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Microplastic contamination in commercial goldfish (*Carassius auratus*) of Yuehai Lake via Laser Direct Infrared Imaging (LDIR)

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ABSTRACT

Freshwater ecosystems are increasingly threatened by microplastic (MP) pollution, which can bioaccumulate in aquatic organisms and pose ecological and human health risks. However, information on MP contamination in freshwater lakes of inland northwest China remains scarce, particularly in locally consumed fish species. This study examined the occurrence, characteristics, and ecological risks of microplastics (MPs) in goldfish (Carassius auratus) from Yuehai Lake, Ningxia, China. Fifty goldfish were collected, and their gills, intestines, and liver were dissected and digested with nitric acid. MPs were extracted, purified, and identified using Laser Direct Infrared Imaging (LDIR) spectroscopy. MPs were detected in all tissues, with an average abundance of 43.2 ± 30.2 particles per individual. The gills exhibited the highest MP abundance, averaging 8.56 ± 3.78 particles per fish, followed by the intestines (2.64 ± 1.02 particles) and liver (1.76 ± 0.48 particles). Across all tissues, 22 MP polymer types were identified, with nine polymers—such as polyethylene (PE), polyethylene terephthalate (PET), and polyvinyl chloride (PVC)—present in all organs. MPs predominantly ranged from 20 to 100 µm, accounting for over 89% of MPs in all tissues. Fibers were the most prevalent morphology, comprising 61.69% in gills, 41.67% in intestines, and 68.29% in liver. Contamination factor (CF) values indicated moderate MP contamination in intestines (2.43) and liver (1.98), and considerable contamination in gills (4.72). Pollution load index (PLI) values exceeding 1 confirmed a general MP pollution burden in goldfish from Yuehai Lake. These findings provide critical baseline data for understanding MP contamination in inland freshwater environments and highlight the urgent need for targeted mitigation strategies.

Keywords: *Microplastics, Goldfish (Carassius auratus), Yuehai Lake, Laser direct infrared (LDIR), Risk assessment*

1. INTRODUCTION

The ecological risk and potential harm of MP pollution have attracted global attention. The concept of MP was first proposed in the study results published in Science [1]. The second United Nations Environment Conference in 2016 also listed plastic pollution as the second most important scientific issue in environmental and Ecological Sciences.

Plastics are widely employed and adaptable owing to their cost-effectiveness, ease of production, and lightweight characteristics. The prevalent presence of MPs in marine environments as emerging pollutants has received significant attention, extending to freshwater and terrestrial ecosystems [2]. Since 1950, plastic manufacturing has surged by 245%, producing 388 million tons of plastic materials [3]. In 2019, over 368 million tons of plastic were produced globally [4]. Schmidt et al. [5] estimated that rivers discharge 0.41 to 4.00 × 10^6 tons of plastic waste into the ocean every year.

Studies have identified six main types of MP polymers in the environment, namely polyethene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyester (PES), polystyrene (PS) and polyamide (PA) [6]. In addition, most MPs in the environment occur in the form of spheres, fibers, fragments, films, and granules [7]. The primary sources of MPs in aquatic environments originate from both terrestrial and aquatic activities. Plastic waste generated during daily activities on land constitutes the main source of MPs in water [8]. Additionally, MPs on land will settle into the water environment under the action of air after entering the atmosphere under the influence of wind, which is also a source of pollution. Aquaculture, ship transportation, and water tourism are the factors that contribute to the MPs' contamination of water supplies [9]. According to their sources, MPs can be categorised as primary and Primary MPs include plastic beads added to cosmetics, toothpaste, facial cleansers, and those generated during laundry. Studies showed that more than 300,000 MP particles can be added to one facial scrub cleanser [10]. Synthetic fabrics have the potential to release between 124 to 308 mg of microfibers per kilogram of fabric per wash, which equates to between 640,000 to 1,500,000 microfibers in each laundry cycle [11]. Secondary MPs are formed through environmental factors such as weathering, UV exposure, mechanical forces, and chemical degradation, which accelerate the breakdown of larger plastic items into smaller fragments [12]. This part of plastic waste is brought into the water environment through water tourism, fishing, and ship transportation [13]. Additionally, wear and tear of plastic products, disposal of plastic wastes, wastewater discharge, fishing gear (such as fishing nets) used in aquaculture, and plastic products (such as films) used in agricultural cultivation contribute to MP pollution. Therefore, many plastics in the environment have become a significant source of MP contamination [14].

MP pollution is no less harmful to the environment than considerable plastic pollution. It is estimated that in another 30 years, global plastic production will reach 25 billion tons, and the amount of plastic waste in the ocean may exceed the total amount of fish [15]. Plastic trash can be broken down into MPs via physical and biological disintegration in lakes. Studies showed that MPs can be ingested by bivalves, zooplankton, fish, shrimp, whales, and other species [16].

Human exposure to MPs can occur through the ingestion of fish. 1.79 million tons of fish were produced worldwide in 2018, with 0.82 million tons coming from aquaculture, or over half of the total produced [17]. Consuming fish that contain MPs exposes humans to dangerous chemicals at different trophic levels. Furthermore, fish that swallow MPs may be subjected to contaminants in their contaminated habitat, which can bioaccumulate and biomagnify [3].

MPs are more likely to enter the human body through the consumption of bivalves and small fish, as these organisms are often eaten whole, including their digestive tracts, which are frequently filled with MP particles. Pre-purification or boiling cannot eliminate MP particles [18-20]. Consequently, the risk of eating fish that contains MPs cannot be eliminated. It has been shown that MP particles can migrate from the gills to the liver and digestive system in juvenile and adult zebrafish (*Danio rerio*) [21]. The common goby (*Eucyclogobius newberryi sp.*) and European tongue bass have also been reported to transport MP particles within their bodies. They all show that MPs are not limited to aquatic animals but can also find their way into animal tissues that humans frequently eat. As a result, there may be a general risk to human health from MPs [22].

Laser Direct Infrared Imaging (LDIR) is a new infrared (IR) spectroscopy technique launched in 2018 that combines a tunable quantum cascade laser (QCL) as an IR light source with fast scanning optics [23]. In this study, LDIR was selected as the primary technique for MP analysis due to its advantages in speed, resolution, and automation. Compared to conventional methods such as visual microscopy and μ-FTIR, LDIR enables rapid, high-throughput scanning while providing accurate polymer identification through infrared spectral data [24]. Unlike Raman spectroscopy, LDIR is not subject to fluorescence interference or thermal damage, making it more reliable for analysing complex biological samples [25]. Additionally, unlike pyrolysis-GC-MS, which is destructive and lacks morphological context, LDIR allows for the simultaneous acquisition of both chemical composition and particle morphology [26]. These features make LDIR particularly suitable for comprehensive qualitative and quantitative MP analysis, aligning well with the analytical demands and sample characteristics of the present study. The use of LDIR in MPs has been investigated in various research, including in groundwater aquifers [27], urban rivers [28], coastal areas [29], atmospheric dust fall [30], agricultural soil [31], and fish gut tissue [32]. In this study, LDIR was used for qualitative and quantitative analysis of the distribution characteristics of MPs in different organs of the goldfish (Carassius auratus). In conclusion, LDIR is an effective tool for infrared spectroscopy and chemical imaging, offering significant advantages over conventional infrared imaging methods in terms of speed, resolution, and automation.

MPs have been observed to originate from food chain transfer in the omnivorous goldfish (*Carassius auratus*). In fish consumed by humans, MPs have been detected across a wide range of species inhabiting the Pacific, Atlantic, Indian, and Mediterranean oceans. Benthic species such as Pleuronectidae and Soleidae, migratory fish like *Thunnus orientalis* and *Dicentrarchus labrax*, as well as commercially important fish such as *Sardina pilchardus* and *Engraulis encrasicolus*, have all been reported to contain MPs [33].

Despite increasing research on MPs in marine environments, relatively little is known about their occurrence and distribution in freshwater lake ecosystems-particularly in inland regions such as Northwest China. Most studies have focused on marine species or large commercial fish, while data on MPs in freshwater omnivorous species like goldfish (*C. auratus*) remain scarce. Additionally, while studies have reported MPs in various fish organs, there is limited information on the organ-specific distribution, polymer composition, and risk levels of MPs in freshwater fish. This knowledge gap is critical, as lakes are important water sources for agriculture, aquaculture, and urban populations in China. Understanding the contamination levels of MPs in lake fish is necessary for evaluating their potential ecological and human health risks. To address these gaps, this study investigated MPs in *C. auratus* from Yuehai Lake, a typical semi-urban lake in Northwest China. The specific objectives are to:

(1) Assess the occurrence and abundance of MPs in goldfish;
(2) Characterise the shape, size, and polymer types of MPs in different goldfish organs;
(3) Evaluate the potential ecological risk posed by MPs to freshwater biota.

Furthermore, this study applies LDIR, a novel, rapid, and precise method for MP analysis, offering advantages over traditional spectroscopic approaches [27-32]. The integration of LDIR technology with freshwater ecological risk assessment makes this study both methodologically innovative and environmentally significant.

2. METHODOLOGY

2.1. Study Site

Yuehai Lake is an artificial lake with over 2667 hectares, a section of the Yellow River system, located in Yinchuan City, Ningxia, northwest China. It was selected as the study site (Figure 1). The lake was created through ecological restoration and water system connectivity projects to protect wetland ecology and promote tourism. Activities around Yuehai Lake include fishing, bird watching, ecological sightseeing tours, and snow and ice recreation programs, enhancing its attractiveness as a leisure destination. 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 [34].

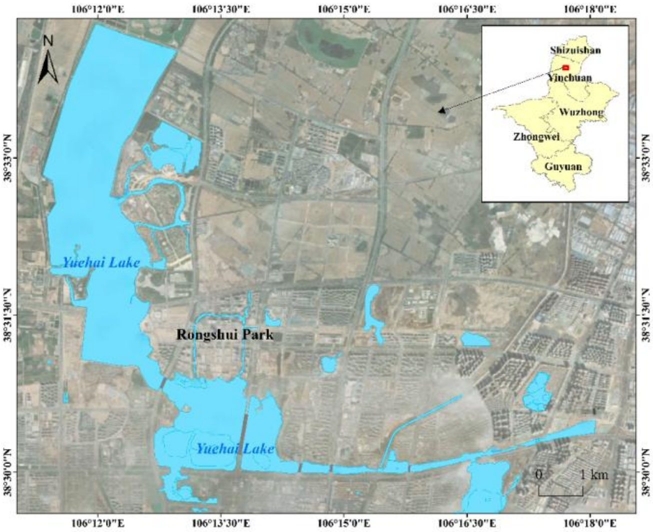


Figure 1. The map of study site

2.2. Sample collection

In July 2023, a total of 50 specimens of goldfish (*C. auratus*) were obtained from local fishermen actively fishing along the shoreline of Yuehai Lake, Ningxia, China. Only visibly healthy adult individuals with body lengths between 13 and 15 cm were selected to ensure consistency and biological relevance of the samples. Fish were collected from multiple fishing spots around the lake to enhance spatial representativeness. Immediately after collection, the specimens were transported on ice to the laboratory. On the same day, all fish were dissected under sterile conditions. The gills, intestines, and livers were carefully removed using stainless steel instruments and stored individually in clean, labelled glass containers for further MP analysis.

2.3. Microplastic extraction

After dissection, the gills, intestines, and liver were carefully separated using sterilised stainless-steel scissors and tweezers. Each organ was rinsed with pre-filtered ultrapure water (0.22 µm) to remove external debris. Samples were transferred to acid-cleaned glass beakers, oven-dried at 60 °C for 18 hours, and then subjected to chemical digestion with 10 mL of 68% nitric acid (HNO_3) at room temperature for 42 hours [35]. The digestion process was conducted in a fume hood with closed lids to minimise airborne contamination. The experimental procedure is shown in Figure 2.

Post-digestion, vacuum filtration was performed using stainless steel filter membranes (13 µm pore size, Whatman). The filters were thoroughly rinsed with pre-filtered ultrapure water and 70% ethanol. Each membrane was placed in ethanol and ultrasonicated at 40 kHz for 20 minutes to detach particles. The ethanol solution was concentrated to 150 µL in a drying oven and drop-cast onto a high-reflectivity infrared substrate for subsequent LDIR analysis.

To prevent contamination, all equipment and containers were rinsed three times with ultrapure water before use. Laboratory surfaces were cleaned with ethanol, and all procedures were conducted in a laminar flow cabinet when possible. Cotton laboratory coats and nitrile gloves were worn throughout the process. Blank controls (including filtered ultrapure water and ethanol blanks) were processed alongside actual samples to monitor background contamination. No MPs were detected in the blanks.

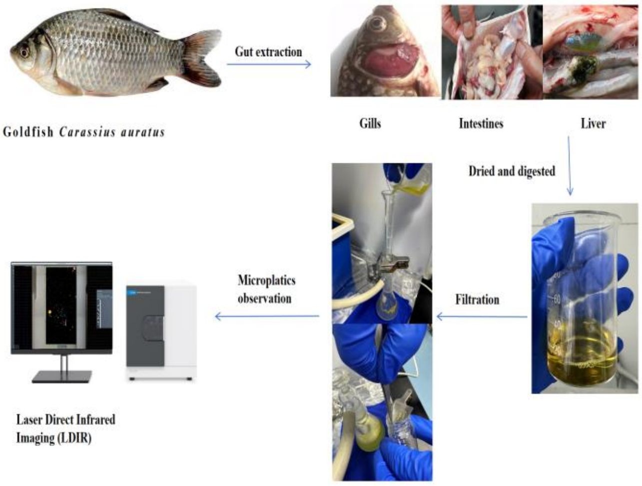


Figure 2. The flowchart of the experiment process

2.4. Microplastic identification

An LD-IR imaging spectrometer (8700 LD-IR, Agilent Technologies, Inc., USA) was used to quantify and characterise the MPs, and a particle analysis mode was selected, with the LD-IR focusing on each particle with a wave number in the range of 20-500 µm. LD-IR targets individual particles while in particle analysis mode of 300–400 particles per hour. All collected particle spectra were matched to a library of reference spectra to identify the polymer. Particles were accepted for MPs when the quality index was 75 % [36] using Fourier Transform Infrared Spectroscopy (FT-IR); current research recommended that the matching quality index acquired via LDIR to be higher than 65% is acceptable for MPs [37,38]. Based on previous studies, in order to increase the data quality, this study uses an 80% quality index to match a specific MP polymer.

The observed MPs were categorised into four groups: fiber, bead, granule, and fragment. Scircle et al. [23] reported the determination of the 3 shapes of fragment, bead, and fiber. A roundness larger than 0.6 is regarded as excessive roundness [39]. As a result, the circularity of the granule's shape was determined to be between 0.6 and 0.9. The four shapes are often defined as follows: MPs with an aspect ratio (width/height) of three or more are classified as fibers, MPs with circularity > 0.9 are beads, MPs with circularity between 0.6 and 0.9 are granules, and the remaining MPs are classified as fragments.

2.5. Contamination and health hazard assessment of plastic particles in fish

The contamination factor (CF) and pollutant load index (PLI) are commonly used to evaluate ecological risk in previous studies [40].The CF calculation formula is as Eq. (1) follows:

$$CF_i = \frac{C_i}{C_o} \tag{1}$$

Here, CF_i is the quotient of the concentration (C_i) of identified plastic particles for each fish species and the minimum concentration of plastic particles (C_0). 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, as Table 1 [41].

Table 1. Contamination degree of CF

CF Values	Contamination degree
<1	Low
1-3	Moderate
3-6	Considerable
>6	Very high

PLI is an approach that considers a variety of contaminants to determine the total amount of pollution present in a specific site or area [42]. This is determined by applying the Eq. (2):

$$PLI = \sqrt[n]{CF_1 \times CF_2 \times CF_3 \ldots \times CF_n} \tag{2}$$

where CF_1, CF_2, ..., CF_n 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 [43]. The PLI values correspond to different hazard and risk categories, as shown in Table 2.

Table 2. Risk level criteria for MPs pollution

PLI Values	Hazard category	Risk category
<10	I	Minor
10-20	II	High
20-30	III	Danger
>30	IV	Extreme danger

Polymer hazard index (PHI) is used to assess the potential risk of specific MP polymer to humans. The Eq. (3) was used to calculate the polymer hazard index:

$$PHI = \sum P_n \times S_n \tag{3}$$

where P_n is the percentage of specific plastic polymers and S_n is the hazard score of plastic polymers [44-46].

2.6. Quality assurance and quality control (QA/QC)

Plastic-free procedures are strictly followed throughout sample collection, storage, handling, and analysis to ensure data reliability and minimize the possibility of external contamination. Specifically, all laboratory consumables were glass, lubricated three times with ethanol, and dried before use [30]. Additional precautions were taken during sample handling and analysis, including nitrile gloves, cotton lab coats, surgical masks, and head covers to prevent contact with plastic items in the operating room.

2.7. Statistical analysis

Data on plastic abundance and characteristics were collected from individual goldfish (C. *auratus*). Samples were grouped by organ type, which was used as a fixed factor in a factorial analysis of variance (ANOVA) to compare differences among organs. Before analysis, normality and homogeneity of variance assumptions were evaluated using the Shapiro-Wilk and Levene’s tests, respectively. When ANOVA indicated significant differences ($p < 0.05$), post hoc multiple comparisons were performed using Tukey’s HSD test. Statistical analyses were conducted using Microsoft Excel 2019 and Origin 8.0.

3. RESULTS AND DISCUSSION

3.1. Abundance of MPs

All 50 goldfish (*C. auratus*) specimens analyzed contained MPs, with an average abundance of 12.96 ± 6.98 MPs per individual, as illustrated in Figure 3. The total MP counts in the gill, intestine, and liver tissues were 428, 132, and 88 particles, respectively. The fish had an average body length of 12.3 ± 0.5 cm and a mean body mass of 179.3 ± 14.1 g. One-way ANOVA revealed a significant difference in MP abundance across the three tissues ($F = 71.06$, $p \leq 0.001$), with gills exhibiting the highest MP load. Furthermore, the MP quantity in fish tissues was strongly positively correlated with body weight ($r = 0.935$, $p < 0.001$), gill weight (r = 0.892, p < 0.01), intestine weight (r = 0.819, p < 0.01), and liver weight (r = 0.751, p < 0.01), indicating that larger fish accumulate more MPs in these organs.

These findings align with previous studies. For instance, Hossain et al. [47] reported that Scomberomorus guttatus exhibited elevated MP concentrations in gills and digestive tracts, averaging 48.7 MPs per individual, corroborating the trend of increased MP burden in larger fish. Similarly, Eberemu et al. [48] documented the presence of MPs in the gills, liver, and kidneys of Nile Tilapia, alongside varying histopathological effects, suggesting that increased size may elevate susceptibility to MP accumulation.

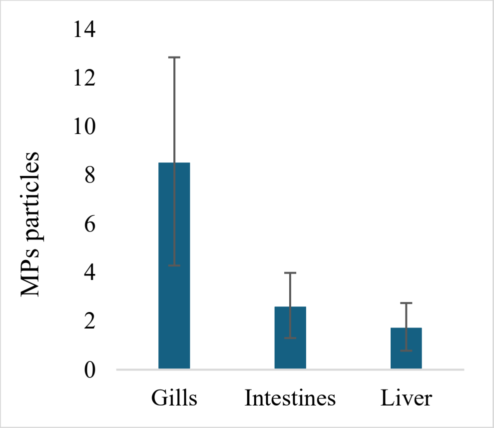


Figure 3. The average abundance of MP in different fish tissues

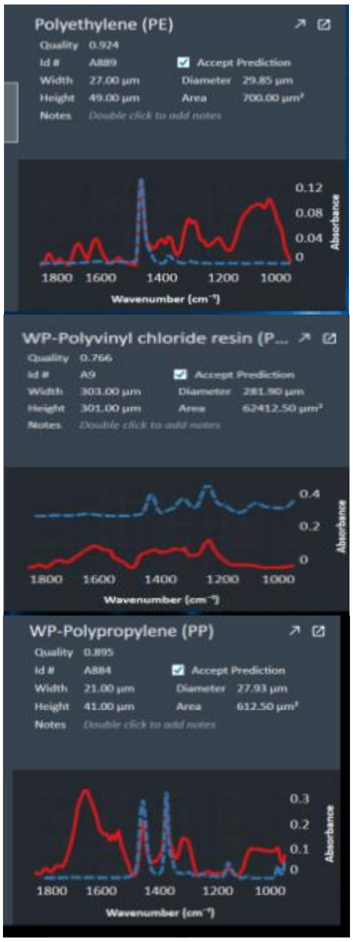
Interestingly, a significant negative correlation was observed between total MP count per individual and body length (r = -0.393, p = 0.0045), indicating that smaller fish tend to harbour fewer MPs. This observation supports Parolini and Romano's [49] conclusion that MP ingestion increases with fish growth, likely due to enhanced feeding activity and habitat exposure.

The predominance of MPs in gill tissue highlights its role as a primary site for MP retention. This enrichment is plausibly explained by the goldfish's respiratory mechanism, wherein water is filtered across the gills to extract dissolved oxygen, allowing MPs suspended in water to be trapped and accumulate in the gill structures. Comparable patterns have been documented in other species; for example, Hossain et al. [47] found an average of 2.56 ± 0.73 MP items per gram of gill tissue in *Scomberomorus guttatus*, markedly higher than the 0.84 ± 0.45 items per gram detected in their digestive tracts. Similarly, Awaluddin et al. [50] observed 9.47 to 13.62 particles per individual in the gills of Rastrelliger species, compared to 8.07 to 12.87 particles per individual in their digestive tracts.

These variations in MP ingestion and tissue distribution have been linked to diverse ecological factors, including fish-feeding strategies [51], vertical habitat distribution [52], and proximity to urban or industrial pollution sources [53]. Together, these results underscore the complex interplay of biological and environmental factors driving MP bioaccumulation in fish.

3.2. Chemical component of MPs

LDIR chemical imaging analysis was employed to identify and characterise MP particles in goldfish (*C. auratus*), providing both absorbance spectra and representative microscopic images of polymers such as polyethylene (PE), polyvinyl chloride (PVC), and polypropylene (PP) (Figure 4). The full list of MP polymers identified via LDIR is summarised in Table 3, detailing their chemical composition and spatial distribution across different tissues.



Polyethylene (PE)
Quality 0.924
Id # A889 ☑ Accept Prediction
Width 27.00 µm Diameter 29.85 µm
Height 49.00 µm Area 700.00 µm²
Notes *Double click to add notes*

WP-Polyvinyl chloride resin (P...
Quality 0.766
Id # A9 ☑ Accept Prediction
Width 303.00 µm Diameter 281.90 µm
Height 301.00 µm Area 62412.50 µm²
Notes *Double click to add notes*

WP-Polypropylene (PP)
Quality 0.895
Id # A884 ☑ Accept Prediction
Width 21.00 µm Diameter 27.93 µm
Height 41.00 µm Area 612.50 µm²
Notes *Double click to add notes*

Figure 4. Representative infrared spectrogram of MPs detected by LDIR

A total of 22 distinct MP polymer types were identified across the gills, intestines, and liver of the specimens. The gill tissues exhibited the highest polymeric diversity, containing 17 different MP types, followed by the intestine (15 types) and liver (14 types). Nine polymers—PE, polyethylene terephthalate (PET), PVC, polyurethane (PU), butadiene rubber (BR), chlorinated polyethylene (CPE), ethylene-vinyl acetate copolymer (EVA), fluoroelastomer (FKM), and fluoro-silicone rubber—were consistently detected in all three tissue types. Tissue-specific MPs included polymethylmethacrylate (PMMA), PP, and polystyrene (PS) in the gills; polycarbonate (PC) and styrene-isoprene-styrene (SIS) in the intestine; and polyvinyl butyral (PVB) and phenolic epoxy resin (EPN) in the liver.

Table 3. Proportion of different types of MPs in *C. auratus.*

MPs	Gills	Intestines	Liver	Average
EVA	3.73%	1.04%	2.44%	2.40%
PE	1.49%	1.04%	1.22%	1.25%
PET	17.91%	1.04%	4.88%	7.94%
PU	2.99%	6.25%	13.41%	7.55%
PVC	13.43%	5.21%	14.63%	11.09%
BR	3.73%	8.33%	1.22%	4.43%
CPE	13.43%	51.04%	2.44%	22.30%
FKM	16.42%	9.38%	43.90%	23.23%
FVMQ	2.24%	8.33%	4.88%	5.15%
SBS	2.99%	1.04%	/	1.34%
ACR	10.45%	1.04%	/	3.83%
ABS	1.49%	3.13%	/	1.54%
PTFE	1.49%	/	4.88%	2.12%
PF	0.75%	/	2.44%	1.06%
PLA	/	1.04%	1.22%	0.75%
PMMA	0.75%	/	/	0.25%
PP	5.97%	/	/	1.99%
PS	0.75%	/	/	0.25%
SIS	/	1.04%	/	0.35%
PC	/	1.04%	/	0.35%
PVB	/	/	1.22%	0.41%
EPN	/	/	1.22%	0.41%

■ >20%
■ 15-20%
■ 10-15%
■ 5-10%
□ 0-5%

In terms of abundance, the gill tissue showed a diverse composition with polymer concentrations ranging from 0.75% to 17.91%, and five polymers exceeded 10%. PET was the most abundant (17.91%), followed by PVC and CPE, each at 13.43%. Similar patterns of high PET and PVC concentrations in fish gill tissues have been reported in previous studies. For example, Pradit et al. (2023) found that PET was the dominant polymer in the gills of Catfish, likely due to its widespread use in consumer products and high environmental persistence.

In the intestines, MP polymer proportions ranged from 1.04% to 51.04%. CPE accounted for over half of the MP load, indicating substantial bioaccumulation through trophic transfer, particularly in contaminated aquatic environments. This is consistent with the findings of Gurjar et al. [54], who reported that MP ingestion by fish may vary depending on the pollutant profile of their habitat and the physicochemical properties of specific polymers. The extended retention time of compounds like CPE in the intestinal tract—due to the mucosal structure and peristaltic dynamics—may also enhance accumulation [55]. Other polymers in the intestine, such as FKM and SBS, were present at lower levels (<10%), with most being rubber-based, suggesting probable sources from urban and road runoff.

In the liver, 14 MP polymers were detected, with concentrations ranging from 1.22% to 43.90%. FKM was again the dominant polymer (43.90%), followed by PVC (14.63%) and PU (13.41%). These results mirror those of Liu et al. [56], who observed high liver concentrations of PVC and PU in fish from highly industrialized river systems in China, indicating hepatic retention and possible hepatotoxicity due to persistent polymer exposure.

Overall, several MP types—including FKM, PVC, and PU—were consistently found in high abundance across all tissue types. This suggests their environmental ubiquity and strong potential for bioaccumulation, irrespective of tissue type. These findings underscore the importance of tissue-specific analyses and align with broader trends documented in both freshwater and marine environments [57].

3.3. Dimension of MPs

LDIR analysis revealed that MPs detected in the tissues of goldfish (*C. auratus*) ranged in size from 20.34 μm to a maximum of 216.09 μm. Specifically, the largest particles were found in the gills (216.09 μm), followed by the intestines (196.29 μm) and liver (183.95 μm), while no particles exceeding 220 μm were observed. To characterise the distribution of MP particle sizes within the goldfish, MPs were categorised into two size classes: 20–100 μm and >100 μm as shown in Figure 5. Most MPs fell into the smaller size range, accounting for 91.04% in the gills, 92.71% in the intestines, and 89.02% in the liver, indicating that approximately 90% of all detected MPs were less than 100 μm in size. MPs within this smaller size category are considered particularly concerning due to their enhanced bioavailability and potential for cellular penetration.

In terms of polymeric composition, MPs larger than 100 μm in the gills included a diverse array of synthetic polymers such as CPE, PTFE, PVC, PET, ACR, PP, PE, EVA, and fluoroelastomers. The intestines contained CPE and FKM, along with BR and PLA. In contrast, PVC and BR were absent in the liver, but PU, PVB, and fluorosilicone rubber were identified. This diversity of polymer types and their varying physicochemical properties underscore the complexity of MP contamination and its implications for aquatic toxicology.

The predominance of small-sized MPs within goldfish tissues likely reflects ongoing environmental fragmentation processes. MPs are known to undergo progressive size reduction through prolonged exposure to ultraviolet (UV) radiation, mechanical abrasion, weathering, and microbial degradation, eventually reaching the nanoscale. At this stage, their toxicity increases markedly due to enhanced surface area and reactivity, facilitating cellular uptake and systemic exposure [58]. These findings are consistent with global observations. For instance, in Korea's Gyeonganchon Stream, MPs in fish predominantly measured 45–100 µm, with additional particles ranging from 20–45 µm and 100–300 µm [58]. In Russia's Ob and Yenisei Rivers, fish gastrointestinal tracts (GITs) contained MPs ranging from 0.15 mm to 5.00 mm [59]. Similarly, in Indonesia's Kahayan River, most MPs in fish were sized between 150–300 µm [60]. In Bac Ninh Province, Vietnam, fish exhibited a notably larger median MP size ranging from 1410 to 2706 µm [61]. Meanwhile, at Malaysia's Tawar Air Coast, MPs found in fish ranged from as small as 8.12 µm to 174.56 µm [62]. Collectively, these studies reflect a wide variability in MP size distributions across geographic regions and aquatic environments, influenced by local hydrodynamics, plastic degradation states, and exposure pathways.

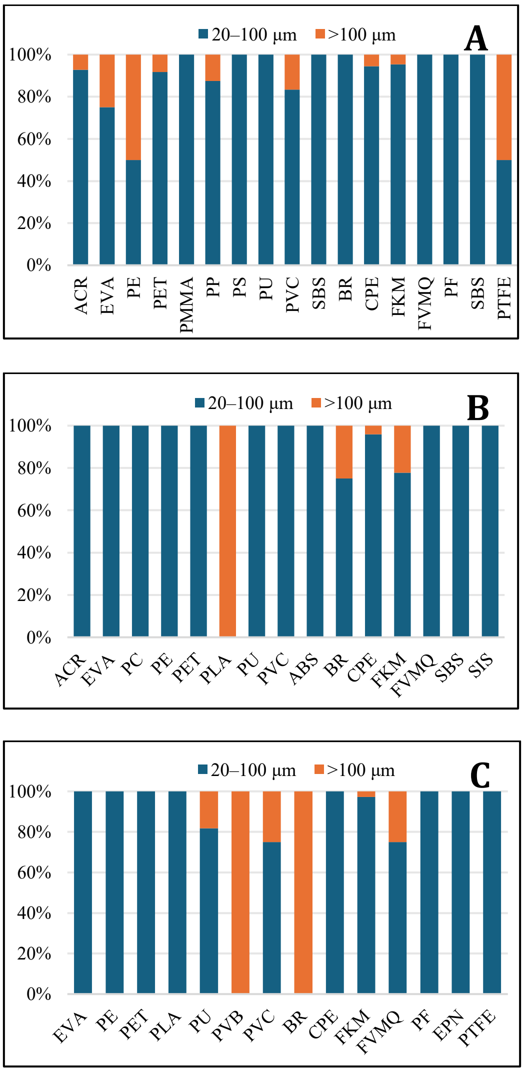


Figure 5. Proportion of MPs in the two particle size ranges (20–100, >100 µm). (A) in the gills, (B)in the intestines and (C) in the liver

3.4. Morphology of MPs

Four distinct morphologies of MPs—fibers, fragments, granules, and beads—were identified in the tissues of goldfish (*C. auratus*). All four shapes were detected in the gills and intestines; however, only three forms (fibers, granules, and fragments) were found in the liver, with no beads observed in this organ. As illustrated in Figure 6, fibers were the dominant shape in the gills, accounting for 61.69% of total MPs, followed by fragments (35.82%), granules (2.02%), and beads (0.26%). In the intestines, fragments were most abundant (52.08%), followed by fibers (41.67%), granules (5.21%), and beads (1.04%). The liver displayed a different pattern, with fibers comprising the majority (68.29%), followed by fragments (29.27%) and granules (2.44%).

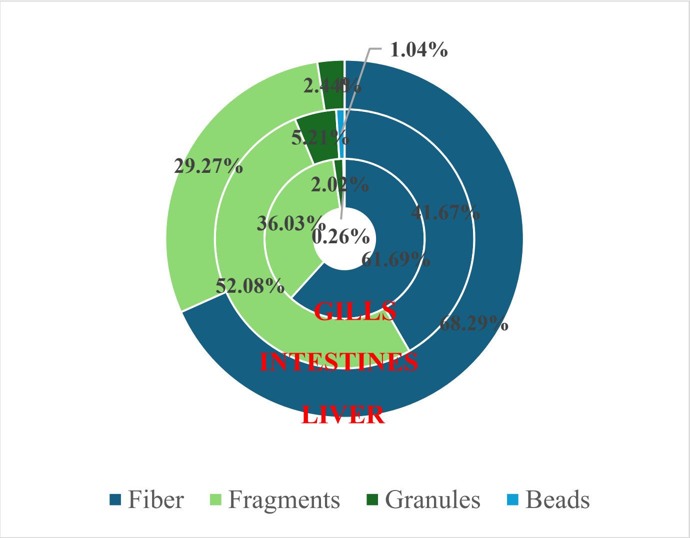


Figure 6. The proportion of different shapes in 3 parts of the goldfish *(C. auratus)*

In terms of size distribution, fiber-shaped MPs ranged from 24 to 65 µm in the gills, 20 to 197 µm in the intestines, and 21 to 28 µm in the liver. Granule-shaped MPs exhibited a broader size range: 20–125 µm in the gills, 20–115 µm in the intestines, and 21–119 µm in the liver. Fragment-shaped MPs showed the widest distribution, ranging from 22 to 220 µm in the gills, 21 to 181 µm in the intestines, and 20 to 184 µm in the liver.

Fibers emerged as the most prevalent MP type across the surrounding aquatic environment, likely reflecting local anthropogenic influences. The intensive tourism activities in the study area are presumed to be a major source of fiber-shaped MPs, as plastics associated with tourism, along with fishing gear and packaging materials used by local fishermen, undergo degradation and fragmentation, contributing to environmental MP loads. This observation aligns with findings from other aquatic systems. For instance, Rasta et al. [63] reported that 74.68% of MPs isolated from fish in the Caspian Sea were fibers. Similarly, in Alvarado Lagoon, fibers constituted 97.53% of all detected MPs [64]. In the Black Sea, Atamanalp et al. [65] found that fibers accounted for 51% of MPs in fish tissues. The ubiquity of fiber-shaped MPs is often attributed to their extensive use in textiles and industrial applications. These fibers are readily transported into aquatic ecosystems through domestic and industrial wastewater discharges, as well as surface runoff [66].

3.5. Pollution risk assessment

In this study, CPE was identified as the dominant MP polymer in goldfish (*C. auratus*). However, due to the absence of an established polymer hazard index (PHI) for CPE, its potential ecological and toxicological risks remain difficult to quantify. In contrast, PVC which was detected in lower abundance, is considered highly hazardous, with a reported polymer hazard score of 10,001, posing substantial threats to human and environmental health through the release of toxic additives such as phthalates and heavy metal stabilisers during degradation.

Contamination factor (CF) analysis revealed that MP levels in the intestine (CF = 2.43) and liver (CF = 1.98) were classified as moderate ($1 < CF < 3$), whereas the gills showed considerable contamination (CF = 4.72). Furthermore, the pollution load index (PLI) exceeded 1 in all examined tissues, confirming that goldfish individuals were contaminated by MPs, with the severity ranked as: gill > intestine > liver.

Beyond the numerical assessments, the biological implications of MP exposure in fish are of critical concern. In the gills, MPs may cause physical abrasion, excessive mucus production, and chronic inflammation, ultimately impairing respiratory efficiency and ion regulation [67]. In the digestive tract, ingested MPs can disrupt nutrient absorption, induce gut microbiota dysbiosis, and trigger inflammatory responses [68]. Once translocated to the liver, MPs may stimulate oxidative stress, mitochondrial dysfunction, and altered detoxification pathways [69]. Furthermore, MPs can act as vectors for persistent organic pollutants (POPs) and pathogenic microorganisms, compounding their toxicity.

From an ecological perspective, MP accumulation in vital fish organs may impair growth, reproduction, and overall fitness, potentially altering population dynamics and food web interactions [70]. Given that goldfish occupy an intermediate trophic level, the bioaccumulation of MPs poses a threat not only to aquatic ecosystems but also to higher trophic organisms, including humans [71]. As such, the presence of MPs in goldfish reinforces their utility as bioindicators for freshwater MP pollution and highlights the urgent need for comprehensive risk management strategies.

4. CONCLUSION

MPs have become a pervasive pollutant in aquatic ecosystems, attracting growing scientific attention due to their widespread occurrence and potential ecological and health impacts. This study investigated the presence, characteristics, and potential risks of MPs in goldfish (*C. auratus*), a commonly consumed freshwater species, collected from Yuehai Lake—an important inland aquatic resource in southern China. Our results confirmed the ubiquity of MPs, with all examined organs—gills, intestines, and liver—containing MP particles. Among these, the gills exhibited the highest MP abundance and diversity, followed by the intestines and liver. MPs were detected in various shapes and sizes, with the majority falling within the 20–100 μm range, indicating a dominance of small-sized particles. Fiber was the most prevalent morphotype, consistent with findings from other freshwater ecosystems. The detected MPs originated from diverse polymer types, some of which are known to release hazardous additives or act as vectors for other contaminants, thereby posing complex toxicological risks. The ingestion of MPs by *C. auratus* is likely linked to anthropogenic activities such as tourism, plastic waste disposal, and fishing practices around Yuehai Lake. Once ingested, MPs may cause physical damage to internal organs, interfere with nutrient absorption, or induce oxidative stress. More concerningly, these particles can transfer up the food chain. Given the popularity of *C. auratus* as a food source, human exposure through dietary intake becomes a tangible risk.

To evaluate ecological and health risks, we applied CF, PLI, and PHI. The CF values indicated moderate to high MP contamination, especially in gill tissues. PLI values > 1 further supported the conclusion that goldfish in Yuehai Lake are polluted by MPs. Moreover, PHI scores varied across polymer types, reinforcing that not all MPs pose equal risks—PVC, for instance, has an exceptionally high hazard ranking. This study contributes novel insights into the presence and impact of MPs in inland lake ecosystems, particularly concerning a commercially and ecologically significant fish species. It fills a critical knowledge gap by providing baseline data for future monitoring, risk assessments, and mitigation efforts. If unaddressed, the continued presence and accumulation of MPs threaten to disrupt trophic structures, cause hazardous bioaccumulation, and potentially lead to biodiversity loss in freshwater environments.

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