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RESEARCH ARTICLE

Microplastics in water, sediments, and fish at Alpine River, originating from the Hindu Kush Mountain, Pakistan: implications for conservation

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Abstract
Microplastics (MP) pollution is an emerging threat to life and the environment. These particles are not restricted to human-inhabited lands but also found in different mountains and glaciers where the human population is relatively low. These MPs make their way to the river ecosystem from glaciers, rains, and municipal and industrial effluents. The current study was designed to highlight MPs' pollution in water, sediments, and fishes of the Swat River: originating from the Hindu Kush Mountain Range. These samples were collected from eight different sites across the river. An average concentration of MPs detected in water samples (305.79 ± 289.66 MPs/m^3), fish (12.54 ± 8.02 MPs/individual), and sediments (588.29 ± 253.95 MPs/kg). The highest concentration was observed among water samples at Mingora city and the lowest at the confluence point of the rivers near Charsadda being 753.71 ± 330.08 MPs/m^3 and 57.64 ± 31.98 MPs/m^3, respectively. MP concentrations in the sediment samples were also the highest at Mingora city (834.0 ± 367.21 MPs/kg), and lowest at Chakdara (215.0 ± 20.0 MPs/kg). Among the fish samples, Schizothorax *plagiostomus* contained the highest while *Wallago attu* contained the lowest MP concentrations corresponding to 17.08 ± 8.27 MPs/individual and 5.0 ± 2.36 MPs/individual, respectively. Fibers were the most prevalent MPs in all the matrices representing 80%, 92%, and 85% of the total MP count in water, sediments, and fish samples. These findings highlighted that freshwater ecosystem are not free from MPs and are as much vulnerable to anthropogenic activities as marine ecosystem. Therefore, need attention not less than marine ecosystem awareness, education, ecotourism, sustainable reduction in plastic use, and strict rules and regulations could be helpful to prevent the anthropogenic menace.

Keywords Anthropogenic contaminants · Microplastic isolation · Nutritional and health aspects · High-altitude · Swat River

Introduction

Extensive usage, limited recycling, and durability of plastic polymers are the most critical factors for plastic waste accumulation in the environment (Thompson et al. 2009). The problem of plastic pollution aggravates when the microplastics items disintegrate into smaller particles due to different physical, chemical, and environmental factors (GESAMP 2015). The larger plastics also enter the aquatic environment via runoff from the land that undergo weathering processes, i.e., photo-degradation, oxidation and mechanical abrasion and gradually degrade into particles > than 5mm are termed as macroplastics, while particles < 5mm are microplastics. The MPs can also be categorized as primary or secondary, where the term primary refers to particles produced in the micro size and secondary refers to MPs produced by the breakdown of MPs (Hanslik 2020; Napper et al. 2015).

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The toxic effects of MPs cannot be neglected because these MPs carry different types of organic and inorganic such as heavy metal pollutants. Being the vector of organic and Inorganic toxic pollutants these MPs further enhance the chances of toxicity. These MPs adsorbed heavy metals and desorbed it inside living bodies such as digestive tract, where low pH environment facilitate desorption (Khalid et al. 2021). Day by day increasing the microplastic pollution, there is a higher likelihood of ecosystem exposure, the annual leaks in our aquatic ecosystem eight million tons of polyethylene bags and plastic production is set to double by 2040 (Hassan et al. 2023; Leslie et al. 2022). Thus, a higher chance of interaction, ingestion, and hazardous effects across food webs, through the biomagnification the microplastics is the potential to impact biota in a variety of different ways (Hassan et al. 2022; Khan et al. 2024). As with macroplastics and macrofauna, at this proportionally smaller scale, microplastics can lead to the entanglement and physical hindrance of organisms such as zooplankton (Ziajahromi et al. 2017). If ingested, microplastics can lead to gut blockages and thus starvation or reduced energy budgets (Cole et al. 2015). Oxidative stress is a commonly observed response to microplastic exposure (Hassan et al. 2023). In addition to chemicals, plastics can act as a vector for organism transport, which thus could introduce non-native species and disease (Reisser et al. 2014). Microplastics is also affecting certain factors including habitat conditions, overall health implications, improper gill functioning early life, reduced feeding intensity, immuno-suppression, compromised reproducibility, fish fatness, season, development pattern, degree of stomach completeness, sexual category, size range, and physical condition (Hassan et al. 2022) and might change the biochemical composition of aquatic organism (Hassan et al. 2022). Microplastics cause damage to human cells and air pollution particles are already known to enter the body and cause millions of early deaths a year. People were already known to consume the tiny particles via food and water as well as breathing them in, and they have been found in the feces of babies and adults. Despite these potential effects it is important to note that, with a few exceptions (Leslie et al. 2022), more realistic environmental timescales, could have knock-on effects for ecosystems, potentially leading to trophic cascades (Galloway et al. 2017). It is further worth noting that such analyses are often based on species and ecosystems that may be considered adaptable or geographically widespread, such as those along temperate coasts.

Several studies support their ingestion and retention in other parts of the gastrointestinal tract in the aquatic, terrestrial, and avian fauna (Zhang et al. 2017). This ingestion and retention can be associated with many physical, physiological, neural, and hormonal problems, mainly reducing the nutrient-absorption area of the intestine, inhibition of gastric and pancreatic enzymatic activity, decreased steroid hormones, and late ovulation (Canesi et al. 2015). Numerous studies have been reported across the globe concerning freshwater MPs, of which many studies are only focused on MP presence in water and sediment samples with no or less focus on the aquatic biota (Schmid et al. 2020; Scherer et al.2020; Tunali et al. 2020; O'Connor et al. 2019; Li et al. 2018; Peng et al. 2018; Rochman et al. 2017). Previously, the focus of the research was towards the marine organisms, but recently, a few studies have also been reported on freshwater fishes, but none of them is from Pakistan; however, several studies have been documented from different regions all over the world (Kasamesiri et al. 2020; Kuśmierek and Popiolek 2020; Sun et al. 2020; Wang et al. 2020; Zhang et al. 2020a).

Recently, Jian et al. (2020) have reported MPs in water and sediments from China's most extensive freshwater lake system. Wang et al. (2020) highlighted MPs in Beijing River and Pearl River China, while Zhang et al. (2020b) published a study on the Yongjiang River. Many other reports have also been published in the last two years, including Li et al. (2020), Cera et al. (2020), Erdoğan (2020), Guan et al. (2020), Wu et al. (2020), Yang et al.(2020), Neama et al. (2020), Akindele et al. (2019), Bordos et al. (2019), Yuan et al. (2019). However, Pakistan lags far behind, and published literature regarding freshwater MP pollution consists of only two studies conducted on Rawal Lake and Ravi River (Irfan et al. 2020a, 2020b). However, there is no such research on freshwater fish from Pakistan, so the current study is the first to establish a correlation between MPs in freshwater fish, sediments, and surface water in the country. Moreover, the Swat River is the remote river at a high altitude in the Northern Mountains of Pakistan. Only a few studies have been reported globally to assess the MP pollution in remote regions. This study can be a valuable addition to present MP literature to establish a relationship between MP pollution level and ingestion in different fish species. It can also be significant to indicate potential sources of plastic pollution in such remotely located freshwater bodies.

Material and Methods

Study area

The Swat River is a 240-km-long river located in Khyber-Pakhtunkhwa (KPK), Pakistan. This perennial river has a basin area of 14,000 km^2 and receives plastic waste mainly due to fishing and tourism activities in the catchment area before joining Kabul River, near Sardaryab (Charsadda-KPK). According to the Ministry of Tourism Khyber Pakhtunkhwa and District administration of Swat more than 2.7 million (exact figure of 2,780,000) tourists have visited the valley in just 5 days of Eid Festival (19 July 2021 to 23 July 2021). A total of eight sampling sites ($n = 8$) were selected for the water, sediments, and fish sampling, including six sites located along with River Swat ($n = 6$; Kalam, Bahrain, Madyan, Mingora, Chakdara, Charsadda) and two locations ($n = 2$) along with the Confluence point of River Swat and Kabul (Fig. 1).

Sampling protocols

A total of 24 samples ($n = 24$) were collected in Autumn season (October and November) from eight sampling sites, and triplicate samples were performed for the surface water, sediments, and fishes from each site. The MPs in water were collected from each site using a manta trawl with a mesh size of 300 µm (Vermaire et al. 2017). The stationary manta trawl net was deployed thrice and fixed at a position along the river's width (left-side, midstream, right-side) for 1 h. The trapped anthropogenic material was separated from the collecting pock of Manta trawl, further rinsed with distilled water into a 500-ml amber glass jar to get maximum material. Three sub-samples of sediment samples collected from the shoreline of the river in the same area, where the samples of surface water were collected, using a stainless-steel quadrate (30 cm) and a spatula. A spatula of stainless steel was used to collect the upper 1 cm layer of sediments inside the quadrate area in a glass jar and for further analysis transported to the laboratory (Irfan et al. 2020a; Klein et al. 2015). A total of 24 fish samples ($n = 24$) belonging to 4 different species were collected using rods and Nylon hand fishing nets with the help of local fishermen. The collected

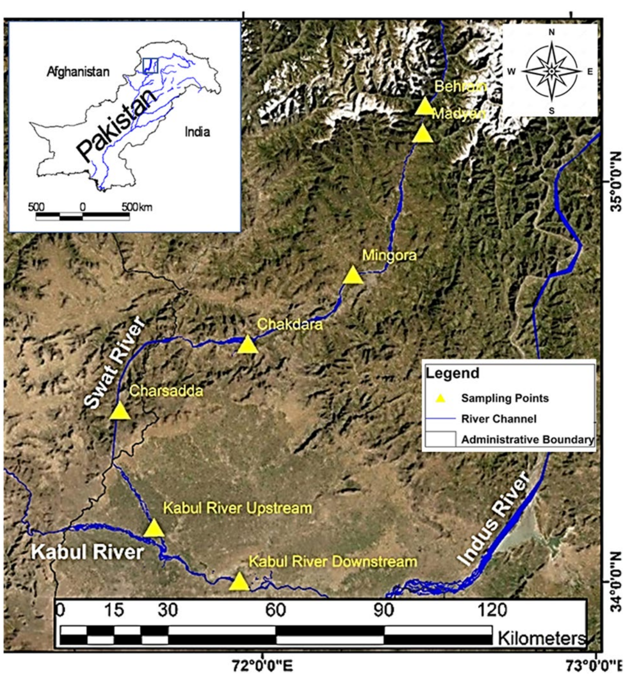

Fig. 1 Map of Swat River indicating sampling sites

samples were weighed, labelled, and stored in the icebox and transported to the Environmental Toxicology Laboratory, College of Earth and Environmental Sciences, University of the Punjab, Lahore, Pakistan. The fish samples were stored in a refrigerator while water and sediment samples kept at room temperature before further analysis.

Preparatory steps

The water samples digested using hydrogen peroxide along with Fenton reagent. Twenty milliliters each of hydrogen peroxide (35%) and Fenton's reagent (an acidic solution of ferrous sulfate) were added into 200 ml of the sample to digest organic materials if present in sample. Then, placed the beaker on a water bath for heating up at 75 °C until the digestion of the organic content; after digestion of organic matter, MPs were segregated using density separation techniques. A customized density separator was used to segregate MPs from the digested sample with concentrated NaCl solution of density 1.18 g/cm^3 (Irfan et al. 2020a; Coppock et al. 2017; Zobkov and Esiukova 2017). About 600 ml NaCl solution was applied and remained undisturbed for 6–8 h of settling time. The supernatant layer was collected and filtered through 300, 150, and 50 µm sieves to get three different size fractions (Irfan et al. 2020a). Each prepared sieve back washed, and MP contents filtered onto filter papers using a vacuum filtration assembly.

The sediment samples were digested and separated, adopting methods (Cashman et al. 2020; Zobkov and Esiukova 2017). For wet peroxide digestion, 25 ml of H_2O_2 (35%) and 25 ml of Fe(II) catalyst solution were poured in beaker holding solids and filtered through a 50 µm sieve (Irfan et al. 2020a). Then, placed the beaker on a water bath for heating up at 75 °C until the digestion of the organic content. The supernatant was then filtered through 300, 150, and 50 µm sieves and transferred to filter papers as described earlier.

Fish samples were thawed for 1–2 h and dissected to collect their guts. Each gut sample of fish was weighed and digested in 250-ml glass bottles using 10% KOH solution with a 5:1 ratio with the sample. Then, incubate the sample at 55 °C for 36 h. Sodium chloride (3:1 v/v) was added to the digested material immediately and thoroughly stirred for 20 min before being left to settle for 2 h. The supernatant layer was collected and filtered through 300, 150, and 50 µm sieves to get three different fractions. The solid contents of each fraction from sieves then backwashed and transferred to filter paper (MCE 0.45 µm pore size and 47 mm diameter) using a vacuum filtration assembly. The walls of the filtration assembly cup washed twice, and the filter papers containing solids dried up for one day in a Petri dish covered with aluminum foil before detection.

Identification and classification of MPs

After drying, the solid material at filter papers analyzed under a stereomicroscope with a digital camera. Then examined coarse range of analyte on filter papers (prepared from 300 µm sieves) under the microscope. At the same time, observation for a fine range of MPs made on the filter papers (from 150 and 50 µm sieves) under the microscope with a digital camera (Irfan et al. 2020a). For the identification of plastic nature of the particles hot needle test were done for all samples and their plastic nature were confirmed before counting them. Particles verified as plastic by hot needle test were referred as MP. While physical shape and color of the MPs were used for the category identification of MPs. These MPs were further classified into fibers, sheets, fragments, foams, and beads. Internationally recognized units for the fish, water, and sediment samples were MPs/individual, MPs/m^3, and MPs/kg, respectively (Hidalgo-Ruz et al. 2012).

Statistics and computations

Descriptive statistics were calculated by SPSS 18. The volume of water filtered through the manta trawl net was calculated using a modified flow rate formula as follows:

$$Vol = Avt$$

where

Vol volume of sampled water in m^3

A area of manta trawl mouth in m^2 (width × height)

V average velocity of the river in m/s

t Sampling time in seconds

Laboratory contamination control

All the precautionary measures considered to prevent material and laboratory contamination. A dedicated portion in the laboratory was used for MP samples to avoid cross-contamination. The tools and glassware used during the sampling and analysis were carefully rinsed with distilled water and covered with aluminum foil when not being used. Reagents and distilled water were also filtered using and covered with aluminum foil to avoid atmospheric contamination. A few filter papers were placed on random locations in the lab for 72 h to measure the suspended load of MPs from the laboratory environment, then analyzed under the stereomicroscope. Six such filter papers were examined during the whole analysis and kept as a control. MPs on the filters were subtracted from the sample to avoid the atmospheric contamination from the laboratory environment.

Results and discussion

MP level in Swat River

An average concentration of MPs (total 24 samples each of water, sediments, and fish analyzed) detected in water samples (305.7 ± 289 MPs/m^3), fish (12.5 ± 8.02 MPs/individual), and sediments (588.2 ± 253 MPs/kg; Figs. 2 and 5). The highest concentration was observed among water samples at Mingora city and the lowest at the confluence point of the rivers near Charsadda being 753.7 ± 330 MPs/m^3 and 57.6 ± 31.9 MPs/m^3, respectively. MP concentrations in the sediment samples were also the highest at Mingora city (834 ± 367 MPs/kg), but the lowest concentrations were recorded in sediments collected from Chakdara (215 ± 20 MPs/kg). Among the fish samples, *Schizothorax plagiostomus* contained the highest while *Wallago attu* contained the lowest MP concentrations corresponding to 17 ± 8.2 MPs/individual and 5 ± 2.3 MPs/individual, respectively (Fig. 3).

The present concentrations of MPs in high altitude surface water (2000 m at Kalam and 980 m at an average altitude of Swat River) were comparable with other high-altitude studies. In a recent study from China, Mao et al. (2020) reported 360 MPs/m^3 in one of the three gorges in Yulin River at an altitude of 1084 m. Feng et al. (2020) described 584.82 MPs/m^3 in freshwater lakes and rivers from Qinghai Tibet Plateau, China, located at 4000 m above sea level. The similarity in the average MP concentrations at higher altitude are more likely due to tourism activities being the primary source of pollution in these areas, as commonly these areas are less populated (Comakli et al. 2020). The increasing number of tourists in these areas leaves behind many plastic food wrappers, disposables, plastic bags, and other types of waste plastics. At higher altitude, the large volume of plastic packed food and different kinds of plastic carried by the tourists. This process supported by a study from Mount Everest where Napper et al. (2020) reported 1000 MPs/m^3 in one of the streams. Comparable results also have been reported from other regions of the world, such as 400 MPs/m^3 from the Trent River, UK, and 400 MPs/m^3 from an Australian freshwater ecosystem (Stanton et al. 2020; Nan et al. 2020). The present concentrations of MPs are lesser than the previous studies from Pakistan, where 2074 ± 3651 MPs/m^3 reported from Ravi River, Lahore, and 1420 MPs/m^3 (originally 0.142 items/0.1 L) from Rawal Lake, Rawalpindi (Irfan et al. 2020a, 2020b). The higher concentrations of MPs in these reports are related to higher

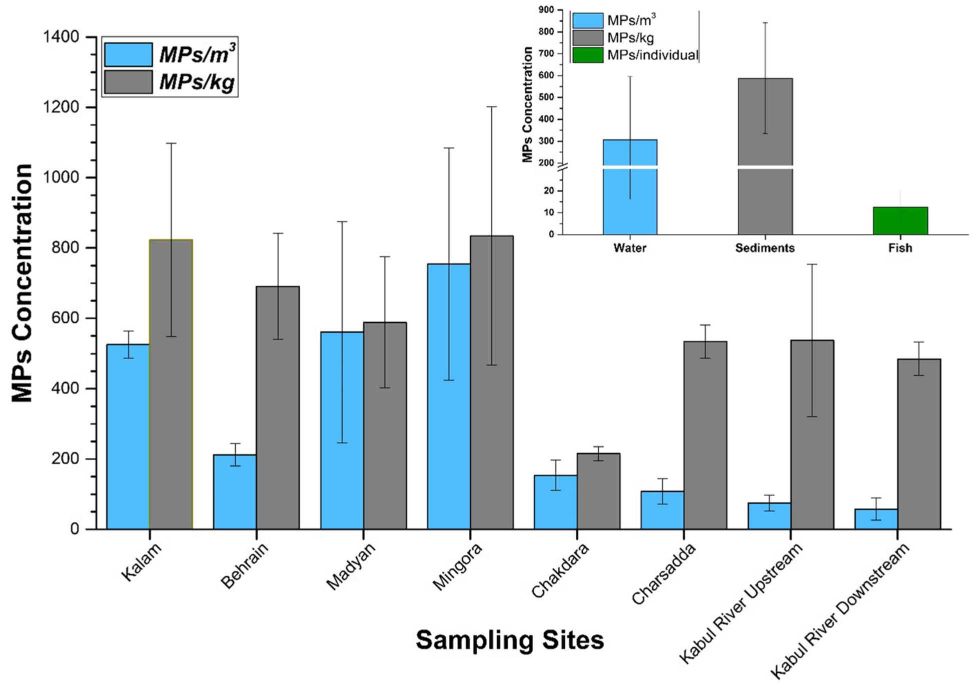

Fig. 2 Comparison of MP concentration in water, sediments and fish samples collected from Swat River

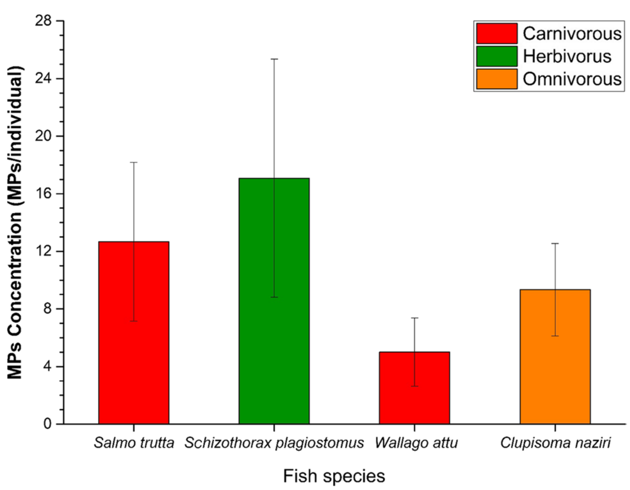

Fig. 3 Ingested MP concentrations among different fish species depending on their trophic level

population density and those water bodies compared to Swat River. The MP concentrations from the Ravi River were also higher than Rawal Lake and Swat River because Lahore is the second highly populated metropolitan city and an industrial hub of the country.

The MP concentration in fish also found to be comparable with the findings of Pegado et al. (2018), who reported an average concentration of 12.8 MPs/individual and 7.8 MPs/individual in *Bagre bagre* and *Bagre marinus* from Amazon River, respectively. Pazos et al. (2017) reported a higher concentration than the present study with 19 MPs/individual from the Argentinean freshwater ecosystem. Recent studies from China have reported lower concentrations of 0.2 ± 0.5 MPs/individual from the Beijing River and 4.8 MPs/individual from the Pearl River (Wang et al. 2020; Roch et al. 2019). A similar pattern of MPs was highlighted by Sun et al. (2020) in river water. In contrast, Zhang et al. (2020a) described the concentration of 4.25 MPs per individual and 0.6 MPs per individual from other Chinese regions. The variation in reported concentrations with the present study may be due to different species with different feeding habits. A general assumption, Carnivore species will get higher concentration as feeding on fishes with ingested MPs compared to herbivores fishes are deviated in our results. The possible reason of lower MP detections in carnivore's fishes than herbivores may be due to longer alimentary canals and more coiled intestines of herbivores fishes, which will possibly hinder the ejection of MPs through defecations.

Further, the habitat of fishes also affects the concentration of MPs consumed by fishes because the concentration of MPs varies in different zones of an aquatic ecosystem.

Similarly, MP concentrations in the sediment samples were also comparable to the concentrations reported from surrounding areas. There were 403 MPs/kg reported from Dongting Lake and 90–550 MPs/kg in Yongjiang River (Yin et al. 2020; Zhang et al. 2019). High concentrations reported from Elbe River, Germany, containing 3350 MPs/kg at an altitude of 1386 m above sea level (Scherer et al. 2020). The possible reason for this higher concentration in the Elbe River is because it is inhabited by 25 million inhabitants as compared to the Swat River which is inhabited by 2.31 million people. Hence populations have a direct impact on the pollution profile of the river. Due to high population density, higher concentrations are reported from Poyang Lake, China, and the Northern-Tunisian freshwater stream with 1936 ± 121 MPs/kg and 2340 ± 227.15 MPs/kg, respectively (Jian et al. 2020; Toumi et al. 2019). Several studies reported the low concentrations of MPs in comparison to the current study, viz., Veeranam Lake, India (309 MPs/kg), Yongfeng River, China (26 ± 23 MPs/kg), Citarum River, Indonesia (166 MPs/kg), Shuangtaizi River, China (170 ± 96 MPs/kg), and Diliao River, China (237 ± 129 MPs/kg). These concentrations are lower than the present study due to multiple geographic and demographic factors (Srinivasalu et al. 2020; Sembiring et al. 2020; Xu et al. 2020). Furthermore, a comparison of some recent studies on concentrations of MPs given in Table 1.

Shapes and size of MPs

Among the water samples, the relative proportion of the fibers remained the highest (80%), and the fragments were minimum (6%). Comparable relative dominancy of fibers also observed by Jian et al. (2020), where fibers were dominant (25–50%) and the fragments were the least (< 25%) among all types of MPs. Scherer et al. (2020) reported 46.5% of fibers and 22.9% fragments, while Zhang et al. (2019) detected 73.90% of fibers and 13.8% fragments in their findings. Sutton et al. (2016) also reported the same pattern in the present study where fibers were 80%, and fragments were 17% of total MPs. Likewise, Baldwin et al. (2016) also reported fibers to be the highest (71%) among the detected MP concentrations. In another study conducted by McCormick et al. (2014), fibers and fragments followed the same trend being 59.28% and 37.14%, respectively. Mason et al. (2016) reported fibers to be 59%, and fragments being 33% of their total MP count. A recently published study from Pakistan also reported the dominancy of fibers in Rawal Lake, with fragments being the second abundant (Irfan et al. 2020b). However, a different trend reported in the second study from Pakistan, where fragments were the most dominant (56.1%) and fibers were the second abundant type (38.6%) among the total MPs detected (Irfan et al. 2020a). These variations result from the inflow of untreated municipal and industrial wastewater into the Ravi River that has deformed the natural shape of the river. The contribution of foams and sheets in the present study was 12% and 2%, respectively, while beads

Table 1 Comparison of MP concentrations reported by different studies

Medium	Region	Concentration	Reference
Water	Pakistan	305.79 ± 289.66 MPs/m^3	Present study
	China	360 MPs/m^3	Mao et al. (2020)
	China	584.82 MPs/m^3	Feng et al. (2020)
	UK	400 MPs/m^3	Stanton et al. (2020)
	Pakistan	1420 MPs/m^3	Irfan et al. (2020b)
	Pakistan	2074 ± 3651 MPs/m^3	Irfan et al. (2020a)
	Australia	400 MPs/m^3	Nan et al. (2020)
	Nepal	1000 MPs/m^3	Napper et al. (2020)
	China	1660 ± 639.1 to 8925 ± 1591 MPs/m^3	Wang et al. (2020)
	South Africa	258 ± 53–1215 ± 277 MPs/m^3	Nel and Froneman (2015)
Sediments	Pakistan	588.29 MPs/kg	Present Study
	Indonesia	166 MPs/kg	Sembiring et al. (2020)
	China	237 ± 129 MPs/kg	Xu et al. (2020)
	Germany	3350 MPs/kg	Scherer et al. (2020)
	China	1936 ± 121 MPs/kg	Jian et al. (2020)
	India	309 MPs/kg	Srinivasalu et al. (2020)
	Tunisia	2340 ± 227.15 MPs/kg	Toumi et al. (2019)
	China	26 ± 23 MPs/kg	Rao et al. (2020)
	Canada	610 MPs/kg	Ballent et al. (2016)
	Canada	616 MPs/kg	Corcoran et al. (2015)
Fish	Pakistan	12.54 MPs/individual	Present study
	China	4.8 MPs/individual	Wang et al. (2020)
	China	4.25 MPs/individual	Sun et al. (2020)
	China	0.6 MPs/individual	Zhang et al. (2020a, b)
	China	0.2 ± 0.5 MPs/individual	Roch et al. (2019)
	Brazil	12.8 MPs/individual	Pegado et al. (2018)
	Argentina	19 MPs/individual	Pazos et al. (2017)

did not observe in any samples. Swat River is not highly polluted, so most of the fibers were broken pieces of fishnets, with some of them from households and clothing.

Fibers were found the most abundant MP type within the sediment samples contributing about 92% to the observed MPs. A recent study by Yin et al. (2020) also reported fibers as a dominant type of MPs with 41–49 to 100% of the total types of MPs. The same highest proportions of fibers documented by Sembiring et al. (2020). In another study, Zhang et al. (2019) detected the fibers in sediments to be 60%, with fragments being 30%. The order of different types of MP abundance detected in present sediment samples was fibers (92%) > fragments (6%) > sheets (2%) > foams and beads (0%). Irfan et al. (2020b) also reported a similar trend in relative abundance, with fibers being dominant over fragments and beads. The low quantity of sheets identified from the sediment owing to flow just beneath the water surface. That is why sheets are generally not deposited into sediments because of the low density of sheets, large surface area, and fast streamflow. Similarly, the absence of beads indicates negligible manufacturing and usage of industrial and cosmetic products in the catchment area.

Following the similar trend as observed in water and sediments, fibers were also dominant in fishes (88%) followed by sheets (7%), fragments (5%), and foams (0%). In the present study, the sheets ranked as the second most ingested form of MPs because they keep floating below the water's surface for being lighter in weight than fragments, which increases their chance of ingestion during fish feeding. Recently, Kuśmierek and Popiolek (2020) described the similar trend of the highest proportion of fibers (99.8%) in the gastrointestinal tract of freshwater fish. Zhang et al. (2020b) and Wang et al. (2020) also reported that the fibers with the highest concentration in native freshwater fish belonging to different trophic levels from Pearl River South China. The possible reason for the highest proportion of fibers in fish species may be its difficulty to excrete with feces as fibers stick with intestinal walls firmly compared to other shape MPs. Further comparison among relative abundance of MP shapes given in Table 2. Phytophagous species may ingest the fibers accidentally as these fibers may resemble algae and phytoplankton.

In terms of defined size, the large-sized MPs (300 μm) were dominant in water samples (62%) followed by medium-sized MPs (150 μm; 20%) and small-sized MPs (50 μm; 18%). This trend was comparable to the findings from Ravi River, Lahore-Pakistan, where larger MP particles were dominant (Irfan et al. 2020a). Zhang et al. (2019) also reported MPs in size range 330 μm–1 mm to be in the highest proportion (59.1%) compared to other size classes. The highest proportion of larger sizes MPs may be due to continuous activities by local inhabitants and tourists, such as using nets for fishing and the breakdown of plastic disposable being left at the bank of the river or directly thrown into the river.

Large-sized MPs (300 μm) were also dominant in the sediment samples (44%), followed by medium- and small-sized MPs in an equal proportion. A similar trend in MP ratio was reported from Veeranam Lake India, with large-sized MPs being the most abundant (Srinivasalu et al. 2020). Zhang et al. (2019) reported the highest concentration (44.8%) of MPs with the size range of 330–1000 μm as compared to other sizes. Rao et al. (2020) also found larger MP particles (200–1000 μm) to be the dominating (40.68%). The highest proportion of large-sized MPs in sediments might be due the following possible reasons that

Table 2 Relative abundance of different MP shapes reported by different studies

Medium	Fibers	Sheets	Fragments	Foam	Beads	Reference
Water	80%	2%	6%	12%	0%	Present study
	25–50%	-	< 25%	-	-	Jian et al. (2020)
	46.5%	-	22.9%	-	-	Scherer et al. (2020)
	73.9%	-	13.8%	-	-	Zhang et al. (2019)
	59%	5%	33%	2%	1%	Mason et al. (2016)
	80%	2%	17%	1%	0%	Sutton et al. (2016)
	71%	-	-	-	-	Baldwin et al. (2016),
	59.28%	0.07%	37.14%	1.25%	2.26%	McCormick et al. (2014)
Sediments	92%	2%	6%	0%	0%	Present study
	41–100%	-	-	-	-	Yin et al. (2020)
	60%	-	30%	-	-	Zhang et al. (2019)
	24.86%	52.3%	22.74%	0%	0.1%	Wahyuningsih et al. (2018)
	73%	2%	21%	4%	0%	Eshom-Arzadon (2017)
	22.3%	12%	47.7%	18%	0%	Wessel et al. (2016)
Fish	88%	7%	5%	0%	0%	Present study
	99.8%	-	-	-	-	Kuśmierek and Popiolek (2020)

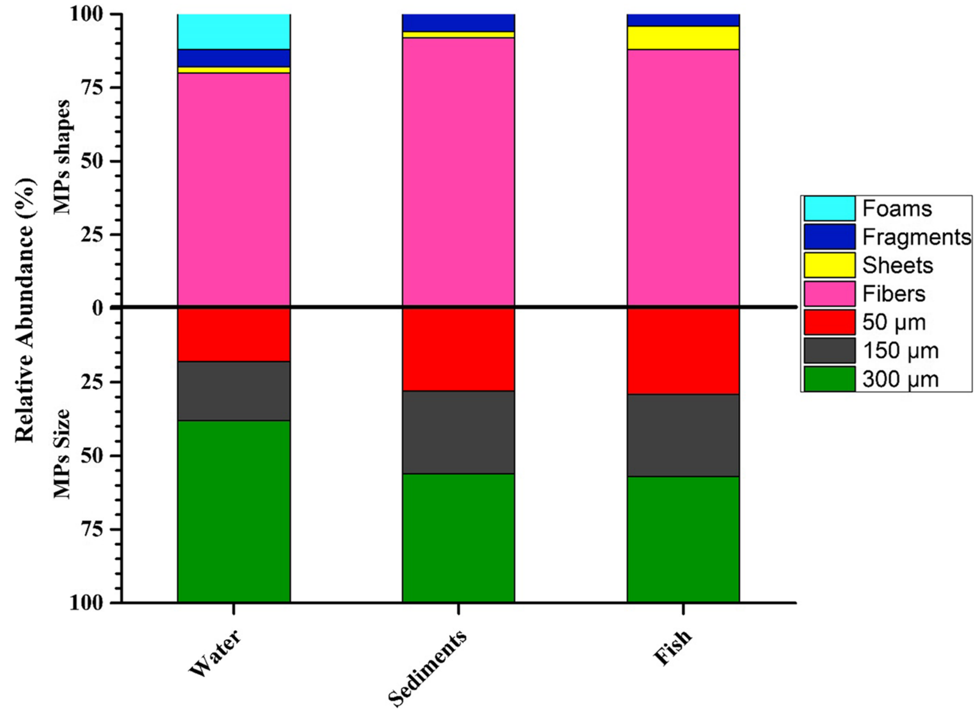

Fig. 4 Relative abundance of MPs among the selected matrices based on shape

there are more large-sized microplastics discharged into the surface water. The colonization of microorganisms (e.g., algae) and the adsorption of solid particles may result in an increase in aggregate densities, facilitating microplastics settlement in sediments. Relatively weak hydrodynamic circumstances and high trophic levels of water allow for the quick formation of biofilm on the surface of microplastics, which causes them to sink into sediments. The particle size of microplastics has a significant impact on their fate and settlement behavior along rivers. The rate of sedimentation increased with increasing diameter for particles between 100 nm and 10 mm (Besseling et al. 2017). Furthermore, the abundance of microplastics with small particle sizes in the sediments tends to be underestimated due to limitations in separation, digestion, identification, and quantification (Fig. 4).

In fish samples, the overall relative abundance of MPs followed a similar trend as in the surface water, and prominent size MPs were dominant (43%), followed by small-sized MPs (29%) and medium-sized MPs (28%). MPs with sizes up to 1000 µm reported being highest (70.5%) in a study by Sun et al. (2020), whereas Wang et al. (2020) reported that 80% of the detected MPs belonged to the size range of 500–1000 µm. The relative proportion of ingested MP sizes also varied according to the three different types of fish feeding habit. Large-sized MPs contributed 76% in one carnivorous species and 56% in other, 75% in herbivorous fish and 59% in omnivorous. Furthermore, the dominance of larger MP particles and the lower proportion of smaller sizes particles in the gut contents may be due to fish inability to excrete along with feces (Fig. 5).

Conclusion

The present research findings showed that the contributions of large-sized MPs (300 µm) were the highest in all the surface water, sediments, and fish samples from a higher altitude to the plain reaches of Swat River, Pakistan. Based on MP types, the fibers were in high proportions in the overall samples. The present study indicated that Swat River is suffering from indiscriminate use of plastic in the catchment. Due to the high influx of tourists, MP pollution has been increased, resulting in a large volume of plastic waste directly or indirectly disposed into the river. It is highly recommended to start an organized campaign to educate the local community and tourists to minimize plastic and stringent enforcement of plastic reduction laws to manage this problem and make it an eco-friendly tourist destination. More detailed research on how micro- and nano-plastics affect the structures and processes of the human body, and whether and how they can transform cells and induce carcinogenesis, is urgently needed, particularly in light of the exponential increase in plastic production. The problem is becoming more urgent with each day.

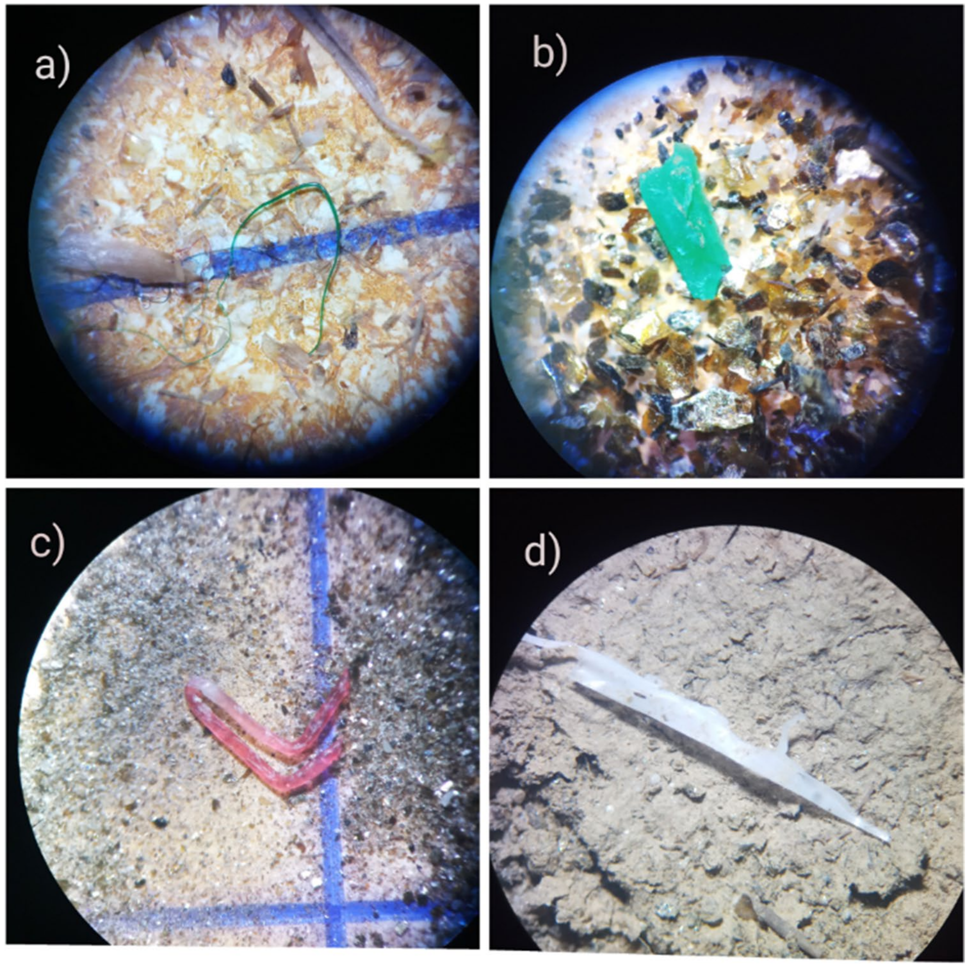

Fig. 5 Microscopic images of identified MP fiber (**a**) and fragments (**b**, **c**, and **d**)

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Author contribution Muhammad Bilal and Habib Ul Hassan designed the study and executed the experimental work and wrote the article. Abdul Qadir and Atif Yaqub supervised the research work. Muhammad Irfan helped in data analysis. Mehmood Aslam participated in chemical analysis.

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Data availability The supplementary file/datasets during the present study are available in the attached file.

Declarations

Ethical approval Not applicable.

Consent to participate All persons involved in this research paper are well connected with me, and I am available to all these people if anyone seeks further clarification and information.

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Conflict of interest The authors declare no competing interests.

References

Akindele EO, Ehlers SM, Koop JH (2019) The first empirical study of freshwater microplastics in West Africa using gastropods from Nigeria as bioindicators. Limnologica 78:125708. https://doi.org/10.1016/j.limno.2019.125708

Baldwin AK, Corsi SR, Mason SA (2016) Plastic debris in 29 Great Lakes tributaries: relations to watershed attributes and hydrology. Environ Sci Technol 50(19):10377–10385. https://doi.org/10.1021/acs.est.6b02917

Ballent A, Corcoran P L, Madden O, Helm PA, Longstaffe FJ (2016) Sources and sinks of microplastics in Canadian Lake Ontario nearshore, tributary, and beach sediments. Mar Pollut Bull 110(1):383–395.

Besseling E, Quik JT, Sun M, Koelmans AA (2017) Fate of nano- and microplastic in freshwater systems: a modeling study. Environ Pollut 220:540–548

Bordos G, Urbányi B, Micsinai A, Kriszt B, Palotai Z, Szabó I, Szoboszlay S (2019) Identification of microplastics in fishponds and natural freshwater environments of the Carpathian basin, Europe. Chemosphere 216:110–116. https://doi.org/10.1016/j.chemosphere.2018.10.110

Canesi L, Ciacci C, Bergami E, Monopoli MP, Dawson KA, Papa S, Corsi I (2015) Evidence for immunomodulation and apoptotic processes induced by cationic polystyrene nanoparticles in the hemocytes of the marine bivalve Mytilus. Mar Environ Res 111:34–40. https://doi.org/10.1016/j.marenvres.2015.06.008

Cashman MA, Ho KT, Boving TB, Russo S, Robinson S, Burgess RM (2020) Comparison of microplastic isolation and extraction procedures from marine sediments. Mar Environ Res 159:111507. https://doi.org/10.1016/j.marpolbul.2020.111507

Cera A, Cesarini G, Scalici M (2020) Microplastics in freshwater: what is the news from the world? Diversity 12(7):276. https://doi.org/10.3390/d12070276

Cole M, Lindeque P, Fileman E, Halsband C, Galloway TS (2015) The impact of polystyrene microplastics on feeding, function and fecundity in the marine copepod *Calanus helgolandicus*. Environ Sci Technol 49:1130–1137

Comakli E, Bingöl MS, Bilgili A (2020) Assessment of microplastic pollution in a crater lake at high altitude: a case study in an urban crater lake in Erzurum, Turkey. Water Air Soil Pollut 231:275. https://doi.org/10.1007/s11270-020-04653-4E

Coppock RL, Cole M, Lindeque PK, Queirós AM, Galloway TS (2017) A small-scale, portable method for extracting microplastics from marine sediments. Environ Pollut 230:829–837. https://doi.org/10.1016/j.envpol.2017.07.017

Corcoran PL, Norris T, Ceccanese T, Walzak MJ, Helm PA, Marvin CH (2015) Hidden plastics of Lake Ontario, Canada and their potential preservation in the sediment record. Environ Pollut 204:17-25.

Erdoğan Ş (2020) Microplastic pollution in Cevdet Dündar Pond: first observation on freshwater of Turkey. Su Ürünleri Dergisi 37(3):1–1. https://doi.org/10.12714/egejfas.37.3.02

Eshom-Arzadon F (2017). Concentration of microplastics in beach sediments surrounding Seattle, Washington in the Puget Sound estuary. Doctoral dissertation. University of Washington

Feng S, Lu H, Yao T, Liu Y, Tian P, Lu J (2020) Microplastic footprints in the Qinghai-Tibet Plateau and their implications to the Yangtze River Basin. J Hazard Mater 124776. https://doi.org/10.1016/j.jhazmat.2020.124776

Gesamp S (2015). Fate and effects of microplastics in the marine environment: a global assessment, ed. Kershaw *PJ* (No. 90, p. 96). IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection): Rep. Stud.–GESAMP

Guan J, Qi K, Wang J, Wang W, Wang Z, Lu N, Qu J (2020) Microplastics as an emerging anthropogenic vector of trace metals in freshwater: Significance of biofilms and comparison with natural substrates. Wat Res 184:116205. https://doi.org/10.1016/j.jhazmat.2020.124776

Galloway TS, Cole M, Lewis C (2017) Interactions of microplastic debris throughout the marine ecosystem. Nat Ecol Evol 1:116

Hanslik L (2020) Microplastics in limnic ecosystems-investigation of biological fate and effects of microplastic particles and associated contaminants in zebrafish (*Danio rerio*) Ph D dissertation. Combined Faculty of Natural Sciences and Mathematics Heidelberg University, Germany

Hidalgo-Ruz V, Gutow L, Thompson RC, Thiel M (2012) Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ Sci Technol 46:3060–3075. https://doi.org/10.1021/es2031505

Hassan HU, Mahboob S, Masood Z, Riaz MN, Rizwan S, Al-Misne F, Abdel-Aziz MFA, Al-Ghanim KA, Gabol K, Chatta AM, Khan NA, Saeed, Waqar M (2023) Biodiversity of commercially important finfish species caught by mid-water and bottom trawls from the Balochistan and Sindh coasts of Arabian Sea, Pakistan: Threats and conservation strategies. Braz J Biol 83:249211. https://doi.org/10.1590/1519-6984.249211

Hassan HU, Razzaq W, Masood Z (2022) Elemental composition of three-spot swimming crab *Portunus sanguinolentus* (Herbst, 1783) shell from the coasts of Sindh and Balochistan Pakistan. Environ Sci Pollut Res 29:25679–25684. https://doi.org/10.1007/s11356-021-17627-8

Irfan M, Qadir A, Mumtaz M, Ahmad SR (2020a) An unintended challenge of microplastic pollution in the urban surface water system of Lahore, Pakistan. Environ Sci Pollut Res 27:16718–16730. https://doi.org/10.1007/s11356-020-08114-7

Irfan T, Khalid S, Taneez M, Hashmi MZ (2020b) Plastic driven pollution in Pakistan: the first evidence of environmental exposure to microplastic in sediments and water of Rawal Lake. Environ Sci Pollut Res 27:15083–15092. https://doi.org/10.1007/s11356-020-07833-1

Jian M, Zhang Y, Yang W, Zhou L, Liu S, Xu EG (2020) Occurrence and distribution of microplastics in China's largest freshwater lake system. Chemosphere 261:128186. https://doi.org/10.1016/j.chemosphere.2020.128186

Kasamesiri P, Thaimuangphol W (2020) Microplastics ingestion by freshwater fish in the Chi river, Thailand. Int J GEOMATE 18(67):114–119. https://doi.org/10.21660/2020.67.9110

Khalid N, Aqeel M, Noman A, Khan SM, Akhter N (2021) Interactions and effects of microplastics with heavy metals in aquatic and terrestrial environments. Environ Pollut 290:118104. https://doi.org/10.1016/j.envpol.2021.118104

Klein S, Worch E, Knepper TP (2015) Occurrence and spatial distribution of microplastics in river shore sediments of the Rhine-Main area in Germany. Environ Sci Technol 49:6070–6076. https://doi.org/10.1021/acs.est.5b00492

Kuśmierek N, Popiołek M (2020) Microplastics in freshwater fish from Central European lowland river (Widawa R., SW Poland). Environ Sci Pollut Res 27(10):11438–11442. https://doi.org/10.1007/s11356-020-08031-9

Li C, Busquets R, Campos LC (2020) Assessment of microplastics in freshwater systems: a review. STOTEN 707:135578. https://doi.org/10.1016/j.scitotenv.2019.135578

Li J, Liu H, Chen JP (2018) Microplastics in freshwater systems: A review on occurrence, environmental effects, and methods for microplastics detection. Water Res 137:362–374. https://doi.org/10.1016/j.watres.2017.12.056

Leslie HA, Van Velzen, MJ, Brandsma SH, Vethaak D, Garcia-Vallejo JJ, Lamoree M H (2022) Discovery and quantification of plastic particle pollution in human blood. Environ Int 163: 107199. https://doi.org/10.1016/j.envint.2022.107199

Mao Y, Li H, Gu W, Yang G, Liu Y, He Q (2020) Distribution and characteristics of microplastics in the Yulin River, China: Role of environmental and spatial factors. Env Pollut 265:115033. https://doi.org/10.1016/j.envpol.2020.115033

Mason SA, Garneau D, Sutton R, Chu Y, Ehmann K, Barnes J, Fink P, Papazissimos D, Rogers DL (2016) Microplastic pollution is widely detected in US municipal wastewater treatment plant effluent. Env Pollut 218:1045–1054. https://doi.org/10.1016/j.envpol.2016.08.056

McCormick A, Hoellein TJ, Mason SA, Schluep J, Kelly JJ (2014) Microplastic is an abundant and distinct microbial habitat in an urban river. Environ Sci Technol 48:11863–11871. https://doi.org/10.1021/es503610r

Nan B, Su L, Kellar C, Craig NJ, Keough MJ, Pettigrove V (2020) Identification of microplastics in surface water and Australian freshwater shrimp *Paratya australiensis* in Victoria. Australia Env Pollut 259:113865. https://doi.org/10.1016/j.envpol.2019.113865
Napper IE, Bakir A, Rowland SJ, Thompson RC (2015) Characterization, quantity and sorptive properties of microplastics extracted from cosmetics. Mar Pollut Bull 99:178–185. https://doi.org/10.1016/j.marpolbul.2015.07.029
Napper IE, Davies BF, Clifford H, Elvin S, Koldewey HJ, Mayewski PA, Thompson RC (2020) Reaching new heights in plastic pollution—preliminary findings of microplastics on Mount Everest. One Earth 3(5):621–630. https://doi.org/10.1016/j.oneear.2020.10.020
Neama AM, Kadhum SA, Ewaid SH, Abed SA, Al-Ansari N, Naji A (2020) Microplastic contamination of surface sediment of Euphrates River, Iraq: a preliminary study. J Phys Conf Sr 1664(1):012139
O'Connor D, Pan S, Shen Z, Song Y, Jin Y, Wu WM, Hou D (2019) Microplastics undergo accelerated vertical migration in sand soil due to small size and wet-dry cycles. Env Pollut 249:527–534. https://doi.org/10.1016/j.envpol.2019.03.092
Pazos RS, Maiztegui T, Colautti DC, Paracampo AH, Gómez N (2017) Microplastics in gut contents of coastal freshwater fish from Río de la Plata estuary. Mar Pollut Bull 122:85–90. https://doi.org/10.1016/j.marpolbul.2017.06.007
Pegado T, Schmid K, Winemiller KO, Chelazzi D, Cincinelli A, Dei L, Giarrizzo T (2018) First evidence of microplastic ingestion by fishes from the Amazon River estuary. Mar Pollut Bull 133:814–821. https://doi.org/10.1016/j.marpolbul.2018.06.035
Peng G, Xu P, Zhu B, Bai M, Li D (2018) Microplastics in freshwater river sediments in Shanghai, China: a case study of risk assessment in mega-cities. Environ Pollut 234:448–456. https://doi.org/10.1016/j.envpol.2017.11.034
Reisser J, Shaw J, Hallegraeff G, Proietti M, Barnes DKA, Thums M, Wilcox C, Hardesty BD, Pattiaratchi C (2014) Millimeter-sized marine plastics: a new pelagic habitat for microorganisms and invertebrates. PloS one 9(6):100289. https://doi.org/10.1371/journal.pone.0100289
Nel, H A, Froneman PW (2015) A quantitative analysis of microplastic pollution along the south-eastern coastline of South Africa. Marine pollution bulletin 101(1):274– 279. https://doi.org/10.1016/j.marpolbul.2015.09.043
Rao Z, Niu S, Zhan N, Wang X, Song X (2020) Microplastics in sediments of River Yongfeng from Maanshan City, Anhui Province. China Bull Environ Contamin Toxicol 104(2):166–172. https://doi.org/10.1007/s00128-019-02771-2
Roch S, Walter T, Ittner LD, Friedrich C, Brinker A (2019) A systematic study of the microplastic burden in freshwater fishes of southwestern Germany-are we searching at the right scale? STOTEN 689:1001–1011. https://doi.org/10.1016/j.scitotenv.2019.06.404
Rochman CM, Parnis JM, Browne MA, Serrato S, Reiner EJ, Robson M, Teh SJ (2017) Direct and indirect effects of different types of microplastics on freshwater prey (*Corbicula fluminea*) and their predator (*Acipenser transmontanus*). PLoS One 12(11):e0187664. https://doi.org/10.1371/journal.pone.0187664
Scherer C, Weber A, Stock F, Vurusic S, Egerci H, Kochleus C, Brennholt N (2020) Comparative assessment of microplastics in water and sediment of a large European river. STOTEN 738:139866. https://doi.org/10.1016/j.scitotenv.2020.139866
Schmid C, Cozzarini L, Zambello E (2020). Microplastic's story. Mar Pollut Bull 111820https://doi.org/10.1016/j.marpolbul.2020.111820
Sembiring E, Fareza AA, Suendo V, Reza M (2020) The presence of microplastics in water, sediment, and milkfish (*Chanos chanos*) at the downstream area of Citarum River, Indonesia. Water Air Soil Pollut 231(7):1–14. https://doi.org/10.1007/s11270-020-04710-y
Srinivasalu S, Natesan U, Ayyamperumal R, Kalam N, Anbalagan S, Sujatha K, Alagarasan C (2020) Microplastics as an emerging threat to the freshwater ecosystems of Veeranam lake in South India: a multidimensional approach. Chemosphere 264:128502. https://doi.org/10.1016/j.chemosphere.2020.128502
Stanton T, Johnson M, Nathanail, MacNaughtan W, Gomes RL 2020 Freshwater microplastic concentrations vary through both space and time. Environ Pollut 114481https://doi.org/10.1016/j.envpol.2020.114481
Sun D, Wang J, Xie S, Tang H, Zhang C, Xu G, Zhou A (2020) Characterization and spatial distribution of microplastics in two wild captured economic freshwater fish from north and west rivers of Guangdong province. Ecotox Environ Saf 207:111555. https://doi.org/10.1016/j.ecoenv.2020.111555
Sutton R, Mason SA, Stanek SK, Willis-Norton E, Wren IF, Box C (2016) Microplastic contamination in the San Francisco Bay, California, USA. Mar Pollut Bull 109:230–235. https://doi.org/10.1016/j.marpolbul.2016.05.077
Thompson RC, Moore CJ, Vom SFS, Swan SH (2009) Plastics, the environment and human health: current consensus and future trends. Philos Trans R Soc Lond B Biol Sci 364:2153–2166. https://doi.org/10.1098/rstb.2009.0053
Toumi H, Abidli S, Bejaoui M (2019) Microplastics in freshwater environment: the first evaluation in sediments from seven water streams surrounding the lagoon of Bizerte (Northern Tunisia). Environ Sci Pollut Res 26(14):14673–14682. https://doi.org/10.1007/s11356-019-04695-0
Tunali M, Uzoefuna EN, Tunali MM, Yenigun O (2020) Effect of microplastics and microplastic-metal combinations on growth and chlorophyll a concentration of Chlorella vulgaris. STOTEN 743:140479. https://doi.org/10.1016/j.scitotenv.2020.140479
Vermaire JC, Pomeroy C, Herczegh SM, Haggart O, Murphy M (2017) Microplastic abundance and distribution in the open water and sediment of the Ottawa River, Canada, and its tributaries. Facets 2(1):301–314. https://doi.org/10.1139/facets-2016-0070
Wahyuningsih H, Bangun AP, Muhtadi A (2018) The relation of sediment texture to macro-and microplastic abundance in intertidal zone. In IOP Conf Ser: Earth Environ Sci 122(1):012101. https://doi.org/10.1088/1755-1315/122/1/012101
Khan W, Hassan HU, Gabol K, Khan S, Gul Y, Ahmed AE, Swelumg AA, Khooharo AR, Ahmad J, Shafeeqi P, Ullah RQ (2024) Biodiversity, distributions, and isolation of microplastics pollution in finfish species in the Panjkora River at Lower and Upper Dir districts of Khyber Pakhtunkhwa province of Pakistan. Braz J Biol 84:10. https://doi.org/10.1590/1519-6984.256817
Wang, S, Zhang C, Pan Z, Sun D, Zhou A, Xie S, Zou J (2020) Microplastics in wild freshwater fish of different feeding habits from Beijiang and Pearl River Delta regions, South China. Chemosphere 127345. https://doi.org/10.1016/j.chemosphere.2020.127345
Wessel CC, Lockridge GR, Battiste D, Cebrian J (2016) Abundance and characteristics of microplastics in beach sediments: insights into microplastic accumulation in northern Gulf of Mexico estuaries. Mar Pollut Bull 109(1):178–183.
Wu M, Yang C, Du C, Liu H (2020) Microplastics in waters and soils: Occurrence, analytical methods and ecotoxicological effects. Ecotox Environ Saft 202:110910. https://doi.org/10.1016/j.ecoenv.2020.110910
Xu Q, Xing R, Sun M, Gao Y An L (2020). Microplastics in sediments from an interconnected river-estuary region. STOTEN 139025https://doi.org/10.1016/j.scitotenv.2020.139025
Yang L, Zhang Y, Kang S, Wang Z, Wu C (2020). Microplastics in freshwater sediment: a review on methods, occurrence, and sources. STOTEN, 141948. https://doi.org/10.1016/j.scitotenv.2020
Yin L, Wen X, Du C, Jiang J, Wu L, Zhang Y, Long Y (2020) Comparison of the abundance of microplastics between rural and urban areas: A case study from East Dongting Lake. Chemosphere 244:125486. https://doi.org/10.1016/j.chemosphere.2019.125486
Yuan W, Liu X, Wang W, Di M, Wang J (2019) Microplastic abundance, distribution and composition in water, sediments, and wild fish from

Poyang Lake, China. Ecotox Environl Saft 170:180–187. https://doi.org/10.1016/j.ecoenv.2018.11.126

Zhang L, Xie Y, Zhong S, Liu J, Qin Y, Gao P (2020) Microplastics in freshwater and wild fishes from Lijiang River in Guangxi, Southwest China. STOTEN 755:142428. https://doi.org/10.1016/j.scitotenv.2020.142428

Zhang W, Zhang S, Wang J, Wang Y, Mu J, Wang P, Ma D (2017) Microplastics pollution in the surface waters of the Bohai Sea, China. Environ Pollut 231:541–548. https://doi.org/10.1016/j.envpol.2017.08.058

Zhang X, Leng Y, Liu X, Huang K, Wang J (2020b) Microplastics' pollution and risk assessment in an urban river: A case study in the Yongjiang River, Nanning City. South China Expos Health 12(2):141–151. https://doi.org/10.1007/s12403-018-00296-3

Ziajahromi S, Kumar A, Neale PA, Leusch FDL (2017) Impact of microplastic beads and fibers on waterflea (*Ceriodaphnia dubia*) survival, growth, and reproduction: implications of single and mixture exposures. Environ Sci Technol 51:13397–13406

Zhang Y, Gao T, Kang S, Sillanpää M (2019) Importance of atmospheric transport for microplastics deposited in remote areas. Environ Pollut 254:112953. https://doi.org/10.1016/j.envpol.2019.07.121

Zobkov M, Esiukova E (2017) Microplastics in Baltic bottom sediments: quantification procedures and first results. Mar Pollut Bull 114(2):724–732. https://doi.org/10.1016/j.marpolbul.2016.10.060