Italian Journal of Food Science, 2024; 36 (3): 40–49

Evidence of microplastic contamination in the food chain: an assessment of their presence in the gastrointestinal tract of native fish

Mehran Hayat[1], Bushra Khan[1]*, Javaid Iqbal[2], Muhammad Nauman Ahmad[3], Ayaz Ali Khan[4], Taqweem-ul Haq[4], Tariq Aziz[5]*, Thamer H. Albekairi[6]

[1]Department of Environmental Sciences, University of Peshawar, Khyber Pakhtunkhwa, Pakistan; [2]Department of Environmental Sciences, University of Lakki Marwat, Khyber Pakhtunkhwa, Pakistan; [3]Department of Agricultural Chemistry & Biochemistry, University of Agriculture, Peshawar, Pakistan; [4]Department of Biotechnology University of Malakand Chakdara Dir Lower Pakistan; [5]Laboratory of Animal Health Food Hygiene and Quality, University of Iaoninna Arta, Ioannina, Greece; [6]Department of Pharmacology and Toxicology College of Pharmacy King Saud University Riyadh Saudi Arabia

***Corresponding Authors:** Bushra Khan, Department of Environmental Sciences, University of Peshawar, 25120, Khyber Pakhtunkhwa, Pakistan. Email: bushraasu@uop.edu.pk; Tariq Aziz, Laboratory of Animal Health Food Hygiene and Quality, University of Iaoninna Arta, 47132, Ioannina Greece. Email: tariqckd@uoi.gr

Received: 31 January 2024; Accepted: 25 May 2024; Published: 1 July 2024

ORIGINAL ARTICLE

Abstract

This research study focused on the primary freshwater surface sources of Khyber Pakhtunkhwa (KP) province, Pakistan—Swat and Kabul rivers. The study aimed to assess microplastic (MP) contamination of fish in the Swat and Kabul rivers. Understanding this contamination is vital for evaluating the environmental and health risks associated with consuming contaminated fish and contributing to the ongoing conservation efforts. The study's objective was to investigate the presence of MPs in the gastrointestinal tracts (GIT) of fish and to delineate the identified MP types. Samples of local dominant fish (*Schizothorax plagiostomus* [Swatay] and *Racoma labiata* [Chunr], *Cyprinus carpio* [Common Carp], and *Clupisoma naziri* [Sher Mayai]) were collected, and their body weight and length assessed to gauge the overall health. The GIT samples were processed, digested and filtered before microscopic examination to detect MPs. Subsequently, the identified MPs were subjected to attenuated total reflectance–Fourier transform infrared spectroscopy for characterization by analyzing their absorption bands. Results of the study showed the presence of MPs in fish samples, predominantly identified as polyethylene (PE), with polypropylene (PP) being the subsequently prevalent plastic type, which manifested fish contamination with MPs. The study revealed MP pollution in both Swat and Kabul rivers, with fish ingesting these particles. This poses potential health risks for fish and health of the ecosystem.

Keywords: bioaccumulation; ecosystem health; ingestion; pollution; rivers Swat and Kabul

Introduction

Globally, the production of plastic is increasing rapidly due to its low production cost. In 2018, the total production of plastics reached 359 million tons (Plastics Europe, 2019). While plastic brings tremendous comfort to our daily lives, its high production and usage rates have accumulated vast amounts of plastic waste. It is estimated that around 4,900 million tons of plastic waste has accumulated in the environment, and by the

ISSN 1120-1770 online, DOI 10.15586/ijfs.v36i3.2532

year 2050, approximately 12,000 metric tons of plastic is predicted to end up in landfills and various compartments of the environment (Geyer *et al.*, 2017). It was also estimated that 12.2 million tons of plastic enter the ocean annually (Jambeck *et al.*, 2015) through various pathways. Large-size plastic waste that poses an ecological problem breaks down into smaller particles over time (Napper and Thompson, 2019). Although no plastics biodegrade significantly, environmental factors, such as sunlight, weaken the materials, causing them to break into fragments of millimeter to micrometer in size (Andrady, 2015). Microplastics (MPs) are found in abundance among these small-sized particles (Arthur *et al.*, 2009). MPs originate from primary and secondary sources. Primary MPs are produced industrially for specific domestic and industrial uses, such as cosmetics and the plastic industry, while secondary MPs result from the disintegration of large plastics because of biological and physiochemical breakdown. MPs undergo various physiochemical and biological weathering processes in the environment (Jahnke *et al.*, 2017).

Microplastics are present in different parts of the environment, such as air, water, and soil (World Health Organization [WHO], 2019; Yu *et al.*, 2024; Abassi *et al.*, 2024; Naveed *et al.*, 2023a; Naveed *et al.*, 2023b; Zameer *et al.*, 2023). The substantial quantity of MPs poses an ecological risk, leading to food contamination and affecting human health (Barboza *et al.*, 2018). In 2014, marine ecologist Richard Thompson reported the distribution of MPs in oceans for the first time (Law and Thompson, 2014). Several studies have also reported the presence of MPs in commercially caught marine fish species (Bellas *et al.*, 2016; Rochman *et al.*, 2015), indicating high exposure to MPs contamination in fish populations. In the North Pacific Central Gyres, a study confirmed the presence of MPs in the gut samples of planktivorous fish (Boerger *et al.*, 2010). Furthermore, MPs have recently been detected in human blood samples, entering the body via contaminated food or water (Leslie *et al.*, 2022). Recent studies have focused on the occurrence and distribution of MPs in freshwater and terrestrial ecosystems (Rochman, 2018). Studies on freshwater fish contamination have shown the presence of MPs in the gastrointestinal tracts (GIT) of fish, confirming their presence in freshwater (Sanchez *et al.*, 2014). Globally, MPs have developed a great interest because they entered into food chains and potential health risks, such as toxicity (Khan *et al.*, 2023; Akram *et al.*, 2023; Xiong *et al.*, 2022). This study aimed to assess the occurrence, distribution, types, and abundance of MPs in the GIT of fish in both Swat and Kabul rivers. Fish is collected for locally consumption from both rivers; however, fishing is mainly carried out for recreational purpose and a very small amount for commercial purposes. Sampling locations were selected under waste ingress locations and potential fish capture sites.

Materials and Methods

Study area

The study focused on the primary freshwater surface water sources of Khyber Pakhtunkhwa (KP) province in Pakistan, specifically Swat and Kabul rivers. In all, 61 fish samples were collected from these rivers. Fish samples were collected randomly from different locations, selected based on major waste drain entry points, mixing zones, and potential fish capture sites at Swat and Kabul rivers. Upstream locations were chosen, with Madyan/Behrain on Swat river and Warsak Dam on Kabul river identified as upstream sites. In total, samples were collected from 10 locations mentioned in Table 1 at both rivers, namely Madyan/Behrain (MS), Khwaza Khela Swat (KKS), Barikot Swat (BS), Landakay Swat (LS), Takhtaband/SherAbad Swat (TS), Chakadara bridge (CS), Warsak Dam (WK), Charsadda bridge (CK), Pir Sabaq (PK), and Khair Abad (KS). The map along with GPS locations of the sampling sites are shown in Figure 1.

Fish samplings and preservation

At each sampling site, we collected native fish species demonstrating local dominance. The following fish species were collected from Swat river: *Schizothorax plagiostomus* (commonly known as Swatay) and *Racoma labiata* (referred to as Chunr). The prevalent native species in Kabul river comprised *Cyprinus carpio* (commonly known as Common Carp) and *Clupisoma naziri* (also known as Sher Mayai). The collection of these dominant native fish species from both Swat and Kabul rivers involved the use of fishing rods, fishhooks, and nets.

Within 1 h of capture, the fish samples were wrapped in aluminum foils and stored at low temperatures. To ensure proper identification and record-keeping, zip-lock polythene bags were utilized to encase fish samples, with labels indicating the sampling location, date, and specific species. The specimens were promptly dissected on the day of collection to excise carefully the GIT. Subsequently, materials in the gut were meticulously preserved in containers containing a prepared solution of Potassium Hydroxide (KOH), optimized for digestion purposes (Wang *et al.*, 2021). Deionized water was used for cleaning instruments and preparing KOH solution. Additionally, all solutions, including the KOH solution, were filtered through glass microfiber filters to prevent external contamination.

Length and weight measurements

Following collection, the fish were weighed to the nearest 0.01 g using a digital balance and measured for total

Table 1. Sampling locations on Swat and Kabul rivers.

	Location	Abbreviation	GPS coordinates	No. of samples
Swat river				
1.	Bahrain Swat	MS	N 72.57335 E 35.23086	2
2.	Khwaza Khela Swat	KKS	N 72.45113 E 34.94386	1
3.	Barikot Swat	BS	N 72.30893 E 34.78667	12
4.	Landakay (Shamazo bridge)	LS	N 72.21085 E 34.68334	25
5.	(Sher Abad) Takhtaband Swat	TS	N 72.12792 E 34.66443	5
6.	Chakdara bridge	CS	N 72.02912 E 34.64410	5
Kabul river				
7.	Warsak Kabul	WK	N 71.40807 E 34.17423	2
8.	Charsadda moterway bridge	CK	N 71.73481 E 34.09274	3
9.	Pir Sabaq	PK	N 72.04987 E 34.01117	4
10.	Khairabad bridge	KS	N 72.21676 E 33.965344	2
	Total			**61**

The sampling took place in distinct rounds in July 2022 and February 2023. Fish were caught using nets, and detailed data concerning their species, weight, and length were meticulously recorded after being caught using balance and a ruler.

length to the nearest 0.01 cm using a measuring tape. Fulton's condition factor (K) was calculated using the following equation:

$$K = \frac{\text{Total body weight (g)}}{\text{Total length (mm)}^3}$$

Dissection

Fish samples were dissected using a razor blade or a pair of sharp scissors, along with forceps, ensuring that all tools were washed with deionized water and air-dried to prevent any contamination. The dissection of fish samples to collect the GIT followed a methodology described in previous studies (Lusher *et al.*, 2013; Xu *et al.*, 2024a). Contents of the GIT were collected in a glass jar/container.

Digestion

In order to isolate MPs from the GIT, it is essential to digest organic matter. However, the use of strong oxidizing agents, particularly at increased temperatures, can potentially damage or degrade synthetic polymers (Welden and Lusher, 2017). Recent studies on GIT digestion have suggested that KOH is the most suitable agent for this purpose (Dehaut *et al.*, 2016; Xu *et al.*, 2024b).

The GITs were transferred to glass jars or beakers, with 10% KOH solution. The volume of KOH solution added to the jars was determined based on the volume of GIT. Subsequently, these solutions containing biological materials were incubated at 60°C for 5 days to ensure complete digestion. A blank check was performed concurrently with other samples to monitor for any potential contamination. The specimens were stored in a dark laboratory environment and consistently agitated to ensure thorough digestion.

Filtration

After the 5-day digestion period, the solutions underwent filtration using a vacuum filtration unit equipped with 0.47-μm microfiber filters. The resulting filter papers were then dried in an oven at 60°C and securely stored in petri dishes to prevent any potential external contamination.

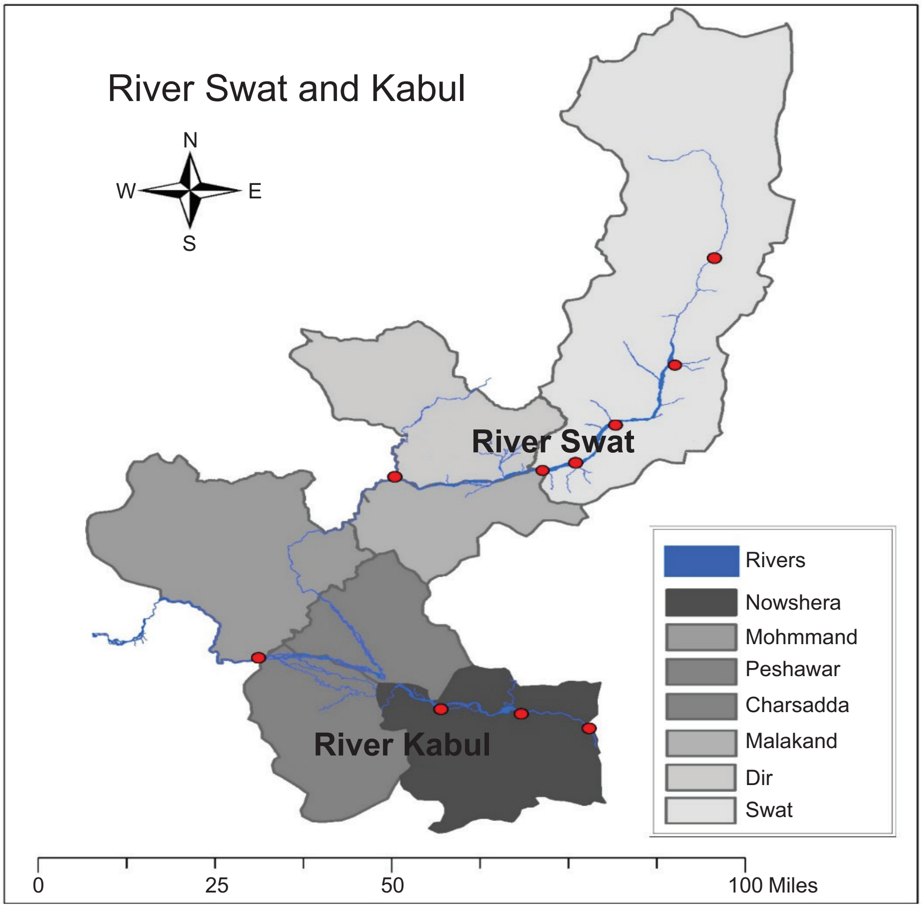


Figure 1. Sampling locations at Swat and Kabul rivers.

Microscopic inspection, identification, characterization, and Fourier transform infrared (FTIR) analysis

Glass microfiber filters enclosed in petri dishes were visually observed with the naked eye. Subsequently, a stereomicroscope (CX41; Olympus Co. Ltd., Japan) coupled to a digital camera (Nikon DS Ri2) was employed to examine the filters containing recovered MP particles. The examination was conducted at total magnifications ranging from 4× (minimum) to 10× (maximum) to identify, quantify, and measure MPs using a ruler. Concentrations of MPs were expressed as the number of particles per sample. Each sample was analyzed individually, and four major categories of MPs based on morphology (foam, fibers, fragments, and pellets) were identified (Hidalgo *et al.*, 2012). During microscopic analysis, the count of MPs present on each filter paper was documented. Additionally, the color and size of each potentially identified MP was recorded, following the approach outlined in the study conducted by Su *et al.* (2016).

Attenuated total reflectance (ATR)–FTIR spectroscopy was employed for the characterization of MP particles. A Perkin Elmer Spectrum 65 FTIR spectrometer with a LiTa detector and a universal attenuated total reflectance (UATR) ZnSe crystal with a 3–4-mm aperture were used to capture spectra in the range of 4,000–5,000 cm^{-1}.

Statistical analysis

For statistical analysis, a simple *t*-test was employed to compare different results. Additionally, maximum, mean, and standard deviation values of MP samples were calculated.

Results and Discussions

Fulton's condition factor

The body weight and length ratio were calculated separately for each sample of fish species collected during sampling. The calculated K factor values for different species are provided in Table 2.

Table 2. Fulton's condition factor (K) calculated for collected samples of individual fish species.

Fish species	Common name	No. of fish samples	Body weight (gm)	Standard deviation for weight	Length (cm)	Standard deviation for length	Fulton's condition factor (K)
Schizothorax plagiostomus	Swatay	29	72.95	44.26	19.19	3.94	1.27
Cyprinus carpio	China kub/paplait	12	55.89	24.12	14.23	2.58	1.31
Racoma labiatus	Chunr	15	38.20	8.66	14.41	0.86	0.88
Clupisoma naziri	Sher Mayai	05	79.02	21.21	23.05	1.48	1.14

The results revealed mean K values for *S. plagiostomus*, *C. naziri*, and *C. carpio* to be higher than 1, indicating good health of these species in their habitat. Conversely, *Racoma Labiatus* showed K < 1, suggesting poor health of this species in its habitat, possibly because of various factors, such as insufficient food supply, ecological stress, modifications in physicochemical parameters, and/or pollution (Akhtar *et al.*, 2021; Zhang *et al.*, 2023). According to Hussain *et al.* (2009), the heavier the fish with respect to its length, the higher its K value. Higher K values (≥1) indicate good conditions for both fish and its habitat, signifying adequate availability of feed.

Microscopic observations

Microscopic analysis through a stereo microscope identified 67 MP particles with different morphologies, such as pellets, fibers, and fragments. In all, 33 fish samples with MPs were identified (details provided in Table 3). Concerning size, only seven MPs had a size > 0.1 mm, while all the remaining MPs had a size ≤ 0.1 mm (11 MPs > 0.1 mm, and 56 MPs ≤ 0.1 mm). The average number of MP particles per fish sample was 1.10 with a standard deviation of 12.98.

In all, 50 fish samples were caught from six locations of river Swat, and 59 MPs were identified in these samples. In all, 11 fish samples were caught from four locations of river Kabul, with eight MPs identified. Location wise on both rivers, 25 fish samples were collected from Landakay Swat, with 16 samples revealing the presence of 43 MPs. Comparatively, the upper areas of river Swat, specifically the Bahrain samples, showed no identified MPs and therefore designated as the reference point. The number of fish samples and MPs discovered in the samples are illustrated in Figure 2.

Stereomicroscopic evaluation of MP particles concerning color was carried out; predominant colors identified were green, blue, yellow, and transparent colors (Saeed *et al.*, 2022). Shown in Figure 3 are different colors and shapes of microplastics identified under the microscope.

Size analysis indicated that size of 16.42% (11 particles) of MPs ranged from 100 μm to 470 μm, and the remaining

Table 3. Microplastic abundance in fish samples collected at each location and number of microplastics per location.

	Location	Abbreviation	No. of samples	Samples with MPs	No. of MPs	Standard deviation
Swat river						
1.	Madyan/Bahrain Swat	MS	2	0	0	
2.	Khwaza Khela Swat	KKS	1	0	0	
3.	Barikot Swat	BS	12	5	7	
4.	Landakay (Shamazo bridge)	LS	25	16	43	
5.	(Sher Abad) Takhtaband Swat	TS	5	4	6	
6.	Chakdara bridge	CS	5	2	3	
Kabul river						
7.	Warsak Kabul	WK	2	1	1	
8.	Charsadda moterway bridge	CK	3	1	2	
9.	Pir Sabaq	PK	4	3	4	
10.	Khairabad bridge	KS	2	1	1	
	Total		**61**	**33**	**67**	**12.98**

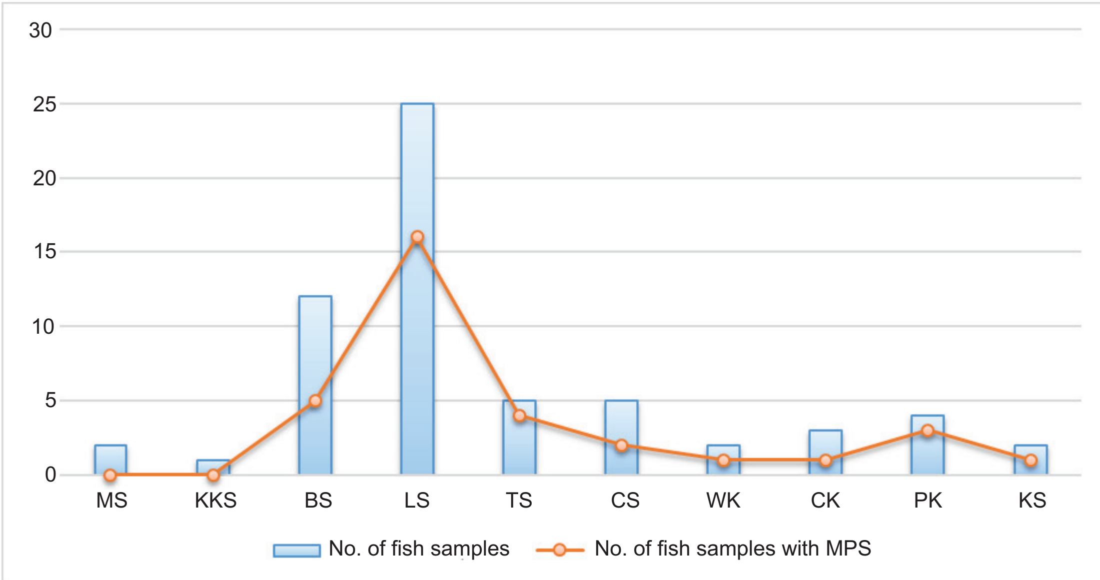


Figure 2. Distribution of microplastics in collected fish samples from Swat and Kabul Rivers.

MPs (86.58%; 56 particles) were of smaller size than 100 µm, their size ranging from 100 µm to 38 µm.

FTIR analysis

Microplastics, verified through microscopy under all conditions, underwent ATR-FTIR analysis for identification of chemical structure. Two types of polymers, polyethylene (PE) and polypropylene (PP), were confirmed. PE was the predominant polymer (52%), followed by PP (27%), while other polymers were not identified by ATR-FTIR. Key PE confirmation included absorption bands at 2,914.8 cm and 2,847.7 cm, corresponding to methylene ($-CH_2$) stretches. The FTIR fingerprint region (600–1,400 cm^{-1}) revealed characteristic PE absorbance bands at 2,914 cm^{-1} and 2,847 cm^{-1}. The FTIR spectra confirming polyethylene (PE) and Polypropylene (PP) type of microplastics are shown in Figures 4 and 5 respectively.

The FTIR spectrum of PP in literature presents a shoulder at 2,875 cm^{-1}, and the asymmetric and symmetric in-plane C–H ($-CH_3$) at 1455 cm^{-1} and a shoulder at 1,358 cm^{-1}. As observed in Figure 5, FTIR spectra of MPs showed bands at 2,875 cm^{-1} and C–H ($-CH_3$) stretching near 1,455 cm^{-1} to confirm that it is a PP.

Conclusion

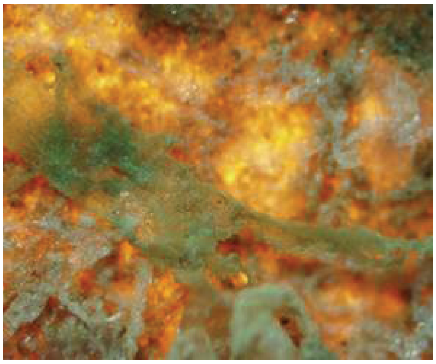
The findings from this study confirmed the presence of MP pollution in both Swat and Kabul rivers. The identification of MPs in the GIT of fish strongly implies their ingestion, potentially raising concerns for the well-being of organisms and the overall health of ecosystem. While the origins of these MPs in both rivers remain undisclosed, plausible contributors encompass urban runoff, agricultural practices, and plastic waste stemming from human activities. Consequently, further investigation is imperative to unveil the precise origins of these MPs and to formulate effective strategies aimed at mitigating the prevalence of MPs in these river systems. FTIR spectra analysis indicated that the predominant MPs discovered in the GIT of fish in both Swat and Kabul rivers were identified as PE and PP. Microplastics, mainly in fragment form, primarily originated from secondary sources, confirming their association with PE and PP plastic types. Moreover, the intricate interplay between MPs pollution, aquatic life, and environmental stability requires comprehensive exploration for devising well-informed conservation measures. Additionally, collaborative efforts involving scientific research, policy implementation, and public awareness campaigns are crucial in fostering a sustainable and unpolluted aquatic environment for both present and future generations.

Conflict of Interest

The authors declare no conflict of interest.

Funding

The funding for this work was provided by the Higher Education Comission (HEC) of Pakistan under National Research Program for Universities (NRPU) with Project grant Number: 20-17232/NRPU/R&D/HEC/2021.

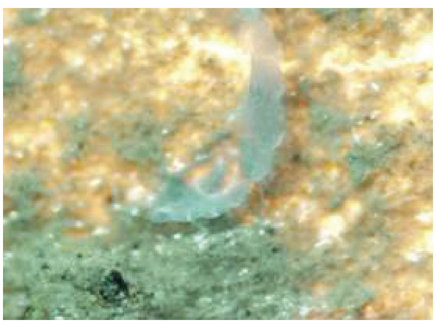


1. Green color of MP

2. White transparent color of MP

3. Green color fragment of MP

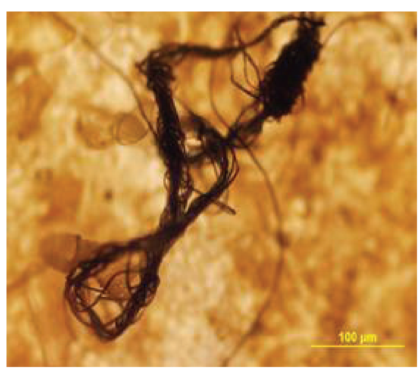
4. Black color thread structure of MP



5. White transparent color of MP

6. Black color thread-like MP

7. Blue fragment structure of MP



8. Thread black color of MP

Figure 3. Microplastics identified under stereomicroscope.

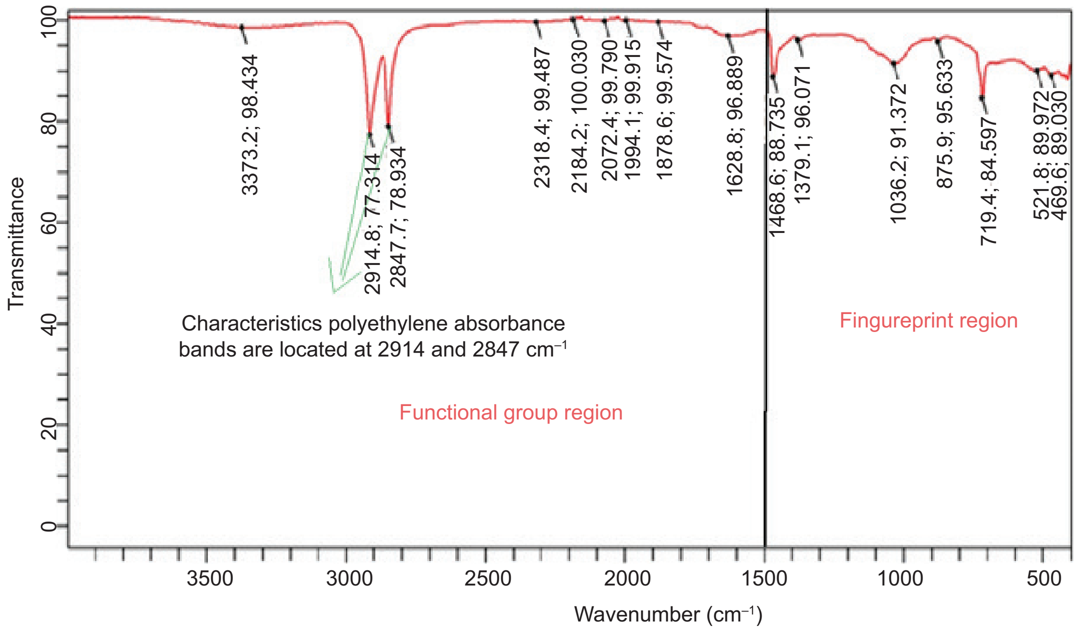


Figure 4. FTIR spectra confirming polyethylene (PE) type of microplastics.

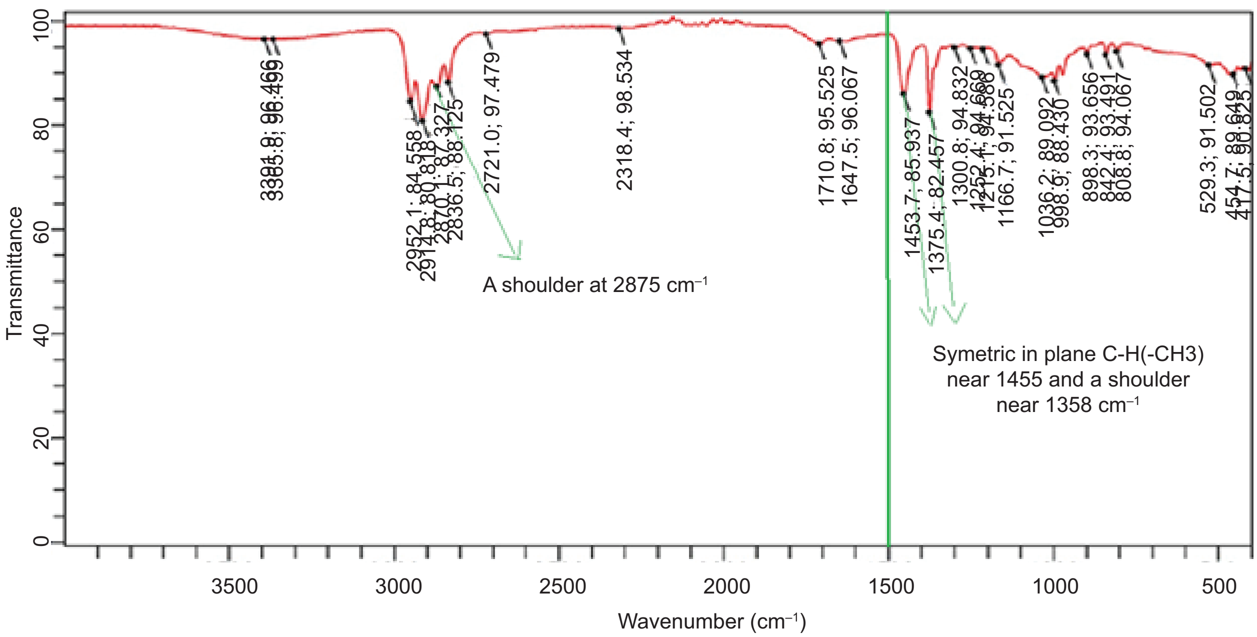


Figure 5. FTIR spectra confirming polypropylene (PP) type of microplastics.

Acknowledgement

The authors greatly acknowledge and express their gratitude to the Researchers Supporting Project number (RSPD2024R568), King Saud University, Riyadh, Saudi Arabia. The authors also greatly acknowledge the Fisheries Department of the Government of Khyber Pakhtunkhwa, Pakistan for their support during Fish sampling and fieldwork.

References

Abbasi M, Khan I, Rehman A, Rahman M, Hayat A, Shah TA, et al. 2024. Bioremediation of Heavy Metals contaminated Soil by using Indigenous Metallotolerant Bacterial Isolates. Appl Ecol Environ Res. 22(2):1623–1648. http://doi.org/10.15666/aeer/2202_16231648

Akhtar T., Ghazanfar A. and N. Shafi N. 2021. Length-weight relationships, condition factor and morphometric characteristics of schizothoracinae from Neelum and Jhelum rivers of Azad Jammu and Kashmir, Pakistan. Pak J Zool. 53(1): 351. https://doi.org/10.17582/journal.pjz/20180216090213

Akram MB, Khan I, Rahman M, Sarwar A, Ullah N, Rahman S, et al. 2023. Mycoremediation of Heavy Metals Contaminated Soil by Using Indigenous Metallotolerant Fungi. Polish J Chem Tech. 25(3): 1–13. https://doi.org/10.2478/pjct-2023-0019

Andrady A.L. 2015. Persistence of plastic litter in the oceans. In: Bergmann M., Gutow L., Klages M. (eds). Marine Anthropogenic Litter. Cham, Switzerland: Springer, pp. 57–72. https://doi.org/10.1007/978-3-319-16510-3_3

Arthur C., Baker J. and Bamford, H. 2009. Proceedings of the international research workshop on the occurrence, effects, and fate of microplastic marine debris. In: NOAA Marine Debris Program (eds). University of Washington Tacoma, Tacoma, WA, USA. Technical memorandum NOS-OR&R-30. https://repository.library.noaa.gov/view/noaa/2509

Barboza L.G.A., Vethaak A.D., Lavorante B.R., Lundebye A.K. and Guilhermino L. 2018. Marine microplastic debris: an emerging issue for food security, food safety and human health. Mar Pollut Bull. 133: 336–348. https://doi.org/10.1016/j.marpolbul.2018.05.047

Bellas J., Martínez-Armental J., Martínez-Cámara A., Besada V. and Martínez-Gómez C. 2016. Ingestion of microplastics by demersal fish from the Spanish Atlantic and Mediterranean coasts. Mar Pollut Bull. 109(1): 55–60. https://doi.org/10.1016/j.marpolbul.2016.06.026

Boerger C.M., Lattin G.L., Moore S.L. and Moore C.J. 2010. Plastic ingestion by planktivorous fishes in the North Pacific Central Gyre. Mar Pollut Bull. 60(12): 2275–2278. https://doi.org/10.1016/j.marpolbul.2010.08.007

Dehaut A., Cassone A.L., Frère L., Hermabessiere L., Himber C., Rinnert E., et al. 2016. Microplastics in seafood: benchmark protocol for their extraction and characterization. Environ Pollut. 215: 223–233. https://doi.org/10.1016/j.envpol.2016.05.018

Geyer R., Jambeck J.R. and Law K.L. 2017. Production, use, and fate of all plastics ever made. Sci Adv. 3(7): e1700782. https://doi.org/10.1126/sciadv.1700782

Hidalgo-Ruz V., Gutow L., Thompson R.C. and Thiel M. 2012. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ Sci Technol. 46(6): 3060–3075. https://doi.org/10.1021/es2031505

Hussain A., Qazi J.I., Shakir H.A., Mirza M.R. and Nayyer A.Q. 2009. Length-weight relationship, meristic and morphometric study of Clupisoma naziri from the river Indus, Pakistan. Punjab Univ J Zool. 24(1–2): 14–25.

Jahnke A., Arp H.P.H., Escher B.I., Gewert B., Gorokhova E., Kühnel D., et al. 2017. Reducing uncertainty and confronting ignorance about the possible impacts of weathering plastic in the marine environment. Environ Sci Technol Lett. 4(3): 85–90. https://doi.org/10.1021/acs.estlett.7b00008

Jambeck J.R., Geyer R., Wilcox C., Siegler T.R., Perryman M., Andrady A., et al. 2015. Plastic waste inputs from land into the ocean. Science. 347(6223): 768–771. https://doi.org/10.1126/science.1260352

Khan BN, Ullah H, Ashfaq Y, Hussain N, Atique U, Aziz T, et al. (2023). Elucidating the effects of heavy metals contamination on vital organ of fish and migratory birds found at fresh water ecosystem. Heliyon. 26;9(11): e20968. https://doi.org/10.1016/j.heliyon.2023.e20968

Kühn S., Van Oyen A., Booth A.M., Meijboom A. and Van Franeker J.A. 2018. Marine microplastic: preparation of relevant test materials for laboratory assessment of ecosystem impacts. Chemosphere. 213: 103–113. https://doi.org/10.1016/j.chemosphere.2018.09.032

Law K.L. and Thompson R.C. 2014. Microplastics in the seas. Science. 345(6193): 144–145. https://doi.org/10.1126/science.1254065

Leslie H.A., Van Velzen M.J., Brandsma S.H., Vethaak D., Garcia-Vallejo J.J., and 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

Lusher A.L., Mchugh M. and Thompson R.C. 2013. Occurrence of microplastics in the gastrointestinal tract of pelagic and demersal fish from the English Channel. Marine Pollution Bulletin. 67(1–2): 94–99. https://doi.org/10.1016/j.marpolbul.2012.11.028

Naveed, M., Naveed, R., Aziz, T. Iqbal F, Hassan A, Saleem A, et al. 2023a. Exploring the potential application of peroxidase enzyme from Acinetobacter baumannii as an eco-friendly agent for the bioremediation of the highly noxious pyrethroid compounds through molecular docking analysis. Biomass Conv. Bioref. 2023: 1–9. https://doi.org/10.1007/s13399-023-05160-2

Naveed M, Makhdoom SI, Rehman SU, Aziz T, Bashir F, Ali U, et al. 2023b. Biosynthesis and Mathematical Interpretation of Zero-Valent Iron NPs Using Nigella sativa Seed Tincture for Indemnification of Carcinogenic Metals Present in Industrial Effluents. Molecules. 28(8): 3299. https://doi.org/10.3390/molecules28083299

Napper I.E. and Thompson R.C. 2019. Marine plastic pollution: other than microplastic. In: Letcher T.M., and Vallero D.A. Waste (Second Edition). Cambridge, Massachusetts, United States. Academic Press, pp. 425–442. https://doi.org/10.1016/B978-0-12-815060-3.00022-0

Plastics Europe. 2019. Plastics—the facts 2019: an analysis of European plastics production, demand and waste data. Plastics Europe, Brussels, Belgium.

Rochman C.M. 2018. Microplastics research—from sink to source. Science. 360(6384): 28–29. https://doi.org/10.1126/science.aar7734

Rochman C.M., Tahir A., Williams S.L., Baxa D.V., Lam R., Miller J.T., et al. 2015. Anthropogenic debris in seafood: plastic debris and fibers from textiles in fish and bivalves sold for human consumption. Sci Rep. 5(1): 1–10. https://doi.org/10.1038/srep14340

Saeed R., Feng H., Wang X., Zhang X. and Fu Z. 2022. Fish quality evaluation by sensor and machine learning: a mechanistic review. Food Control. 137: 108902. https://doi.org/10.1016/j.foodcont.2022.108902

Sanchez W., Bender C. and Porcher J.M. 2014. Wild gudgeons (Gobio gobio) from French rivers are contaminated by microplastics: preliminary study and first evidence. Environ Res. 128: 98–100. https://doi.org/10.1016/j.envres.2013.11.004

Su L., Xue Y., Li L., Yang D., Kolandhasamy P., Li D., & Shi H. 2016. Microplastics in Taihu Lake, China. Environ. Pollut, 216: 711–719.

Xiong J., Wen D., Zhou H., Chen R., Wang H., Wang C., et al. 2022. Occurrence of aflatoxin M1 in yogurt and milk in central-eastern China and the risk of exposure in milk consumers. Food Control. 137: 108928. https://doi.org/10.1016/j.foodcont.2022.108928

Xu M., Ni X., Liu Q., Chen C., Deng X., Wang X., et al. 2024a. Ultra-high pressure improved gelation and digestive properties of Tai Lake whitebait myofibrillar protein. Food Chem X. 21: 101061. https://doi.org/10.1016/j.fochx.2023.101061

Xu M., Liu Q., Ni X., Chen C., Deng X., Fang Y., et al. 2024b. Lipidomics reveals the effect of hot-air drying on the quality characteristics and lipid oxidation of Tai Lake whitebait (Neosalanx taihuensis Chen). Food Sci Technol (LWT). 197: 115942. https://doi.org/10.1016/j.lwt.2024.115942

Yu Z., Xu X., Guo L., Yuzuak S. and Lu Y. 2024. Physiological and biochemical effects of polystyrene micro/nano plastics on Arabidopsis thaliana. J Hazard Mater. 469: 133861. https://doi.org/10.1016/j.jhazmat.2024.133861

Wang W., Xu J., Zhang W., Glamuzina B. and Zhang X. 2021. Optimization and validation of the knowledge-based traceability system for quality control in fish waterless live transportation. Food Control. 122: 107809. https://doi.org/10.1016/j.foodcont.2020.107809

Welden N.A. and Lusher A.L. 2017. Impacts of changing ocean circulation on the distribution of marine microplastic litter. Integ Environ Assess Manag. 13(3): 483–487. https://doi.org/10.1002/ieam.1911

World Health Organization (WHO). 2019. Microplastics in drinking-water. WHO, Geneva, Switzerland.

Zameer M, Tahir U, Khalid S, Zahra N, Sarwar A, Aziz T, et al. (2023). Isolation and characterization of indigenous bacterial assemblage for biodegradation of persistent herbicides in the soil. Acta Biochim Pol. 31;70(2): 325–334. https://doi.org/10.18388/abp.2020_6563

Zhang Y., Xiao X., Feng H., Nikitina M.A., Zang X.,., and Zhao Q. 2023. Stress fusion evaluation modeling and verification based on noninvasive blood glucose biosensor for live fish waterless transportation. Front Sustain Food Syst. 7: 1172522. https://doi.org/10.3389/fsufs.2023.1172522