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Microplastics in Different Tissues of Five Common Fishes from Yuehai Lake: Accumulation, Characterization, and Contamination Assessment

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Microplastic (MP) pollution in freshwater ecosystems poses growing threats to biodiversity and human health. This study employed laser direct infrared imaging (LDIR) to analyze MP contamination in gills and gastrointestinal tracts (GIT) of five fish species (n=100) from Yuehai Lake, China. Results revealed significantly higher MP loads in omnivorous species compared to carnivorous counterparts, with GIT containing greater MP abundance than gills. MP characteristics exhibited tissue-specific patterns: fibers dominated gill samples (64.32%) while fragments prevailed in GIT (50.50%). Size distribution analysis showed >80% of MPs measured 20-100 μm. Polymer composition differed markedly between tissues, with fluoroelastomer (FKM, 17.87%) and polyvinyl chloride (PVC, 17.79%) predominant in gills, versus polyethylene terephthalate (PET, 18.74%) and chlorinated polyethylene (CPE, 17.63%) in GIT. Pollution indices (1<CF<3, PLI>1) confirmed significant ecological contamination. These findings provide crucial evidence of MP pollution pathways in freshwater food webs and highlight potential risks to ecosystem integrity and public health.

Keywords: Microplastics; fishes; lake; Laser Direct Infrared Imaging (LDIR); Yuehai Lake

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MP pollution is a growing environmental concern, particularly in freshwater ecosystems like lakes. MPs, defined as plastic particles smaller than 5 mm, have been identified in multiple studies as a significant hazard to aquatic ecosystems, adversely affecting both marine organisms and human health. Approximately 368 million tonnes of plastics were produced worldwide in 2019 [1]. Estimates from the International Union for Conservation of Nature indicate that roughly 8 million tonnes of plastic garbage enter the ocean annually [2]. The majority of MPs originate from mismanaged waste, urban runoff, and industrial activities [3]. The primary MPs are plastic particles that are released directly into the environment, including tiny fibers from textiles and clothing. Secondary MPs are generated from the degradation of larger plastic materials [4]. The principal issue is that MPs, often made from ordinary plastics such as polyethylene (PE) and polypropylene (PP), can endure in the environment for extended durations and proliferate extensively. PE and PP are the predominant polymers in aquatic ecosystems, collectively constituting an important proportion of MPs in freshwater systems [4]. Other polymers such as polystyrene (PS), polyvinyl chloride (PVC), polyamide (nylon), and polyester also contribute to the composition of MPs in aquatic environments. MPs can be found in various forms, including fibers, fragments, and films, which can further complicate their environmental impact and detection [5].

MPs in aquatic environments originate from various sources, significantly impacting ecosystems and human health. The primary contributors include land-based activities, recreational use, and the degradation of larger plastic items. Inland activities include many aspects of daily life, agricultural activities, industry, and transportation. The high concentrations of MP found in community swimming pools indicate that everyday activities can lead to serious MP pollution [6]. Plastic mulch and film, which are widely used in agricultural production, can break or degrade during use, releasing tiny plastic particles that can enter the soil and water bodies through wind or water currents [7]. During driving, the friction between the tires and the ground can generate tiny plastic particles, which enter the water bodies through rainwater runoff [7]. Industrial emissions often contain MPs, which can enter aquatic systems [3], further exacerbating environmental pollution. The main thing that raises the amount of methanol in natural waterways during recreational activities is fibers from synthetic fibers [6]. Once released into the environment, plastics can be carried by wind into water bodies and degrade

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into smaller particles over time. Other sources of MP pollution in freshwater ecosystems include aquaculture, shipping, and water tourism [8]. Meanwhile, rainwater can wash plastics from urban areas into waterways, exacerbating MP pollution [3]. MP pollution have a wide range of ecological impacts, as MPs can transport other pollutants over long distances, enriching ecosystems with harmful substances. These MPs make toxins more bioavailable by absorbing and building up in living things. Toxins then enter the food chain and affect many different species. MPs are eaten by marine animals like bivalves, zooplankton, fish, and even whales, spreading them all over the ecosystem [9, 10].

MPs significantly impact aquatic organisms in lake water, leading to various ecological consequences. These tiny particles disrupt food webs and harm aquatic life through ingestion and habitat alteration. Studies indicate that MPs are prevalent in various fish species, with contamination rates reaching 46.9% in marine fish from the Gulf of Thailand [11]. MP particles were all detected in benthic species like Pleuronectidae and Soleidae, migratory species like Thunnus orientalis and Dicentrarchus labrax, and commercially significant species like Sardina pilchardus and Engraulis encrasicolus [12]. Freshwater fish, such as those from the Mun River, show even higher levels, averaging 17.70% per fish [13]. Common types of MPs found include fibers and fragments, primarily made of polyester and polyethylene [13]. Zooplankton frequently mistake MPs for food, resulting in their ingestion, which can lead to tissue damage and growth impairment [14]. MPs absorb harmful pollutants and pathogens, increasing the toxicity of the water and posing health risks to organisms [15]. According to Biswal [14], MPs in lakes can change the balance of food webs because they build up in primary producers like phytoplankton and are then eaten by higher trophic levels. A study in Kolavai Lake discovered a negative relationship between the number of MP and the number of zooplankton species. This suggests that these important food web components may be declining [15]. MPs are surfaces that microbes can colonize. This can change the structure of the bacterial community and could bring pathogenic bacteria into the ecosystem [16]. Some bacteria may break down MPs, which could change how nutrients move through an ecosystem and how it works, which would make the environmental effects even more complicated [16].

Humans are exposed to MPs primarily through the consumption of seafood. With 1.79 million tonnes of fish produced worldwide in 2018, over half of which came from aquaculture [17], the risk of MPs entering the human body through fish consumption is significant. Small fish and bivalves are particularly susceptible to MP ingestion, as they often consume MPs whole. MPs can build up in animals' digestive tracts after they eat them, and studies have shown that traditional preparation methods like boiling or pre-purification are not effective at getting rid of them [18-20]. Although large fish may have fewer MPs after certain parts are removed, such as the viscera and gills, the potential for human exposure remains. The estimated daily intake of MPs through seafood can range from 0.03 to 0.1 pieces per person [11]. MPs cause inflammatory responses and cytotoxicity in humans, with potential long-term health implications [21]. The systematic review indicates that humans may ingest up to 1,531,524 pieces MPs daily from various food sources, including seafood [22]. This highlights the importance of addressing the issue of MP contamination in the food supply, as humans could be ingesting MPs along with the fish they consume.

While numerous techniques exist for MP analysis, including scanning electron microscopy, Fourier transform infrared spectroscopy (μ-FTIR), Raman spectroscopy, and stereomicroscopy [23], LDIR stands out as a superior integrated approach, overcoming key limitations of these established methods. Although several techniques can identify MPs smaller than 500 μm, LDIR offers significant advantages: it is faster, provides better resolution, is highly automated, and operates without damaging samples or inducing fluorescence interference [24]. Specifically, compared to μ-FTIR, LDIR achieves dramatically higher throughput (10-50 times faster) and enables full automation in detecting, isolating, and characterizing particles, making it exceptionally efficient for processing large environmental datasets. Crucially, unlike Raman spectroscopy, LDIR is immune to fluorescence interference from organic residues, pigments, or biological materials common in complex environmental samples like lake water, sediments, or biological tissues, ensuring more reliable identification. Furthermore, while techniques like Pyrolysis-Gas Chromatography-Mass Spectrometry (Py-GC-MS) provide only bulk chemical composition data, LDIR delivers essential per-particle morphological information (size, shape) alongside polymer identity, which is critical for understanding environmental fate, biological uptake, and risk assessment. LDIR's non-contact laser method also preserves particle integrity. Its reproducibility and robustness further support its growing recognition as a candidate for standardization in monitoring programs. Consequently, LDIR uniquely balances speed, automation, resolution, robustness against interference, morphological detail, and chemical specificity, making it exceptionally suited for large-scale environmental MP research, such as the Yuehai Lake study. This capability is demonstrated by its successful application in diverse environments, including groundwater aquifers [25], urban rivers [26], coastal areas [27], agricultural soils [28], and fish gut tissue [29]. As a qualitative and quantitative analytical tool, LDIR provides vital information for understanding MP distribution and impacts.

Yuehai Lake has rich biodiversity, but the MP pollution of fish in the water area is still unknown. The ecological environment of the study area is threatened by waste management, agriculture, urbanization, and human recreational activities in surrounding areas. This study examined commercially valuable and palatable fish species in Yuehai Lake. Subsequently, it employed LDIR technology to examine the distribution of MPs within the gills and digestive system. It conducted a risk assessment to address significant gaps about long-term trends and the bioaccumulation of certain species, as well as to facilitate future research on the impact of MPs on human health. Despite Yuehai Lake's significant ecological value, documented severe pollution (exceeding self-purification capacity and experiencing eutrophication), inadequate wastewater treatment practices (only partial secondary treatment), and its location in an arid region vulnerable to pollution impacts, no studies have investigated the occurrence, characteristics, sources, or ecological risks of MP pollution in the lake.

EXPERIMENTAL

Study Site

The study site is Yuehai Lake, a man-made lake that spans over 2667 hectares and is situated in Yinchuan City, Ningxia, northwest China. It is a section of the Yellow River system (Figure 1). In an effort to safeguard wetland ecology and advance tourism, the lake was established through a series of ecological restoration and water system connectivity initiatives.

The attractiveness of Yuehai Lake as a leisure destination is further enhanced by the activities that surround it, such as bird watching, fishing, ecological sightseeing excursions, and snow and ice activities. The development of Yuehai Lake is closely related to tourism, and industrial activities in the surrounding area have focused more on the service sector and the construction of tourism infrastructure [30].

Sample Collection

A total 100 fish of 5 species were gathered and species characteristics of collected fish were analysed in this investigation, named Carassius auratus, Cyprinus carpio, Hemiculter leucisculus, Culter alburnus, Lateolabrax japonicus, seperately. For each species, 20 individuals were collected. The fish were purchased from local fishermen operating around Yuehai Lake, ensuring that the samples reflected natural seasonal feeding conditions. Upon collection, all specimens were transported to the laboratory on ice and processed on the same day. The weight and length of the fish were measured separately, and the average was determined.

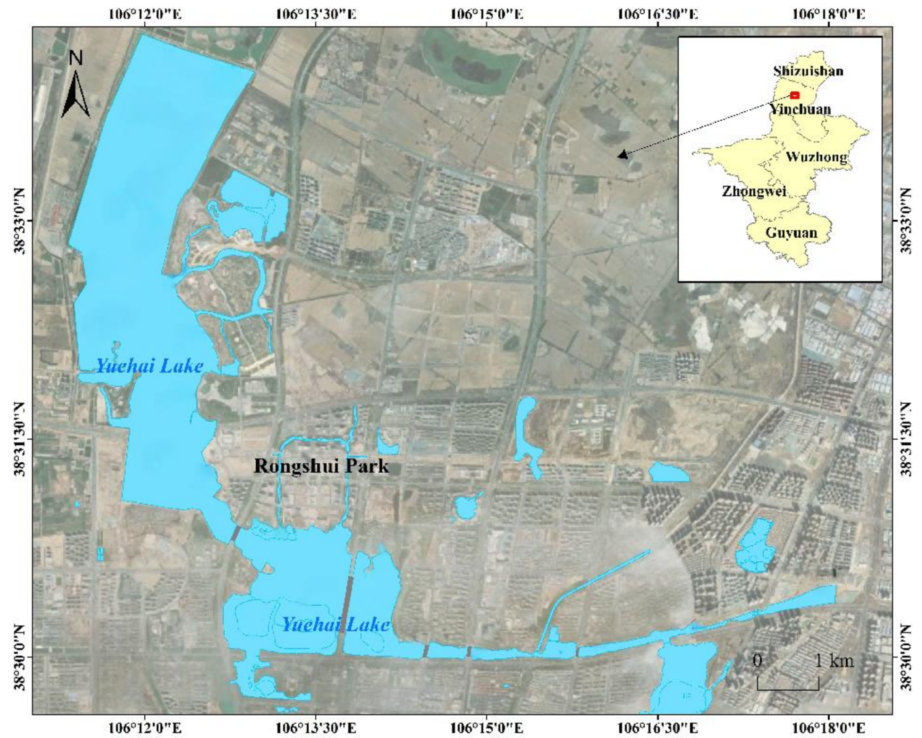


Figure 1. The map of study site.

MP Extraction and Digestion

The gills and GIT were removed using surgical scissors in a closed chamber and separately dried in the oven for 18 hours. Subsequently, concentrated nitric acid (68%) was applied to each portion of the fish, and the samples were subjected to digestion for 42 hours at the room temperature. Vacuum filtering was conducted with a steel membrane with a pore diameter of 13 μm [24]. Following many rinses with filtered ultrapure water and ethanol, the membrane was submerged in an ethanol solution, where ultrasonic treatment dispersed the particle spots on the membrane. The membrane was extracted from the ethanol solution, rinsed multiple times with ethanol, and subsequently concentrated to 150 ml in an oven. It was then put dropwise to a highly reflective glass and permitted to evaporate entirely for LDIR testing.

MP Identification

An LD-IR imaging spectrometer (8700 LD-IR, Agilent Technologies, USA) was employed to detect MPs in the gills and GIT of five fish species and quantify their concentrations. The particle analysis mode was selected with the range of 20-500 μm. An infrared light with a wavelength of 1800 cm^{-1} was used by the LDIR to rapidly detect MPs, analyzing 300-400 particles per hour and providing an overview of all potential MPs. Then, they are individually located using mid-infrared spectroscopy's transmittance and reflection methods [27,31]. All particle information was collected using Agilent Clarity software. This information was then compared to the Agilent spectral library of MPs. Each particle was given a match degree based on comparing the spectrum of a particular particle to the MPs in the Agilent spectral library. The match degree ranged from 0-1. The higher the match, the better the match between the detected spectral curve and the standard particles. Considering the uncertain environmental conditions affecting MPs in the analyzed samples and the difficulties associated with accurately evaluating their impact, we provided data with a matching degree greater than 0.65, in accordance with the established methodologies found in the literature [32-34]. The machine automatically divides the particles into two groups with different size distributions (20–100 μm and 100–500 μm). In this study, the 20-100 μm group was divided into two subgroups: 20-50 μm and 50-100 μm, to enhance the understanding of size distribution. Particles ranging from 20-100 μm are classified as small-sized MPs, while those ranging from 100-500 μm are classified as large-sized MPs.

Quality Assurance and Quality Control (QA/QC)

Develop detailed experimental protocols, including sample collection, processing, and analytical methods, to ensure the experiment's consistency and reproducibility. Conduct the operation on a clean bench with doors and windows closed and no wind to reduce airflow contamination of the sample [35]. Use ultrapure water to set up a blank control group to correct for possible MP contamination during the experiment [36]. Strict no-plastic procedures are implemented throughout sample collection, storage, processing, and analysis, with priority given to glass or metal containers to ensure data reliability. In particular, all reagents were filtered to avoid the potential contamination of MPs in the reagents from affecting the experimental results [37]. All laboratory consumables were made of glass, rinsed thrice with ethanol before use, and allowed to dry [38]. The experimenters used nitrile gloves, cotton lab coats, surgical masks, and head covers to reduce sample contamination during sample processing and analysis.

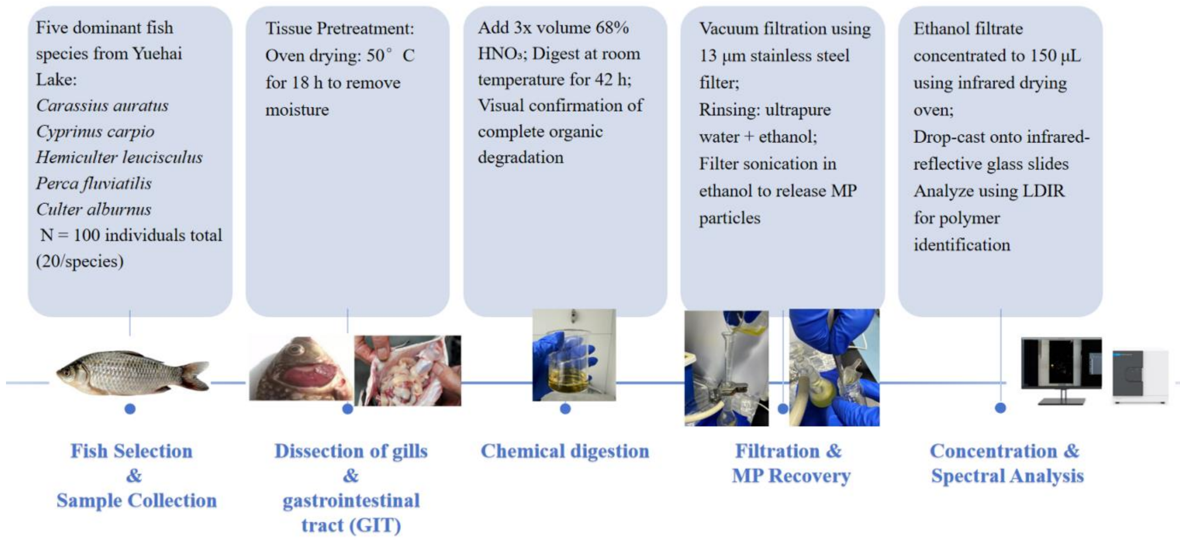


Figure 2. The flow chart of methodology.

Polymer Risk Assessment

The contamination factor (CF) and pollutant load index (PLI) are commonly used to evaluate ecological risk in previous researches [39]. The CF calculation formula is:

$$CF_i = {}^{C_i}/_{C_o}$$

Here, CFi is the quotient of the concentration (Ci) of identified plastic particles for each fish species and the minimum concentration of plastic particles (C0). The CF is an indicator that measures the degree of contamination of a certain pollutant in a sample relative to a reference or background value [40].

PLI is an approach that considers a variety of contaminants to determine the total amount of pollution present in a specific site or area [36]. This is determined by applying:

$$PLI = \sqrt[n]{CF_1 \times CF_2 \times CF_3 \ldots \times CF_n}$$

where CF1, CF2, ⋯, CFn are the contamination factors for each of the individual pollutants measured and n is the total number of pollutants considered. A PLI >1 means the area is polluted [41].

Polymer hazard index (PHI) is to assess the potential risk of specific MPs polymer to humans. To calculate the polymer hazard index:

$$PHI = \sum P_n \times S_n$$

where Pn is the percentage of specific plastic polymers and Sn is the hazard score of plastic polymers [42-44].

Statistical Data Analysis

Plastic abundance and characteristic data were collected for each fish. The results of the current study are presented as mean values ± standard deviation for MPs, reflecting the central tendency and variability. Differences between means were considered statistically significant when $p < 0.05$. We used Excel 2019 for table organization, calculations, and standard deviation assessment. We performed the Spearman correlation statistical analysis using Origin software.

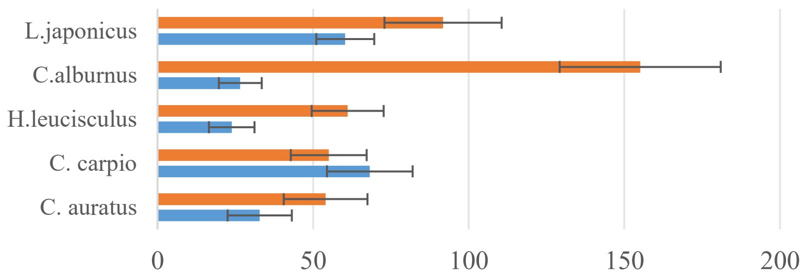
RESULTS AND DISCUSSION

Occurrence and Abundance of MPs

The highest mean weight recorded was 920.3 ± 40.9g (C. carpio), and the lowest was 117.1 ± 12.4g (H. leucisculus). Specimens of C.auratus had the shortest total length at 12.8 cm, and the longest total length of 32.9 cm was recorded for C. carpio. Three species habitats (benthic, demersal and pelagic) were identified to be occupied by the sampled specimen. The feeding types of the sampled species were omnivorous and carnivorous.

Table 1. The composition of fish species collected.

No	Scientific name	Common name	Habitat	Feeding type	Morphological measurement	
					Weight (g)	Length (cm)
1	Carassius auratus	Common Carp	Benthic	Omnivorous	185.2±15.2	13.3±0.5
2	Cyprinus carpio	Carp	Benthic	Omnivorous	920.3±40.9	31.3±1.6
3	Hemiculter leucisculus	White Strip	Benthic/ Demersal	Carnivorous	117.1±12.4	17.2±0.3
4	Culter alburnus	Topmouth culter	Demersal	Carnivorous	297.6±16.5	23.1±0.4
5	Lateolabrax japonicus	Asian Sea Bass	Demersal/Pelagic	Carnivorous	702.8±23.4	27.9±0.8



	C. auratus	C. carpio	H.leucisculus	C.alburnus	L.japonicus
Intestines	54	55	61.1	155.08	91.74
Gills	32.83	68.2	23.83	26.59	60.32

Figure 3. Abundance of MPs in different parts of the *C. auratus.*

MPs were detected in every fish species from Yuehai Lake. Each fish species underwent individual examination of its gills and GIT. The incidence of MP was 100% across all species and in the gills and GIT. Figure 3 illustrates the abundance of MPs in different organs of fish. The average MP particle burden in the examined species is evident. The MPs abundance in the gills was ranked as follows: C. carpio (68.20±13.77) > L. japonicus (60.32±9.31) > C. auratus (32.83±10.32) > C. alburnus (26.59±6.89) > H. leucisculus (23.83±7.32 item/individual). The recorded order of MP abundance in the GIT was as follows: C. alburnus (155.08±25.88) > L. japonicus (91.74±18.83) > H. leucisculus (61.10±11.56) > C. carpio (55.00±12.19) > C. auratus (54.00±13.45 item/individual), as illustrated in Figure 3. Significantly higher levels of MP were observed in the GIT compared to the gills, except for C. carpio. Other researchers identified MPs in different organs of mullets and mackerel during a study. The amount of MPs varies between species, with some having higher levels in their gills than in their GIT [45]. H. leucisculus exhibited the lowest average MP count of 23.83±7.32 items per individual in the gills, whereas C. carpio demonstrated the highest MP count of 68.20±13.77 items per individual. C. auratus exhibited the lowest average MP count of 54.00±13.45 items per individual in the GIT, whereas C. alburnus demonstrated the highest MP count of 155.08±25.88 items per individual in the gills. Fish consume MPs via their diet, including animals that may have previously ingested these MPs particles. This leads to elevated levels of MPs in the GIT relative to the gills [46]. Studies have shown that fish from lakes have higher levels of MPs in the GIT than fish from other water bodies, indicating that the environmental concentration of MPs is also an essential factor [47].

It is noteworthy that omnivorous fish species (C. auratus and C. carpio) have more MPs than carnivorous fish species (H. leucisculus, C. alburnus, and C. alburnus). This result is the same as the distribution of six common fish species along the coast of the Bay of Bengal [48], marine fish in Hong Kong [49], and fish in the Han River [50]. Omnivorous fish eat a variety of things, such as trash and plant matter, which are more likely to be contaminated with MP than the food that carnivorous fish eat [48]. According to Sultana et al. [48], the digestive systems of omnivorous fish may allow MPs to stay in the GIT for longer, which leads to higher accumulation rates. According to Cáceres-Farías et al. [51], omnivores are likelier to eat MPs because they are not as picky about their food sources as carnivores. The fish living in the benthic zone exhibited the highest concentration of MPs, followed by those in the demersal and pelagic zones in this study. MPs tend to accumulate in benthic environments due to their density and the settling of particles from the water column. This results in a higher concentration of MPs in sediments, which are the primary habitat for benthic organisms [52].

Morphology of MPs

Fibers, fragments, and film were detected in the organs of common fishes except in the gills of H. leucisculus (no film) (Figure 4). Fiber was the dominant MP in the gills, accounting for 64.32% on average, with a range of 59.40%-72.47%. The fragments in the gills account for 35.85%, 23.03%, 39.85%, 32.00%, and 28.70%, respectively. Each species' gills contain fewer than five particles of film. Similar contributions of fibers in the gills were found in previous studies. Research on fish from the Caspian Sea reported that 74.68% of the MPs found in fish gills were fibers [53]. In the Alvarado Lagoon, a study found that 97.53% of the MPs in the gills were fibers, further supporting the notion that fibers are the most common MP shape in fish gills [54]. Fibrous MPs are abundant in freshwater systems due to their widespread use in textiles and other industries. They are released into the environment through wastewater and runoff, leading to high concentrations in aquatic habitats where fish reside [55]. Fibers are long, thin, and flexible, allowing them to entangle with fish's gill structures easily. This entanglement is facilitated by the fibrous shape, which can adhere to the mucous membranes of the gills, making them difficult to expel once trapped [56].

Fragments were the most common shape in the GIT, accounting for 50.50% on average, with a range of 38.31%–62.93%. Fiber was the second dominant shape in the GIT, accounting for 43.25% on average. Every species' GIT had more fragments than fiber except for the GIT of H. leucisculus. The range of film in the GIT is from 0.65% to 12.00%. In a study of parrotfish from Ekas Bay, fragments were found to be the most common shape in the stomach as well [57]. A study on cultured common carp found that fragments were the predominant shape, making up 65% of the carp's GIT [58]. Fragments comprised 70% of the MPs found in the digestive tracts of dace in the Tom River in West Siberia. This demonstrates their prevalence in freshwater ecosystems [59]. Fragments are a common byproduct of the degradation of larger plastic items, such as bottles and packaging materials, which break down into smaller pieces over time due to environmental factors like UV radiation, mechanical abrasion, and microbial activity [60]. Due to their widespread distribution and persistence, fragments are frequently detected in various aquatic environments, including rivers, oceans, and lakes. This makes them readily available for ingestion by fish [61].

Dimension of MPs

The study was categorized into three groups to characterize the size of MPs in common fish species (Figure 5). The predominant size range in the gills is 20-50 μm, with respective frequencies of 49.25%, 44.38%, 61.56%, 48.00%, and 50.93%. The most 50-100 μm MPs were found in C. alburnus (48.0%), then in C. auratus (41.79%), L. japonicus (40.74%), H. leucisculus (32.33%), and C. carpio (31.46%). In C. carpio, the >100 μm size exhibited the highest frequency at 24.16%, followed by C. auratus at 8.96%, L. japonicus at 8.33%, H. leucisculus at 6.02%, and C. alburnus at 4.00%. When it came to the GIT, C. auratus had the most 20-50 μm MPs (73.96%), followed by H. leucisculus (73.70%), C. alburnus (67.17%), C. carpio (64.0%), and L. japonicus (61.90%). The size range of 50-100 μm exhibited the highest frequency at 29.76% in L. japonicus, followed by 24.89% in C. alburnus, 24.00% in C. carpio, 19.16% in H. leucisculus, and 18.75% in C. auratus (38.4%). The highest proportion of MPs exceeding 100 μm was recorded in C. carpio at 12.00%, followed by L. japonicus at 8.33%, C. alburnus at 7.94%, C. auratus at 7.29%, and H. leucisculus at 7.14%.

The result showed that MPs in gills and GIT of common fishes were concentrated in the 20-100 μm size range, with a significant portion being in the 20-50 μm range. In freshwater ecosystems, such as the Han River in South Korea, fish have been found to contain MPs predominantly in the 45-100 μm size range [62]. Studies, including the Mun River in Thailand and the Melayu River in Johor, have documented the widespread presence of MPs in fish; the size of these MPs often falls within the 20-50 μm range, making them easily ingestible by fish [13]. Fish ingest MPs through their normal feeding activities, mistaking them for food due to their size and appearance. Pelagic planktivores, for instance, are more prone to ingesting MPs due to their feeding strategies [63]. At the same time, the 20-50 μm size is particularly significant because these particles are small enough to be ingested but large enough to remain in the GIT, causing potential harm [64].

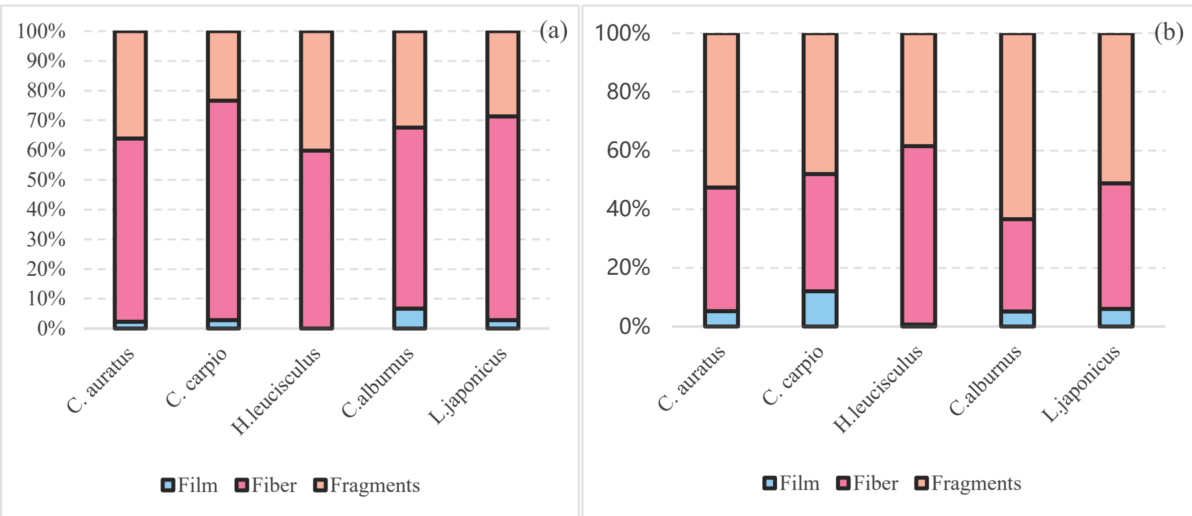


Figure 4. The proportion of different shapes in common fishes: (a) in the gills, and (b) in the GIT.

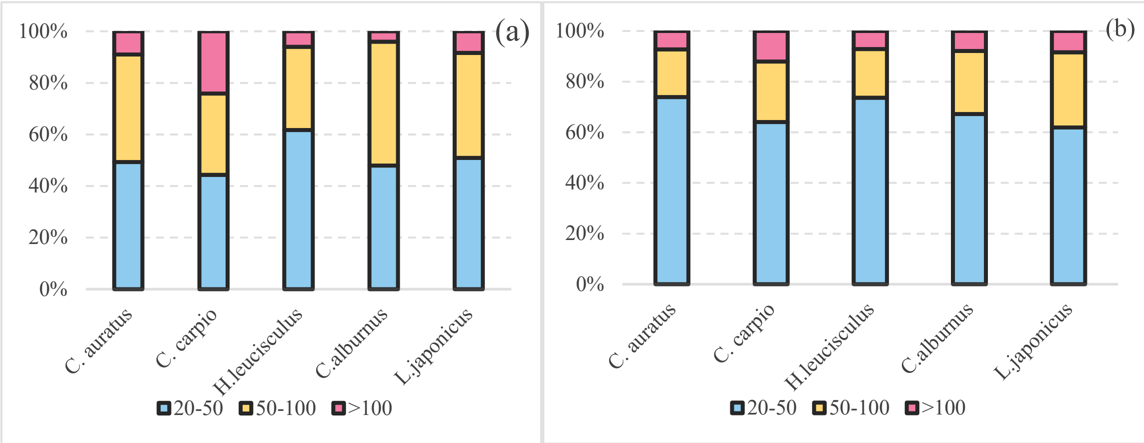


Figure 5. Proportion of MPs in the three-particle size ranges (20–50, 50-10, >100 μm): (a) in the gills, and (b) in the GIT.

Chemical Component of MPs

Figure 6 presents the MPs' chemical composition in common fishes' gills. Twenty-six different MP polymers were detected in common fishes. We identified 8 MP polymer types in all five fish species, accounting for over 80% of the total, except C. carpio. They were Chlorinated polyethylene (CPE), Fluororubber (FKM), PVC, Acrylates (ACR), PP, Polyurethane (PU), Fluorosilicone rubber (FVMQ), and Polyethylene terephthalate (PET). Among them, FKM and PVC are the predominant polymers found in the gills of the five fish species, comprising an average of 17.87% and 17.79%, respectively. CPE followed with an average of 13.33%, while the other polymers constituted less than 10%. The distribution of MP polymer types within the gills exhibits variability. The gills of C. auratus exhibit the highest proportion of PET at 17.91%, followed by FKM at 16.42% and PVC at 13.43%. In the gills of C. carpio, the eight polymers, which account for 55.62%, are the same as those in the gills of the other four fish species, except for PVC, which accounts for 22.47 percent, CPE, which accounts for 18.54 percent, and SBS, which accounts for more than 10%. FKM was the most abundant MP polymer in the gills of both H. leucisculus and C. alburnus, accounting for 23.31% and 30.67%. This was followed by CPE (17.29%) and PU (17.29%) in H. leucisculus and PVC (17.33%) and FVMQ (17.33%) in C. alburnus. PVC is detected as the most abundant in the gills of L. japonicus, with 25.93%, followed by FVMQ (20.37%) and FKM (17.89%). These predominant polymers, grouped by common source categories, are presented in Table 2.

Previous studies in fish gills include PE, PP, PS, and PET. These polymers are prevalent due to their widespread use in consumer products and packaging [55]. Polymers like nylon, polyester, and PVC have also been found in the fish gills [65], showing that MP pollution in aquatic environments comes from many different places. Other research showed similar results. PVC has been detected in the gills of zebrafish, where it causes stress and increased biological activity, likely due to gill blockage and disruption of water filtration processes [66]. Exposure to PVC MPs has enriched pathogenic bacteria and spread antibiotic resistance genes in carp, indicating a broader ecological impact [67]. The histopathology changes and cells are killed when PVC builds up in the gill tissues of Nile tilapia [68].

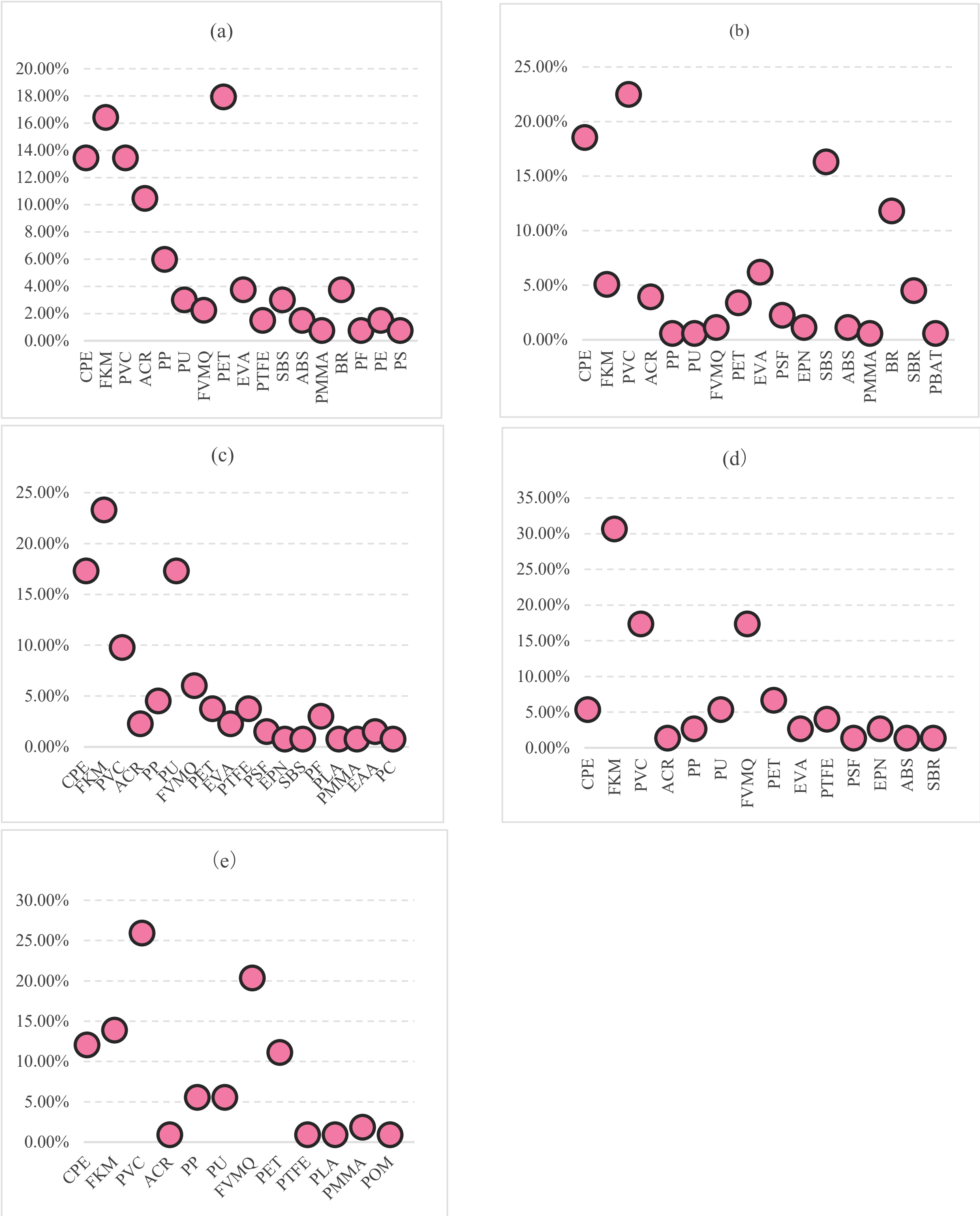


Figure 6. The MP polymer in the gills of :(a) C.auratus; (b) C.carpio; (c) H. leucisculus; (d) C. alburnus; (e) L. japonicus.

Table 2. Predominant MP Polymers in Fish Gills, Grouped by Primary Source Category.

Primary Source Category	Polymer Type	Average % (5 species)	Key Species-Specific Findings
Industrial/Manufacturing	CPE	13.33%	Highest in C. carpio (18.54%)
	FKM	17.87%	Most abundant in H.leucisculus (23.31%), C. alburnus (30.67%)
	FVMQ	<10%	High in C. alburnus (17.33%), L. japonicus (20.37%)
	PU	<10%	High in H. leucisculus (17.29%)
Packaging/Consumer Goods	PP	<10%	-
	PET	<10%	Highest in C. auratus (17.91%)
Construction	PVC	17.79%	Most abundant in L. japonicus (25.93%), High in C. carpio (22.47%)
Coatings/Adhesives	ACR	<10%	-

Note: "Average %" refers to the mean abundance across the five species where these polymers were predominant. Species-specific high abundances are noted.

In the GIT, the common fishes were found to possess the same six MPs polymer types, as illustrated in Figure 7. They were PE, PET, PU, PVC, CPE, and FKM. Among them, PET and CPE were the main components in the GIT of 5 fishes, accounting for 18.74% and 17.63% on average, followed by PU (15.88%). Each species' other MP polymer types are listed in Table 3. In the GIT of C. auratus, CPE was the most common MP polymer type, accounting for over half; the other polymer types were less than 10%. PVC and PE were most common in the GIT of C. carpio, both accounting for 16.00%, followed by PU (12.00%), CPE (12.00%), and PIB (12.00%). PU accounted for more than half of the content, the main MP component enriched in the GIT of H. leucisculus. PET was the predominant MP polymer in the GIT of C. alburnus, accounting for 76.42%, followed by FVMQ (6.80%) and PVC (5.90%). In the GIT of L. japonicus, FKM was the dominant MP polymer, accounting for 26.19%, followed by CPE at 21.43%. These polymers and their primary source categories are summarized in Table 4.

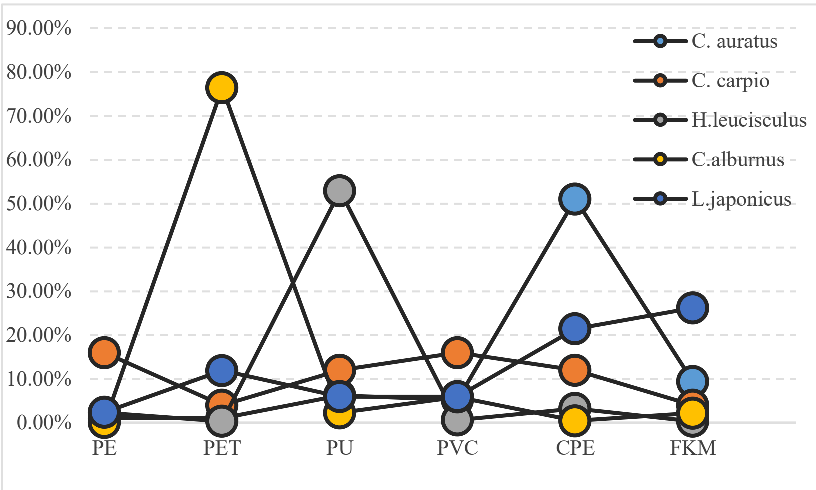


Figure 7 The common MP polymer component in the GIT of 5 fishes

The GIT of fish contains a variety of MPs due to the prevalence of these contaminants in the aquatic environment. MP particles are ingested by fish directly or indirectly through food, causing them to accumulate in the gastrointestinal tract. The ingestion of MPs by fish is influenced by a number of factors, including the size and type of MPs, the feeding habits of the fish, and the level of pollution in their habitat. The composition of MPs in fish GIT is indeed diverse, as evidenced by multiple studies across different geographical locations and fish species. PE was found to be predominant in fish from Lake Singkarak and the Kahayan River [69]. Additionally, it was the most detected polymer in aquaculture systems [70]. Researchers identified PVC in the water, sediment, and fish of the Kahayan River [69]. PET was prevalent in marine fish from the Beibu Gulf and freshwater fish in Asia [71]. As Hossain et al. [72] also said, PVA, PP, and nylon were found in fish samples, which shows that fish eat a lot of different kinds of plastic.

Table 3. The other MP polymer component in the GIT of fishes.

No	MPs polymer type	C.auratus	C.carpio	H.leucisculus	C.alburnus	L.japonicus
1	ACR	1.04%	/	23.38%	3.63%	2.38%
2	Ethylene-Vinyl Acetate Copolymer (EVA)	1.04%	/	2.92%	0.30%	2.38%
3	Polylactic Acid (PLA)	1.04%	4.00%	0.32%	/	1.19%
4	FVMQ	8.33%	/	/	6.80%	2.38%
5	Polyformaldehyde (POM)	/	4.00%	0.32%	0.08%	/
6	Cis-1,4-Polybutadiene Rubber (BR)	8.33%	/	/	/	2.33%
7	Polystyrene (PS)	/	8.00%	/	0.08%	/
8	Polysulfone (PSU)	/	4.00%	/	0.53%	/
9	Phenolic Resin	/	/	0.32%	0.08%	/
10	Polymethyl methacrylate (PMMA)	/	/	12.99%	0.08%	/
11	Acrylonitrile Butadiene Styrene Copolymer (ABS)	3.13%	/	/	/	1.19%
12	Styrene-Butadiene-Styrene Copolymer (SBS)	1.04%	/	/	/	2.38%
13	PP	/	/	/	0.76%	11.90%
14	Styrene-Isoprene-Styrene Copolymer (SIS)	1.04%	/	/	/	/
15	Polycarbonate (PC)	1.04%	/	/	/	/
16	Polyisobutylene (PIB)	/	12.00%	/	/	/
17	Polybutadiene (PB)	/	4.00%	/	/	/
18	Phenolic Epoxy Resin	/	/	/	0.23%	/
19	PS	/	/	/	0.08%	/
20	Ethylene Acrylic Acid Copolymer (EAA)	/	/	/	0.08%	/

Table 4. Common MP Polymers in Fish GIT, Grouped by Primary Source Category.

Primary Source Category	Polymer Type	Average % (5 species)	Key Species-Specific Findings
Packaging/Consumer Goods	PET	18.74%	Dominant in C. Alburnus (76.42%)
	PE	4.35%	Most common in C. carpio (16.00%)
	PP	See Table 3	Highest in L. japonicus (11.90%)
Industrial/Manufacturing	CPE	17.63%	Dominant in C. auratus (>50%), High in L. japonicus (21.43%)
	FKM	8.42%	Dominant in L. japonicus (26.19%)
	PU	15.88%	Dominant in H. leucisculus (>50%), High in C. carpio (12.00%)
Construction	PVC	6.74%	Most common in C. carpio (16.00%)

Note: "Average %" refers to the mean abundance across the five species where these polymers were predominant. Species-specific high abundances are noted.

Table 5. The hazard value of MP polymer.

MPs polymer type	Hazard Score	PHI	Hazard level	Risk category
PVC	10001	307730.77	V	Extreme danger
PU	7384	4569.52	IV	Danger
PE	11	507.65	IV	Danger
PET	4	33.12	III	High
PP	1	14.79	III	High

Pollution Risk Assessment

At present, a polymer risk index-based hazard grading technique was used to analyze the potential harmful effects of plastics based on various polymeric chemical compositions [73]. Our findings revealed the risk of plastic contamination in the studied fish (Table 5). With the highest potential hazard index (Category V) and the most significant hazard score, PVC was found to be an extremely substantial danger to human health due to plastic exposure in the gills of common fishes. PET was the predominant MP polymer in the GIT, with minor potential risks (Category III). Mancuso et al. [74] also identified PU and PET in the GIT of Trematomus bernacchii. The estimated PHI values indicated medium to high risk. Gholizadeh et al. [75] indicated PHI values of PES (8403.78) and PS (535.80) for fishes in the southern Caspian Sea. Nithin et al. [44] revealed medium risk (hazard category II) with PHI scores 1-10 for fish in Parangipettai, India. Our findings align with these studies, demonstrating comparable levels of relevance and risk.

To better contextualize the risk levels identified (e.g., Category V for PVC indicating extreme danger, Category III for PET indicating minor risk), it is important to consider the broader regulatory landscape. While standardized international safety thresholds specifically for MP polymer hazards in seafood are still evolving and may not be universally established [76, 77], frameworks exist for assessing chemical contaminants and particulate matter in food [78, 79]. Regulatory bodies like the European Food Safety Authority (EFSA) and the World Health Organization (WHO) emphasize the potential risks associated with chemical migration from plastics and the presence of particulate matter, particularly at nano-scale [76, 80, 81]. Our classification of PVC as Category V (extreme hazard) aligns with concerns raised by such agencies regarding specific plastic-associated chemicals (e.g., phthalates, heavy metals) leaching from high-risk polymers [82,83]. Similarly, the lower risk category (III) assigned to PET reflects its generally recognized lower propensity for harmful chemical leaching under typical conditions [84, 85], though the physical impacts of particles remain a concern [86].

In this study, the CF values of the common fishes ranged from 1.0 to 2.57, suggesting that these fish organs were moderately contaminated (1 < CF < 3) by MP particles. Similarly, the PLI values of the fish samples were > 1, implying that the studied fishes were polluted due to the accumulation of plastic debris in their body parts. The overall findings revealed that the values of the contamination factor and pollutant load index were the following among the five species: L. japonicus ranked higher than C. alburnus, C. auratus, and H. leucisculus. It's also possible that the abundance is linked to population density, illegal waste dumping, economic growth, increased tourism, people's lifestyles, and resource use [87] which may contribute to the overall environmental burden of plastics.

CONCLUSION

Our study identified the presence of MPs in the gills and GIT of all 5 common fish species in Yuehai Lake, China. Most fish have more MPs in their GIT than in their gills. Fiber and fragment were most common in the gills and GIT, respectively. Over 80% of particles were small-sized MPs. Both the gills and GIT were affected by a variety of MP polymers, but some polymers were simultaneously explored in five common fish species, while there were also lower abundance of MPs that were only explored in one or a few fish species. Pollution risk assessment showed different fishes were exposed to varying degrees of harm and confirmed that Yuehai Lake does indeed have MP pollution. Future research directions could be the mechanism of MP intake by animals at high trophic levels, and exploring to what extent human health can be affected by the intake of MPs through fish.

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