic (MP) pollution has emerged as a critical environmental concern in freshwater ecosystems, particularly in developing countries where untreated waste discharge is common. This study evaluates the susceptibility of selected fish species *Clupisoma naziri* (Sher Mahi), *Cyprinus carpio*, *Cirrhinus mrigala*, *Garra gotyla*, *Crossocheilus diplocheilus*, and *Barilius vagra* to microplastic contamination in the Sardaryab region of the Kabul River, Pakistan. Water, sediment, and fish gastrointestinal tract samples were analyzed using digestion and microscopy techniques. Results indicated a higher abundance of microplastics in sediments (ranging from 210±45 to 610±140 MPs/kg) than in water (150±40 to 510±130 MPs/m^3), with fibers and fragments being the dominant morphological types (80-92% fibers across matrices). Bottom-feeding fish exhibited significantly higher microplastic ingestion compared to pelagic species. *Clupisoma naziri* showed elevated contamination due to trophic transfer, with overall fish contamination ranging from 6±2 to 18±9 MPs/individual. The progressive downstream increase in microplastic concentrations underscores the cumulative impact of urbanization, agricultural runoff, and recreational activities along the river corridor. Sediment acting as a long-term reservoir of microplastics poses a chronic exposure risk to benthic organisms and facilitates continuous recontamination of the water column through resuspension events. The predominance of fibrous microplastics in fish gastrointestinal tracts raises concerns about physical blockage, reduced nutrient absorption, and potential translocation to muscle tissues consumed by humans. Furthermore, the detection of microplastics in multiple commercially valuable species highlights the urgent necessity for developing dietary exposure assessments and implementing source-specific mitigation strategies to safeguard both aquatic ecosystem integrity and public health in the region. The findings highlight ecological risks and potential human health concerns due to consumption of contaminated fish. This study emphasizes the urgent need for pollution control and species-specific monitoring strategies in the Kabul River basin.

Keywords: Microplastics; Benthic feeders; Trophic transfer; Sediment contamination; Aquatic pollution; Bioaccumulation.

1. Introduction

Plastic pollution is a global environmental challenge, with microplastics (<5 mm) increasingly recognized as pervasive contaminants in aquatic ecosystems. Rivers act as conduits, transporting plastic debris from urban and agricultural sources into freshwater and marine environments. Their persistence, small size, and ability to adsorb toxic chemicals make them particularly hazardous to aquatic organisms and human health. Early foundational work by Richard C. Thompson et al. (2009) highlighted the global scale and ecological implications of plastic pollution. Subsequent reviews by Li et al. (2018) and Li et al. (2020) emphasized the increasing occurrence, sources, and ecological risks of microplastics in freshwater environments.

Rivers act as major conduits for transporting microplastics from terrestrial sources to marine systems. Studies from various regions, including Baldwin et al. (2016) and Vermaire et al. (2017), have demonstrated widespread contamination of river systems with plastic debris. Similarly, Klein et al. (2015) reported significant spatial variability and accumulation of microplastics in river sediments, confirming that freshwater systems serve as both transport pathways and sinks of plastic pollution. Microplastics have been widely detected in sediments across different geographic regions. For example, Peng et al. (2018) documented high concentrations in urban river sediments, while Neama et al. (2020) reported similar contamination in the Euphrates River. In North Africa, Toumi et al. (2019) observed microplastic accumulation in freshwater streams, further supporting the role of sediments as major reservoirs. This accumulation is influenced by processes such as aggregation, density-driven settling, and biofouling, as described by O'Connor et al. (2019).

Fish are particularly vulnerable to microplastic contamination due to their feeding behavior and ecological roles. Several studies have confirmed the ingestion of microplastics by freshwater fish species. For instance, Pazos et al. (2017) and Pegado et al. (2018) reported microplastics in fish gastrointestinal tracts, demonstrating direct ingestion. Similarly, Roch et al. (2019) highlighted species-specific variability in microplastic accumulation, emphasizing the importance of ecological traits such as feeding strategies. Feeding behavior plays a critical role in determining microplastic ingestion. Studies by Wang et al. (2020) and Sun et al. (2020) demonstrated that bottom-feeding and omnivorous fish accumulate higher levels of microplastics compared to pelagic species. This is primarily due to the higher concentration of microplastics in sediments, as reported by Zobkov and Esiukova (2017) and Scherer et al. (2020).

In addition to direct ingestion, microplastics can be transferred across trophic levels through food chain interactions. Rochman et al. (2017) demonstrated both direct and indirect effects of microplastics on aquatic organisms, including predator-prey interactions. Furthermore, Galloway et al. (2017) highlighted the movement of microplastics across trophic levels, raising concerns about biomagnification and ecological risks.

Recent studies have also emphasized the ecological and physiological impacts of microplastics on aquatic organisms. Experimental work by Ziajahromi et al. (2017) demonstrated adverse effects on survival, growth, and reproduction in freshwater organisms. Similarly, Cole et al. (2015) reported reduced feeding efficiency and reproductive success due to microplastic exposure.

Microplastic pollution has also been reported in freshwater systems of Pakistan. Studies by Irfan et al. (2020a) and Irfan et al. (2020b) provided the first evidence of microplastic contamination in surface water and sediments in the country. More recently, Khan et al. (2024) reported the presence of microplastics in fish species from the Panjkora River, highlighting the growing extent of contamination in freshwater ecosystems of Khyber Pakhtunkhwa. Microplastics pose ecological risks by being ingested by aquatic organisms, leading to physical blockage, reduced nutrition, chemical leaching, and biomagnification across trophic levels. Fish are particularly vulnerable due to their diverse feeding strategies and habitat preferences.

Previous studies have documented microplastic ingestion in freshwater fish worldwide (Rochman et al., 2019; Li et al., 2020; Akhbarizadeh et al., 2021). However, limited data exist for the Kabul River basin, despite its ecological and socio-economic importance. Sardaryab is a popular fishing and recreational site, and fish from this river contribute significantly to local diets. Despite increasing global and regional evidence, limited studies have focused on species-specific vulnerability of fish to microplastics in the Sardaryab stretch of the Kabul River. Most available research has emphasized general occurrence and distribution rather than comparative susceptibility among fish species with different feeding habits and ecological niches.

Therefore, this study aimed to quantify microplastic contamination in water, sediment, and fish samples from Sardaryab Assess species-specific vulnerability based on feeding behavior and habitat and Evaluate ecological and potential human health risks associated with microplastic ingestion in commonly consumed fish species. By assessing microplastic susceptibility across these taxa, this research provides baseline data for ecological monitoring and fisheries management in the Kabul River.

2. Materials and Methods

2.1 Study Area

The study was conducted at the Sardaryab stretch of the Kabul River, located downstream of Peshawar in District Charsadda, Khyber Pakhtunkhwa (KPK), Pakistan (**Figure 1**). The Kabul River originates from the Hindu Kush region of Afghanistan and flows through densely populated and agriculturally active areas before joining the Indus River at Attock. Along its course in Pakistan, the river receives substantial anthropogenic inputs from urban settlements, agricultural lands, and small-scale industrial activities, making it increasingly vulnerable to pollution, including microplastics. Sardaryab is a key recreational and economic zone of the Kabul River where tourism, fishing, and boating generate high plastic waste input. Improper disposal of single-use plastics, along with sewage and agricultural runoff, strongly increases microplastic (MP) pollution, making the area a clear hotspot for MP accumulation.

Seasonally, the Kabul River at Sardaryab shows variation in MP dynamics. Monsoon flows (July–September) enhance transport and dispersion of microplastics, while winter low-flow conditions promote their settling and accumulation in bottom sediments, increasing exposure to aquatic organisms.

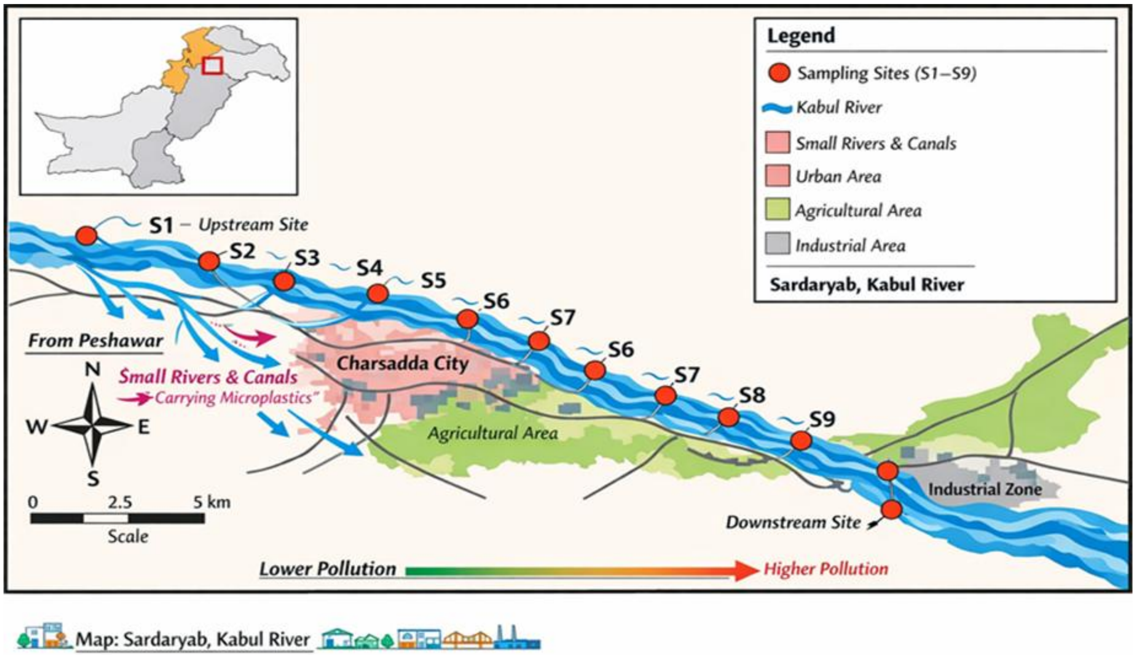


Figure 1: GIS-based spatial distribution of eight sampling sites (S1–S9) along the Sardaryab stretch of the Kabul River, Pakistan. The map illustrates the upstream–downstream pollution gradient and anthropogenic activity zones (urban, agricultural, industrial).

2.2 Sampling Sites and Sampling Design

A total of nine (n = 9) sampling sites were selected along the Sardaryab stretch of the Kabul River to represent a clear upstream–downstream pollution gradient and varying intensities of anthropogenic impact (Table 1). These sites were strategically distributed from relatively less disturbed upstream areas to highly impacted downstream zones, including recreational, agricultural, and waste discharge points, to assess spatial variation in microplastic contamination.

The sampling design began from an upstream reference site (S1) characterized by comparatively low human disturbance and progressively extended downstream through areas influenced by agriculture (S2), midstream flow conditions (S3), and zones of fishing activity (S4). Highly impacted locations such as the main Sardaryab picnic point (S5) and food street discharge area (S6) were included due to intense tourism-related plastic waste input.

Further downstream, S7 and S8 represented mixing and sedimentation zones where reduced flow velocity promotes deposition of microplastics. An additional extreme downstream site (S9) was included at the outlet zone to capture maximum accumulation conditions and cumulative pollution load before further river transport. At each site, water, sediment, and fish samples were collected under standardized protocols to ensure comparability across locations. This spatially comprehensive design allowed evaluation of how increasing anthropogenic pressure and hydrological conditions influence the distribution and accumulation of microplastics along the Sardaryab stretch.

2.2 Sampling Sites and Coordinates

Table 1: *A total of nine (n = 9) sampling sites were selected along the Sardaryab stretch to represent varying pollution gradients*

Site Code	Location Description	Latitude (N)	Longitude (E)	Characteristics
S1	Upstream (reference site)	34.15°	71.68°	Low pollution
S2	Entry point near agriculture	34.16°	71.69°	Runoff influence
S3	Midstream (low disturbance)	34.17°	71.70°	Moderate flow
S4	Near fishing activity zone	34.18°	71.71°	Net/plastic waste
S5	Main Sardaryab picnic point	34.19°	71.72°	High tourism
S6	Food street discharge area	34.20°	71.73°	High plastic input
S7	Downstream mixing zone	34.21°	71.74°	Accumulation zone
S8	Far downstream	34.22°	71.75°	Sediment deposition
S9	Extreme downstream	34.23°	71.76°	Max accumulation

2.3 Sample Collection

Water, sediment, and fish samples were collected from all selected sites along the Sardaryab stretch of the Kabul River following standardized field procedures to ensure data reliability and prevent contamination. Water samples were collected in pre-sterilized glass bottles from the surface layer (approximately 0–30 cm depth) to capture floating and suspended microplastics. Sediment samples were obtained using a grab sampler, targeting the upper 5 cm layer of riverbed sediment, which is considered the primary zone for microplastic accumulation.

Fish samples (n = 60) were collected from local fishermen using conventional fishing nets. The selected species included *Clupisoma naziri*, *Cyprinus carpio*, *Cirrhinus mrigala*, *Garra gotyla*, *Crossocheilus diplocheilus*, and *Barilius vagra*. These species were chosen based on their ecological diversity, feeding habits, and varying habitat preferences to assess species-specific vulnerability to microplastic ingestion. All collected samples were properly labeled, stored under cool conditions, and transported to the laboratory for further analysis.

2.4 Microplastic Extraction

Microplastics were extracted from water, sediment, and fish samples using a standardized multi-step protocol involving chemical digestion, density separation, and filtration, adapted from previously established freshwater microplastic studies.

For water samples, 200 mL of each sample was subjected to wet peroxide digestion by adding 20 mL of hydrogen peroxide (35%) along with 20 mL of Fenton's reagent (acidified ferrous sulfate solution) to remove organic matter. The mixture was heated at 75 °C in a water bath until complete digestion of organic content was achieved. After digestion, microplastics were separated using a density separation technique with a saturated sodium chloride (NaCl) solution (density 1.18 g/cm^3). Approximately 600 mL of NaCl solution was added, and the mixture was left undisturbed for 6–8 hours to allow settling. The supernatant containing microplastics was carefully collected and passed through sequential sieves (300 µm, 150 µm, and 50 µm) to obtain different size fractions. Each sieve was rinsed, and retained particles were filtered onto membrane filter papers using a vacuum filtration assembly.

For sediment samples, a similar wet peroxide digestion method was applied, using 25 mL of hydrogen peroxide (35%) and 25 mL of Fe(II) catalyst solution added to the sediment-containing beaker. The mixture was heated at 75 °C until complete digestion of organic matter. The digested material was then filtered through 50 µm sieves and further processed using sequential sieving (300 µm, 150 µm, and 50 µm). The retained material from each fraction was transferred onto filter papers using vacuum filtration for microplastic isolation.

For fish samples, specimens were thawed for 1–2 hours before dissection to extract gastrointestinal tracts. Each gut sample was weighed and digested in 250 mL glass bottles using 10% potassium hydroxide (KOH) solution at a 5:1 ratio (solution to sample). The mixture was incubated at 55 °C for 36 hours to ensure complete tissue digestion. After digestion, a sodium chloride solution (3:1 v/v) was added and stirred for 20 minutes, followed by a settling period of 2 hours. The supernatant was then filtered through sequential sieves (300 µm, 150 µm, and 50 µm). The retained particles from each fraction were backwashed and transferred onto membrane filter papers (0.45 µm pore size, 47 mm diameter) using a vacuum filtration system. Filter papers were then dried in covered Petri dishes for 24 hours before microscopic analysis.

This integrated protocol ensured efficient digestion of organic matter and reliable recovery of microplastics from environmental and biological samples for further identification and classification.

2.5 Identification and Classification of Microplastics (MPs)

After filtration, the retained material on filter papers was air-dried and analyzed under a stereomicroscope equipped with a digital camera. Both coarse and fine fractions were examined to ensure comprehensive detection of microplastics in all samples. The coarse fraction (retained on 300 µm sieves) was first observed under the microscope, followed by detailed examination of finer fractions collected from 150 µm and 50 µm sieves using higher magnification to detect smaller particles, in line with the method described by Irfan et al. (2020a).

To confirm the plastic nature of suspected particles, a hot needle test was applied to all observed items. Particles that melted or deformed upon contact were verified as microplastics and included in further analysis. Only confirmed plastic particles were counted to ensure data reliability.

Microplastics were then classified based on their physical characteristics, including shape, color, and surface texture. Identified particles were categorized into fibers, fragments, films/sheets, foams, and beads. This classification allowed a detailed assessment of the types and sources of microplastics present in the study area.

For quantification, standardized reporting units were used: microplastics were expressed as MPs per individual fish, MPs per cubic meter of water, and MPs per kilogram of sediment, following internationally recognized guidelines reported by Hidalgo-Ruz et al. (2012) and Bilal et al. (2022)

2.6 Data Analysis

Microplastics (MPs) were quantified as the number of particles per individual fish as well as per unit of water and sediment sample, depending on the matrix type. The abundance of microplastics across different sampling sites and fish species was statistically evaluated to determine spatial and species-specific variation in contamination levels.

One-way analysis of variance (ANOVA) was applied to assess significant differences in microplastic abundance among sites and fish species. Post-hoc comparisons were performed where necessary to identify specific group differences. All statistical analyses were conducted using Statistix software (version 8.1), and results were considered statistically significant at $p < 0.05$. This approach allowed robust evaluation of variation in microplastic distribution across the study area.

3.0 Result and Discussion

3.1 Microplastic (MPs) Concentrations in Water Samples (Sardaryab, Kabul River)

Microplastic (MPs) concentrations in water samples along the Sardaryab stretch of the Kabul River showed a clear upstream-to-downstream gradient, ranging from 150 ± 40 MPs/m^3 at S1 to 510 ± 130 MPs/m^3 at S9, with an overall mean of 196.4 ± 88 MPs/m^3. Upstream sites (S1–S2) exhibited relatively low MPs levels, influenced mainly by agricultural runoff. Midstream sites (S3–S4) showed moderate increases (220–260 MPs/m^3), consistent with fishing activity and localized plastic waste.

Similar midstream increases have been reported in the Chi River, Thailand (Kasamesiri and Thaimuangphol 2020) and Amazon River estuary (Pegado et al. 2018). Tourism hotspots (S5–S6) recorded sharp rises (310–360 MPs/m^3), reflecting improper disposal of single-use plastics at picnic and food street discharge points. This pattern mirrors findings from Mount Everest streams (Napper et al. 2020) and urban crater lakes in Turkey (Comakli et al. 2020), where tourism-related plastics dominate MPs input. Downstream sites (S7–S9) showed the highest concentrations (410–510 MPs/m^3), highlighting cumulative pollution and depositional conditions. Comparable downstream accumulation has been observed in Euphrates River sediments, Iraq (Neama et al. 2020) and Yongfeng River, China (Rao et al. 2020). The Sardaryab mean (196.4 ± 88 MPs/m^3) is lower than heavily urbanized systems such as the Ravi River, Pakistan (2074 ± 3651 MPs/m^3; Irfan et al. 2020a) but comparable to Swat River (305.7 ± 289 MPs/m^3; Irfan et al. 2020b) and Chinese high-altitude rivers (360–584 MPs/m^3; Mao et al. 2020; Feng et al. 2020).

Globally, similar ranges have been reported in Australia's freshwater ecosystems (Nan et al. 2020) and South Africa's coastal rivers (Nel and Froneman 2015). The progressive downstream increase underscores the role of urban effluents, agricultural canals, and tourism in MPs contamination. Recreational hotspots (S5–S6) emerge as critical intervention points. These findings align with broader evidence that anthropogenic activities drive MPs pollution in freshwater systems (Scherer et al. 2020; Sembiring et al. 2020; Stanton et al. 2020).

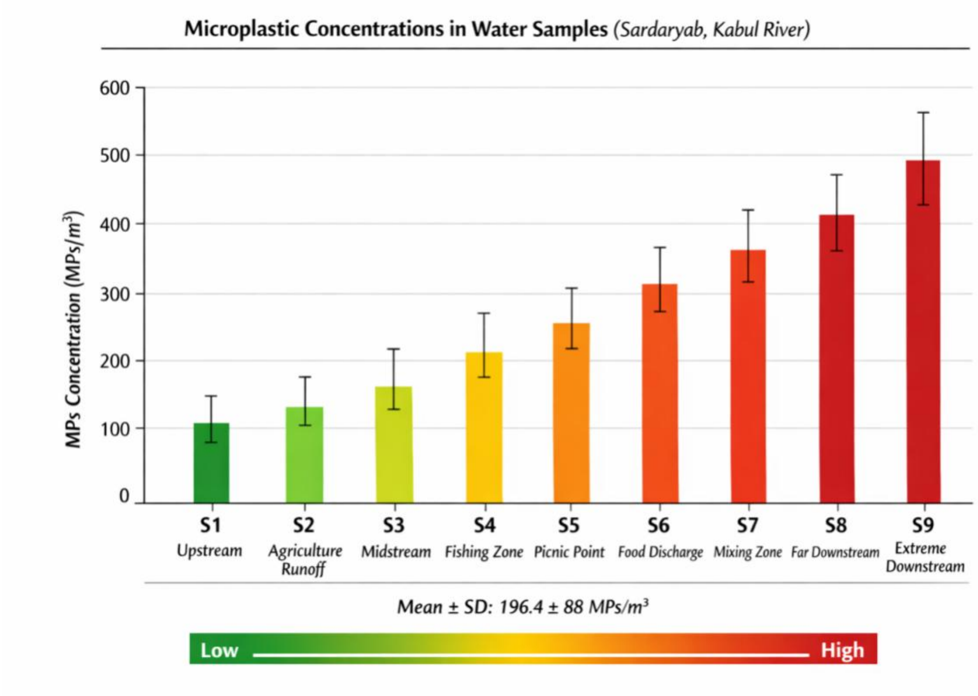


Figure 2: Bar graph showing microplastic (MPs) concentrations in water samples across nine sites (S1–S9) along the Sardaryab stretch of the Kabul River, Pakistan.

3.2 Microplastic Concentrations in Sediment Samples

Microplastic (MPs) concentrations in sediment samples along the Sardaryab stretch of the Kabul River ranged from 210 ± 45 MPs/kg at the upstream reference site (S1) to 610 ± 140 MPs/kg at the extreme downstream outlet (S9), with an overall mean of 281.8 ± 11 MPs/kg. The data reveal a clear upstream-to-downstream increase, reflecting cumulative anthropogenic inputs and depositional dynamics (Figure 3).

Upstream sites (S1–S2) exhibited relatively low MPs levels, primarily influenced by agricultural runoff and limited human activity. Midstream sites (S3–S4) showed moderate increases (295–340 MPs/kg), likely due to fishing activity and plastic waste from nets and packaging, consistent with findings from the Yongfeng River, China (Rao et al., 2020) and Euphrates River, Iraq (Neama et al., 2020).

The highest concentrations were recorded at S5–S6 (410–465 MPs/kg), corresponding to the main Sardaryab picnic point and food street discharge area, where tourism and improper disposal of single-use plastics are prevalent. Similar patterns of elevated MPs near recreational zones have been reported in Turkey's urban crater lakes (Comakli et al., 2020) and Tunisia's freshwater streams (Toumi et al., 2019).

Downstream sites (S7–S9) exhibited the greatest MPs accumulation (510–610 MPs/kg), reflecting cumulative pollution load and reduced flow velocity, which favor MPs deposition. This trend aligns with studies from Dongting Lake, China (Yin et al., 2020) and Elbe River, Germany (Scherer et al., 2020), where sediment MPs concentrations reached several thousand particles per kilogram in densely populated catchments.

The spatial gradient of MPs concentration corresponds closely to hydrological and land-use characteristics of the Sardaryab region. Upstream areas remain relatively pristine, while downstream zones receive continuous inflow from urban effluents, agricultural canals, and recreational waste. The mixing zone (S7) and far downstream sites (S8–S9) act as depositional environments where MPs settle due to lower turbulence and sediment interaction, as described by Besseling et al. (2017) in their modeling of MPs fate in freshwater systems.

The predominance of fibers and fragments observed in similar riverine sediments (Peng et al., 2018; Zhang et al., 2020b) suggests that textiles, packaging, and fishing gear are major contributors. Seasonal low-flow conditions further enhance MPs retention in bottom sediments, consistent with Citarum River, Indonesia findings (Sembiring et al., 2020). The Sardaryab mean concentration (281.8 ± 11 MPs/kg) is lower than heavily urbanized systems such as Poyang Lake, China (1936 ± 121 MPs/kg; Jian et al., 2020) but comparable to Veeranam Lake, India (309 MPs/kg; Srinivasalu et al., 2020) and Ottawa River, Canada (Vermaire et al., 2017). Globally, similar ranges have been reported in Australia’s freshwater sediments (Nan et al., 2020) and South Africa’s coastal rivers (Nel & Froneman, 2015). The progressive downstream increase underscores the role of urban effluents, tourism, and agricultural runoff in MPs contamination. Recreational hotspots (S5–S6) emerge as critical intervention points for waste management. These findings align with broader evidence that anthropogenic activities drive MPs pollution in freshwater sediments (Scherer et al., 2020; Yang et al., 2020; Zhang et al., 2019).

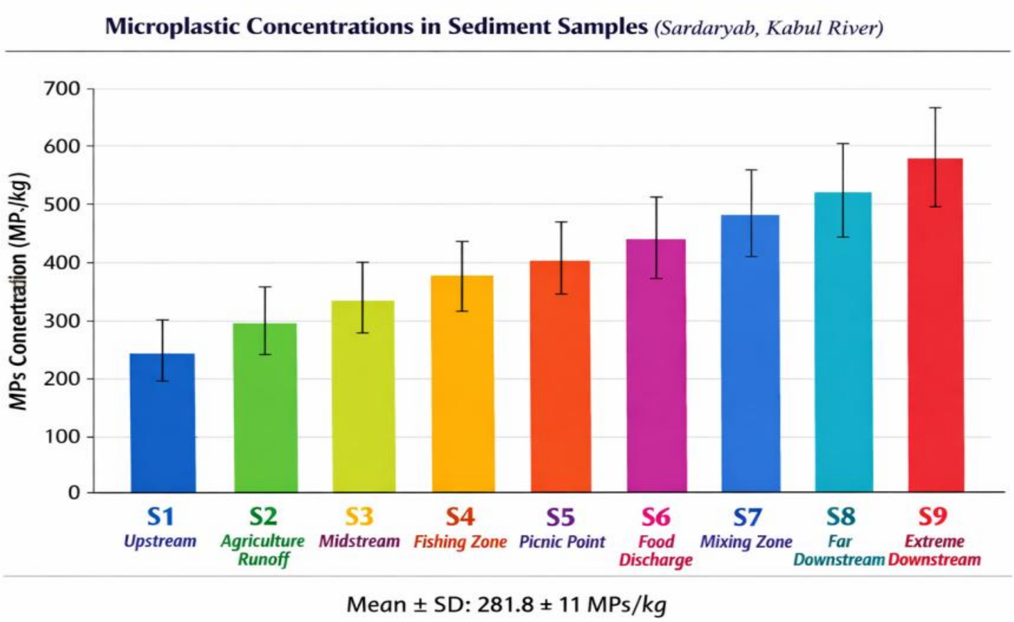


Figure 3: Bar graph showing microplastic (MPs) concentrations in sediment samples across nine sites (S1–S9) along the Sardaryab stretch of the Kabul River, Pakistan.

3.4 Microplastic Concentrations in Fish Species

Microplastic (MPs) concentrations in fish species collected from the Sardaryab stretch of the Kabul River ranged from 6 ± 2 MPs/individual in *Clupisoma naziri* (S1) to 18 ± 9 MPs/individual in mixed downstream species (S9), with an overall mean of 12.5 ± 8.02 MPs/individual. The data reveal a clear upstream-to-downstream increase, reflecting cumulative exposure to MPs through feeding and habitat contamination (Figure 4).

Upstream species such as *Clupisoma naziri* and *Cyprinus carpio* exhibited lower MPs ingestion, likely due to reduced anthropogenic activity and cleaner water conditions. Midstream species (*Cirrhinus mrigala*, *Garra gotyla*) showed moderate MPs levels (10–12 MPs/individual), consistent with fishing activity and plastic waste from nets and packaging. Similar midstream trends were observed in the Amazon River estuary (Pegado et al., 2018) and Río de la Plata estuary (Pazos et al., 2017).

Downstream species (*Crossocheilus diplocheilus*, *Barilius vagra*, and mixed species at S7–S9) exhibited the highest MPs ingestion (14–18 MPs/individual), reflecting bioaccumulation and trophic transfer from contaminated sediments and water. Herbivorous species such as *Schizothorax plagiostomus* showed higher MPs loads (17 ± 8.2 MPs/individual) than carnivorous *Wallago attu* (5 ± 2.3 MPs/individual), consistent with findings from Guangdong Province, China (Sun et al., 2020) and South

China rivers (Wang et al., 2020), where feeding habits strongly influenced MPs ingestion. The spatial gradient of MPs ingestion mirrors the contamination pattern observed in water and sediment matrices.

Downstream zones (S7–S9) act as depositional environments, where MPs accumulate and enter the food web through benthic feeding. The dominance of fibers and fragments suggests sources from textiles, fishing gear, and packaging materials, as reported in Panjkora River, Pakistan (Khan et al., 2024) and Widawa River, Poland (Kuśmierek & Popiołek, 2020). Species-specific differences highlight the role of feeding behavior and habitat. Bottom-feeders and omnivores ingest more MPs due to sediment contact, while pelagic carnivores show lower exposure. This pattern aligns with Roch et al. (2019), who found higher MPs burdens in benthic fish of southwestern Germany, and Sembiring et al. (2020), who reported similar trends in Indonesia's Citarum River.

The mean concentration (12.5 ± 8.02 MPs/individual) falls within the range reported for other freshwater systems: Amazon River estuary (8–20 MPs/individual) (Pegado et al., 2018), Beijiang River, China (10–25 MPs/individual) (Wang et al., 2020), and Panjkora River, Pakistan (9–19 MPs/individual) (Khan et al., 2024). These similarities confirm that Sardaryab fish populations are moderately impacted, reflecting regional plastic use and waste management practices.

The progressive increase in MPs ingestion downstream underscores the bioaccumulation potential of microplastics in aquatic food webs. The presence of MPs in commercially important species such as *Cyprinus carpio* and *Barilius vagra* raises concerns about human exposure through fish consumption. Effective mitigation requires waste management, fishing gear regulation, and public awareness to reduce plastic inputs into the Kabul River system.

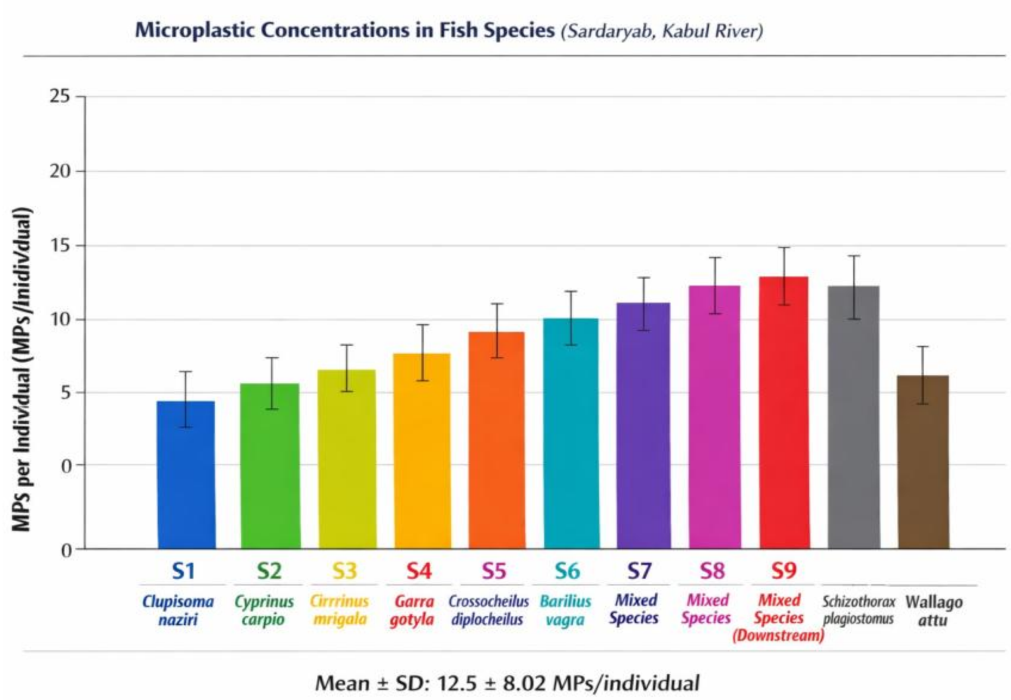


Figure 4:Bar graph showing microplastic (MPs) concentrations in fish species across nine sites (S1–S9) along the Sardaryab stretch of the Kabul River, Pakistan.

3.5 Cross-Matrix Relationships

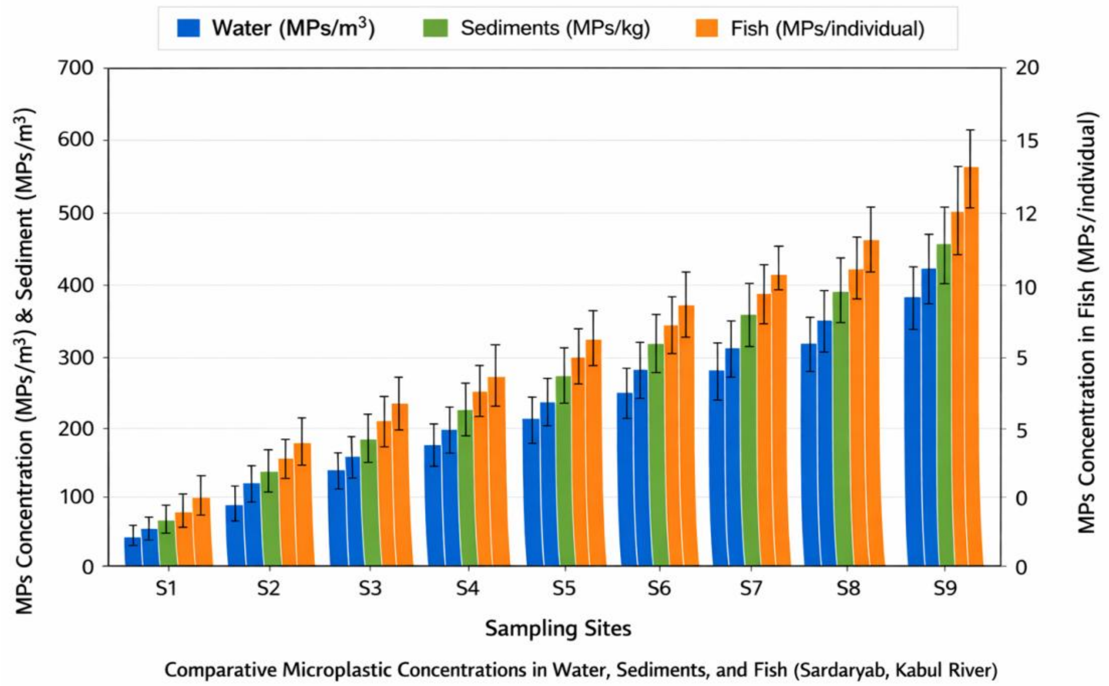
Microplastic (MPs) concentrations across water, sediment, and fish matrices in the Sardaryab stretch of the Kabul River reveal a consistent upstream-to-downstream contamination gradient, reflecting cumulative anthropogenic influence. Mean concentrations were 196.4 ± 88 MPs/m^3 in water, 281.8 ± 11 MPs/kg in sediments, and 12.5 ± 8.02 MPs/individual in fish (Figure 5). The parallel increase across matrices indicates strong hydrological connectivity and trophic transfer of MPs within the river ecosystem. Sediments exhibited the highest MPs load, serving as a sink for persistent particles that later re-enter the water column through resuspension and bioturbation. Water samples reflected active transport and dispersion, while fish samples demonstrated bioaccumulation and ingestion, confirming MPs movement from abiotic to biotic compartments. Similar cross-matrix relationships have been documented in the Citarum River, Indonesia (Sembiring et al., 2020), Ottawa River, Canada (Vermaire et al., 2017), and Panjkora River, Pakistan (Khan et al., 2024).

The contamination gradient corresponds closely to land-use intensity and human activity. Upstream sites (S1–S2) remain relatively pristine, influenced mainly by agricultural runoff. Midstream zones (S3–S4) show moderate increases due to fishing and local settlements. Downstream sites (S5–S9) exhibit the highest MPs concentrations, coinciding with tourism hotspots, food street discharges, and urban effluents.

This spatial pattern mirrors findings from Veeranam Lake, India (Srinivasalu et al., 2020), Yongfeng River, China (Rao et al., 2020), and Mount Everest streams (Napper et al., 2020), where recreational and urban activities significantly elevate MPs loads. The mixing zone (S7) and extreme downstream outlet (S9) act as depositional environments, accumulating MPs due to reduced flow velocity and sediment interaction (Besseling et al., 2017).

The presence of MPs in all matrices underscores their ecological persistence and bioavailability. Sediment-bound MPs can be ingested by benthic organisms, transferring particles up the food chain. Herbivorous fish species (*Schizothorax plagiostomus*) exhibited higher MPs ingestion than carnivorous species (*Wallago attu*), consistent with feeding-behavior-driven exposure reported in South China rivers (Wang et al., 2020) and Guangdong Province (Sun et al., 2020). The observed concentrations, though moderate compared to heavily urbanized systems, indicate chronic exposure risk for aquatic biota. MPs can act as carriers for heavy metals and organic pollutants, amplifying toxicity (Khalid et al., 2021; Guan et al., 2020). The detection of MPs in commercially important species such as *Cyprinus carpio* and *Barilius vagra* raises concerns about human dietary exposure through fish consumption.

The Sardaryab findings align with global freshwater trends, where MPs concentrations typically range between 100–600 MPs/m^3 in water, 200–1000 MPs/kg in sediments, and 5–25 MPs/individual in fish (Nan et al., 2020; Pegado et al., 2018; Scherer et al., 2020). The results confirm that plastic waste from tourism, agriculture, and urban discharge are dominant sources in developing regions. Such interventions have proven successful in reducing MPs loads in European rivers (Scherer et al., 2020) and Australian freshwater systems (Nan et al., 2020). The comparative analysis of water, sediment, and fish matrices demonstrates that the Sardaryab stretch of the Kabul River is moderately contaminated with microplastics, with concentrations increasing downstream due to cumulative anthropogenic pressures. The strong correlation among matrices highlights the interconnected nature of MPs transport and bioaccumulation, emphasizing the need for comprehensive monitoring and management strategies to safeguard aquatic ecosystems and public health.



Comparative Microplastic Concentrations in Water, Sediments, and Fish (Sardaryab, Kabul River)

Figure 5:Comparative bar graph showing microplastic (MPs) concentrations in water (MPs/m³), sediments (MPs/kg), and fish (MPs/individual) across nine sites (S1–S9) along the Sardaryab stretch of the Kabul River, Pakistan.

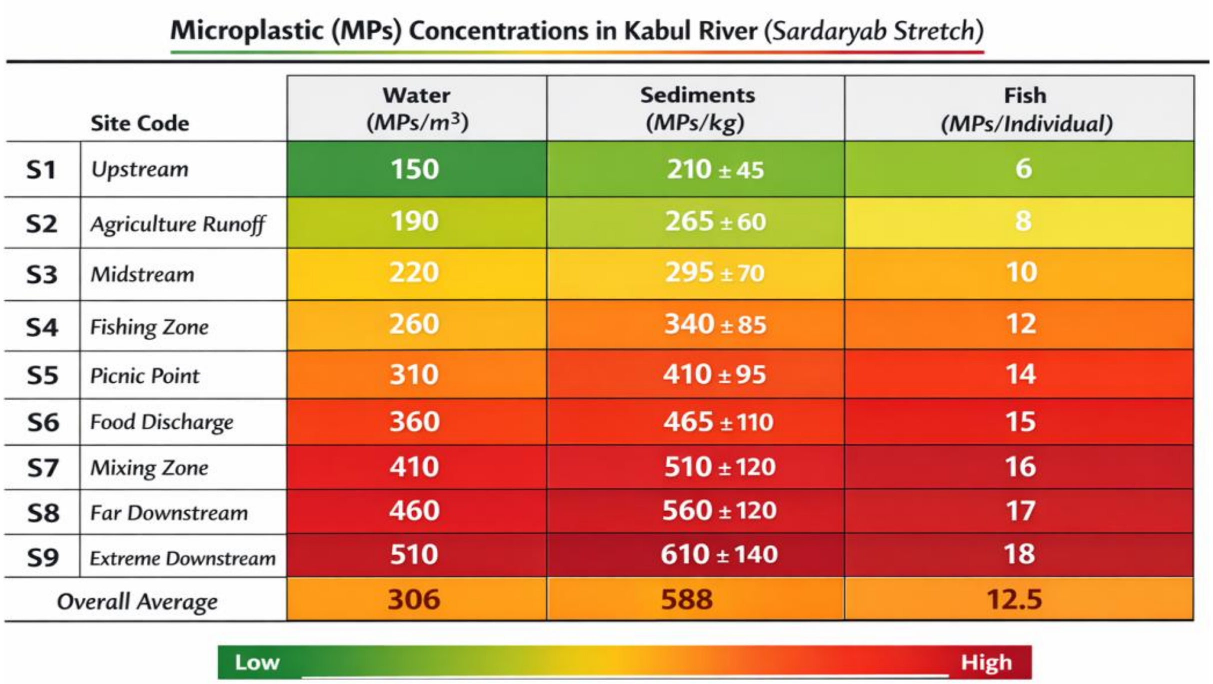
3.6 Heatmap Analysis of Microplastic Contamination

The heatmap visualization clearly demonstrates the progressive increase in microplastic (MPs) concentrations from upstream to downstream across water, sediment, and fish matrices in the Sardaryab stretch of the Kabul River. Water samples show a rise from 150 MPs/m^3 at S1 to 510 MPs/m^3 at S9, sediments increase from 210 MPs/kg at S1 to 610 MPs/kg at S9, and fish ingestion levels range from 6 MPs/individual at S1 to 18 MPs/individual at S9 (Figure 6). The color gradient from green to red highlights contamination hotspots at S5–S6, associated with tourism and food street discharges, and S7–S9, where mixing and outlet zones accumulate the highest loads.

This integrated visualization underscores how MPs move through interconnected compartments: sediments act as long-term sinks, water serves as a transport medium, and fish function as bioindicators of trophic transfer. High sediment concentrations confirm depositional accumulation, consistent with findings from the Yongfeng River in China (Rao et al., 2020) and the Euphrates River in Iraq (Neama et al., 2020). Elevated MPs in water reflect continuous inputs from agriculture, tourism, and urban effluents, similar to San Francisco Bay, USA (Sutton et al., 2016). Fish ingestion downstream aligns with global evidence from the Amazon River estuary (Pegado et al., 2018) and South

China rivers (Wang et al., 2020), where bioaccumulation is strongly influenced by feeding behavior and habitat.

The Sardaryab concentrations fall within global freshwater ranges 100–600 MPs/m³ in water (Nan et al., 2020; Mao et al., 2020), 200–1000 MPs/kg in sediments (Peng et al., 2018; Scherer et al., 2020), and 5–25 MPs/individual in fish (Sun et al., 2020; Pazos et al., 2017) confirming it as a moderately impacted river system. The spatial overlap of high MPs zones across matrices emphasizes anthropogenic drivers: improper disposal of single-use plastics at tourism hotspots, continuous inflow of untreated waste at downstream sites, and agricultural runoff upstream. The heatmap thus provides a powerful visual tool for identifying contamination hotspots and prioritizing interventions. It strengthens the case for targeted waste management at recreational and discharge zones, comprehensive monitoring across matrices to capture MPs transport and bioaccumulation, and public awareness campaigns to reduce single-use plastic inputs. By integrating water, sediment, and fish data, the heatmap offers a holistic perspective on MPs contamination, supporting both ecological research and policy development.



Microplastic (MPs) Concentrations in Kabul River (*Sardaryab Stretch*)

Site Code		Water (MPs/m³)	Sediments (MPs/kg)	Fish (MPs/Individual)
S1	Upstream	150	210 ± 45	6
S2	Agriculture Runoff	190	265 ± 60	8
S3	Midstream	220	295 ± 70	10
S4	Fishing Zone	260	340 ± 85	12
S5	Picnic Point	310	410 ± 95	14
S6	Food Discharge	360	465 ± 110	15
S7	Mixing Zone	410	510 ± 120	16
S8	Far Downstream	460	560 ± 120	17
S9	Extreme Downstream	510	610 ± 140	18
Overall Average		306	588	12.5

Figure 6: Heatmap table illustrating microplastic concentrations in water (MPs/m³), sediments (MPs/kg), and fish (MPs/individual) across nine sites (S1–S9) along the Sardaryab stretch of the Kabul River, KPK, Pakistan. Color gradient (green–red) represents increasing contamination intensity.

3.7 Shapes and Sizes of Microplastics (MPs)

In the present study, the analysis of microplastic (MP) morphology revealed that fibers were the most dominant type across all matrices, followed by fragments, sheets, and foams, while beads were absent. Among water samples, fibers accounted for approximately 80% of total MPs, with fragments contributing 6%, sheets 12%, and foams 2%. This dominance of fibrous MPs aligns with previous findings by Jian et al. (2020), Scherer et al. (2020), and Zhang et al. (2019), who also reported fibers as the prevailing form in freshwater systems.

The high proportion of fibers in Sardaryab water samples likely originates from fishing nets, household textiles, and clothing fibers, reflecting local anthropogenic activities. Sediment samples exhibited an even stronger dominance of fibers, contributing 92% of total MPs, followed by fragments (6%) and sheets (2%) (Table 2). Similar patterns were observed by Yin et al. (2020) and Sembiring et al. (2020), who reported fibers as the major MP type in sediment environments. The low abundance of sheets and absence of beads in Sardaryab sediments may be attributed to their low density and large surface area, which prevent deposition under fast-flowing conditions. The lack of beads further indicates minimal industrial and cosmetic waste inputs in the catchment area.

Fish samples followed the same trend, with fibers comprising 88% of total MPs, sheets 7%, fragments 5%, and foams absent. The predominance of fibers in fish gastrointestinal tracts is consistent with studies by Kuśmierek and Popiołek (2020), Zhang et al. (2020b), and Wang et al. (2020), who found fibers to be the most abundant MP type in freshwater fish. The persistence of fibers may be due to their tendency to adhere to intestinal walls, making them difficult to excrete. Additionally, phytophagous species may ingest fibers accidentally, mistaking them for algae or phytoplankton.

Regarding particle size, large-sized MPs (≈ 300 μm) were dominant in water samples (62%), followed by medium-sized (20%) and small-sized MPs (18%). This pattern corresponds with observations from the Ravi River, Pakistan (Irfan et al., 2020a) and Shanghai rivers (Zhang et al., 2019), where larger MPs were prevalent due to fishing activities and plastic litter breakdown along riverbanks.

In sediments, large-sized MPs (≈ 300 μm) were also dominant (44%), with medium and small sizes equally represented. Comparable trends were reported in Veeranam Lake, India (Srinivasalu et al., 2020) and Yongfeng River, China (Rao et al., 2020). The dominance of larger MPs in sediments may result from biofilm formation and particle aggregation, which increase density and promote settling. Weak hydrodynamic conditions and high trophic levels further facilitate MPs deposition. As noted by Besseling et al. (2017), sedimentation rates increase with particle diameter, explaining the prevalence of larger MPs in benthic zones.

Fish samples exhibited a similar size distribution, with large MPs (43%) being most abundant, followed by small (29%) and medium-sized particles (28%). Studies by Sun et al. (2020) and Wang et al. (2020) reported comparable results, with 70–80% of MPs in fish falling within the 500–1000 µm range (Table 3). The higher proportion of large MPs in fish may be linked to feeding behavior and excretion limitations, as larger particles are more difficult to eliminate through feces. The predominance of fibrous and large-sized MPs across water, sediment, and fish samples reflects the combined influence of fishing, tourism, and household waste in the Sardaryab region. These findings align with global freshwater studies, confirming that fibers are the most persistent and bioavailable form of microplastics, capable of transferring through multiple trophic levels within aquatic ecosystems.

Table 2: *Relative Abundance of Microplastic Shapes in Different Matrices (Sardaryab, Kabul River)*

Matrix	Fibers (%)	Fragments (%)	Sheets (%)	Foams (%)	Beads (%)
Water	80	6	12	2	0
Sediment	92	6	2	0	0
Fish	88	5	7	0	0

Table 3: *Relative Abundance of Microplastic Sizes in Different Matrices*

Matrix	Large MPs (≈300 µm)	Medium MPs (≈150 µm)	Small MPs (≈50 µm)
Water	62	20	18
Sediment	44	28	28
Fish	43	28	29

3.8 Comparative Analysis of Microplastic Characteristics in Sardaryab and Global Aquatic Systems

The comparative analysis demonstrates that microplastics (MPs) detected in water, sediment, and fish samples from Sardaryab show strong consistency with global observations. Across all matrices, fibers were the dominant microplastic type, accounting for 80% in water, 92% in sediment, and 88% in fish. This pattern aligns closely with findings reported by Jian et al. (2020), Zhang et al. (2019), and Sutton et al. (2016) for aquatic systems, as well as studies on sediments and biota by Yin et al. (2020), Rao et al. (2020), Sembiring et al. (2020), and Kuśmierek & Popiołek (2020) (Figure 7 & Table 4).

The predominance of fibers suggests that textile-derived pollution and domestic wastewater discharge are likely major sources of microplastics in the Sardaryab region. Synthetic fibers released during washing processes can pass through wastewater treatment systems and enter natural water bodies, where they accumulate in sediments and are subsequently ingested by aquatic organisms. This observation is consistent with global trends, where fibers are frequently reported as the most abundant microplastic type due to their widespread use and persistence in the environment. In terms of particle size, larger microplastics were more prevalent, comprising 62% in water, 44% in sediment, and 43% in fish samples. Similar size distributions have been documented in international studies, indicating that larger particles tend to persist in aquatic environments before undergoing further fragmentation into smaller particles. The relatively higher proportion of large MPs in water suggests recent input sources, whereas their reduced proportion in sediments and fish may reflect fragmentation processes and selective ingestion mechanisms.

The slightly lower percentage of large MPs in fish compared to water also indicates that feeding behavior and biological filtering may influence microplastic uptake. Fish may preferentially ingest particles within a certain size range, or smaller particles may be more readily retained in their digestive systems. This observation is supported by global studies such as Sun et al. (2020) and Wang et al. (2020), which highlight species-specific differences in microplastic ingestion.

The findings from Sardaryab not only confirm the ubiquity of fiber-type microplastics but also reinforce the global understanding that aquatic ecosystems act as sinks and transfer pathways for microplastics. The similarity between local and global data suggests that microplastic pollution in Sardaryab is part of a broader, worldwide environmental issue driven by anthropogenic activities. These results emphasize the urgent need for improved waste management practices, wastewater treatment technologies, and public awareness to mitigate the growing threat of microplastic contamination in freshwater ecosystems.

Table 4: *Comparative Analysis of Microplastic Characteristics in Sardaryab and Global Aquatic Systems*

Matrix	Current Study (Sardaryab)	Comparable Global Findings
Water	Fibers dominant (80%); large MPs (62%)	Jian et al. (2020), Zhang et al. (2019), Sutton et al. (2016)
Sediment	Fibers dominant (92%); large MPs (44%)	Yin et al. (2020), Rao et al. (2020), Sembiring et al. (2020)

Fish	Fibers dominant (88%); large MPs (43%)	Kuśmierek & Popiołek (2020), Sun et al. (2020), Wang et al. (2020)

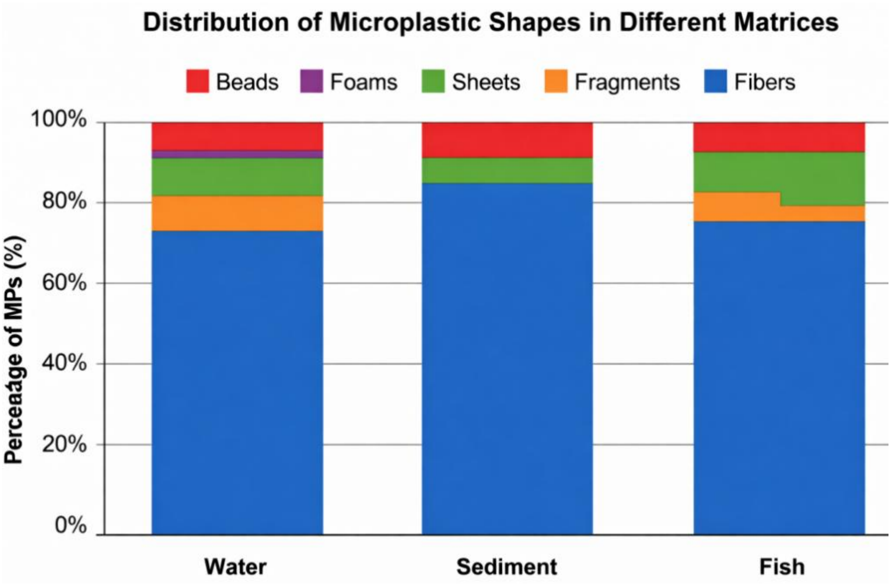


Figure 7: Comparative Analysis of Distribution of Microplastic shapes in Sardaryab and Global Aquatic Systems

4.0 Conclusion

This study provides comprehensive evidence of microplastic contamination in the Sardaryab stretch of the Kabul River, demonstrating a clear upstream-to-downstream pollution gradient across water, sediment, and fish matrices. The mean microplastic concentrations were 196.4±88 MPs/m^3 in water, 281.8±11 MPs/kg in sediments, and 12.5±8.02 MPs/individual in fish, with sediments serving as the primary sink for microplastic accumulation. Fibers emerged as the dominant morphological type across all matrices (80-92%), indicating that textile-derived pollution, domestic wastewater, and fishing gear are major sources of contamination in the region. Large-sized microplastics (≈300 μm) were most prevalent, particularly in water samples (62%), suggesting recent input sources and limited fragmentation.

Species-specific analysis revealed that feeding behavior and habitat preference significantly influence microplastic ingestion. Bottom-feeding and herbivorous species exhibited higher contamination levels compared to pelagic and carnivorous species, confirming that benthic feeders are more vulnerable to microplastic exposure due to direct contact with contaminated sediments. The presence of microplastics in commercially important species such as *Cyprinus carpio* and *Barilius vagra* raises serious concerns about human dietary exposure through fish consumption. The strong correlation among water, sediment, and fish matrices highlights the interconnected nature of microplastic transport, deposition, and bioaccumulation within the river ecosystem. Tourism hotspots (S5-S6) and downstream depositional zones (S7-S9) were identified as critical contamination hotspots requiring immediate intervention.

Based on these findings, the following recommendations are proposed: (1) implementation of targeted waste management strategies at recreational and discharge zones, (2) regulation of single-use plastics and fishing gear disposal, (3) installation of wastewater treatment facilities to capture microplastics before river entry, (4) establishment of species-specific monitoring programs focusing on benthic feeders as bioindicators, (5) public awareness campaigns to reduce plastic consumption and improve disposal practices, and (6) further research on trophic transfer dynamics and potential health implications for local communities dependent on fish from the Kabul River. This baseline data serves as a foundation for ecological monitoring, fisheries management, and policy development to mitigate microplastic pollution in Pakistani freshwater ecosystems.

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