CHARACTERIZATION OF MICROPLASTIC POLLUTION IN THE PASUR RIVER OF THE SUNDARBANS ECOSYSTEM (BANGLADESH) WITH EMPHASIS ON WATER, SEDIMENTS, AND FISH

Nowshin Nawar[1], Md. Mostafizur Rahman[1,2]#, Shumayta Marzia[1], Mir Mohammad Ali[3], Md. Ahedul Akbor[4], Md. Abu Bakar Siddique[4], Mst. Afifa Khatun[5], Md. Shahjalal[5], Roksana Huque[5], Guilherme Malafaia[6]##

[1]Department of Environmental Science, Bangladesh University of Professionals, Dhaka-1216, Bangladesh

[2]Laboratory of Environmental Health and Ecotoxicology, Department of Environmental Sciences, Jahangirnagar University, Dhaka-1342, Bangladesh

[3]Department of Aquaculture, Sher-e-Bangla Agricultural University, Dhaka, 1207, Bangladesh

[4]Institute of National Analytical Research and Service (INARS), Bangladesh Council of Scientific and Industrial Research (BCSIR), Dhanmondi, Dhaka 1205, Bangladesh

[5]Food Safety and Quality analysis Division, Institute of Food and Radiation Biology, Bangladesh Atomic Energy Commission, Savar, Dhaka, Bangladesh

[6]Laboratory of Toxicology Applied to the Environment, Goiano Federal Institute, Urutaí, GO, Brazil. Post-Graduation Program in Conservation of Cerrado Natural Resources, Goiano Federal Institute, Urutaí, GO, Brazil. Post-Graduation Program in Ecology, Conservation, and Biodiversity, Federal University of Uberlândia, Uberlândia, MG, Brazil. Post-Graduation Program in Biotechnology and Biodiversity, Federal University of Goiás, Goiânia, GO, Brazil.

E-mail address: nawshinn8@gmail.com, shumayta12@gmail.com, guilhermeifgoiano@gmail.com (G. Malafaia).

CORRESPONDING AUTHORS.

#Dr. Md. Mostafizur Rahman. Laboratory of Environmental Health and Ecotoxicology, Department of Environmental Sciences, Jahangirnagar University, Dhaka-1342, Bangladesh. Email: rahmanmm@juniv.edu

##Dr. Guilherme Malafaia. Laboratory of Toxicology Applied to the Environment, Goiano Federal Institution – Urutaí Campus. Rodovia Geraldo Silva Nascimento, 2,5 km, Zona Rural, Urutaí, GO, Brazil. CEP: 75790-000. Phone: +55 64 3465 1995. Email: guilhermeifgoiano@gmail.com.

ABSTRACT

An emerging concern of today's world, due to their universal dispersion worldwide, is the environment's microplastic pollution. The Sundarbans, the world's largest mangrove, have unique and dynamic environmental settings with numerous pollution risk exposures, including microplastics (MPs). Thus, the present study has focused on the MP pollution in water, sediment, and fish samples of the Sundarbans of Bangladesh for the first time. Water and sediment samples were collected (n=30/each) from sampling locations along the Pasur river (Bangladesh). Furthermore, nine species of fish samples were collected from a local fish market situated at the Mongla port. Results show that 100% of the analyzed samples have evidence of MPs. On average, 2.66×10^3 plastic particles/L and 1.57×10^5 particles/kg were found in water and sediment samples, respectively. Furthermore, results show a higher number of MPs in the animals' gastrointestinal tract (GIT) (10.41 particles/g), concerning the average concentration recorded in the muscles (4.68 particles/g). *O. pama* and *H. nehereus* were the species that showed the highest MPs accumulation in the GIT. In the muscles, the highest MP levels were observed in *T. ilisha* and *L. calcarifer*. Most of the particles were smaller than 1 mm; black-colored particles dominated the pool. FT-IR analysis revealed the presence of seven polymer types where polyamide was abundant in water and sediment samples. SEM analysis showed morphological structures and adsorbed particles on the surface of plastic samples, and the spatial distribution of MPs indicates that the location with high human intervention has elevated levels of MPs. Therefore, our study demonstrates that Sundarbans mangrove forests are highly contaminated with MPs and that its fisheries can be a potential source of human exposure to these pollutants.

Keywords: Microplastics, mangrove, sediment, polymers, FT-IR, SEM, spatial distribution.

1. INTRODUCTION

Microplastics (MPs) have been established as one of the most concerning problems in today's world. It is used in everyday commodities for its lower cost and broader applications (Thompson et al., 2009, Cordova et al., 2021). It has been stated in most common environments and rare places on the earth (Barnes et al., 2009). A ubiquitous element of the environment, the particles of plastic known for their microscopic sizes are microplastics, which are widely used in industrial manufacture (Cole et al., 2011; Vermaire et al., 2017). It is an emerging synthetic plastic pollutant of less than 5 mm to not more than 1 micrometer in size that needs to be tackled in no time (Afrin et al., 2020; Guo et al., 2020; Lebreton et al., 2018; Thompson et al., 2004). It is a general term for microscopic plastic particles, including their polymer types, size, origin, and shapes (Laermanns et al., 2021).

MPs are formed by the breakdown and fragmentation of larger plastic particles due to various processes like waves and UV radiation from the sun (LI et al., 2016). The larger plastic particles are less harmful than the microplastics as these can hamper microscopic organisms, which further may build up in higher organisms by adopting bioaccumulation mechanisms (Mohamed Nor & Obbard, 2014). MPs can be of many diverse types. However, depending on their origin, they are mainly divided into primary and secondary types (Garcés-Ordóñez et al., 2020). Primary microplastics are micro-sized particles typically used in cosmetic products and medicines and reported by some studies in air blasting technologies (Cole et al., 2011; Derraik, 2002; Patel et al., 2009). They are derived from synthetic textiles, car tires, and products used to manufacture other plastic items (Duis & Coors, 2016). When these plastic particles break down even further, the smaller particles are known as secondary microplastics, which are generally used in agricultural sectors and industrial processes; these are also derived from primary plastic particles, illegal waste dumping, and mismanagement of sanitation (Ryan et al., 2009; Thompson et al., 2004; Afrin et al., 2020; Barnes et al., 2009; Deng et al., 2021). Weathering plays a role in changing MPs' size, shape, and polymer structures (Lehtiniemi et al., 2018). According to their shapes, microplastics can be of several types, of which the most common are fragment, fiber, film, pellet, foam, etc. (Arias et al., 2019; Lambert et al., 2017; Wu et al., 2018). Their chemical bonds and polymer types can be distinct and identifiable using infrared radiation. Polyethylene (PE), Polystyrene (PS), polypropylene (PP), high-density polyethylene (HDPE), low-density polyethylene (LDPE), Polyvinyl chloride (PVC), etc., are some of the common types of microplastics found in the environment (Rakib et al., 2022).

The MP pollution issue applies to Bangladesh, especially in the Sundarbans mangrove forest. It is the world,' yet it is affected by the intrusion of microplastics in every environmental aspect. Mangrove forests are the intermediate area adjoining terrestrial lands with the coastlines, which nurtures various life forms of land and water (Deng et al., 2021; Zuo et al., 2020). Mangroves are significant in the sense of food providers to diverse life forms and as a protection from natural disasters (Bayen, 2012; Kulkarni et al., 2018). The Sundarbans support diverse local and exotic wildlife; it is also home to many people who depend on the forest for their food and livelihood. Recently microplastic pollution has been established as a global concern as well as a national concern from the perspective of our country (Parvin et al., 2021). Although a significant sink of microplastics, there have been fewer studies involving mangrove forests, presumably due to the hostile environment, risk of wildlife, and sampling challenges (Mohamed Nor & Obbard, 2014). But this has only made it more significant to identify the elements contaminated by MPs.

In addition to the lack of research concerning the mangrove environment, especially the Sundarbans, little and unclear information was found on the spatial distribution of the MPs. MPs in sediment have very limited research when compared with aquatic MPs. No universal method was developed for the sampling and extracting of MPs from soil and sediments. The Fourier transform infrared spectroscopy (FTIR) analysis of polymer types, and their peaks are also not evident in the studied research. There are assumptions that MP sources from the atmosphere; however, very little research has been done.

As microplastic pollution has gained attention recently, it is plausible that the largest mangrove forest, Sundarbans, has also been affected by its presence. The study hypothesizes that a higher number of MP particles are present in the Sundarbans mangrove forest's sediment, water, and aquatic life forms. Specifically, the study aims to identify and quantify the presence of MPs in the sediment, water, and fish samples of the Pasur river, to characterize the identified MPs according to their shapes, sizes, and polymer types; and, to represent the spatial distribution of microplastics in the study area.

2. MATERIALS AND METHOD

2.1. Study area

Being the world's largest delta blessed with mangrove forests, Sundarbans is located on the mouth of Brahmaputra, Ganges, and Meghna, three mighty rivers (Getzner & Islam, 2020). The total forest area is about 10,284 km, with 58.5% in Bangladesh (Chowdhurym et al., 2016). Sundarbans is located between 22.29713E and 89.56718 N. About 117 river flows over Sundarbans to mix with the Bay of Bengal, of which, Pasur is one of the major river systems in Sundarbans, an extension of the Rupsa River. Pasur river is about 48 km south of Khulna district (Shil et al., 2017). The left bank of the river falls within the Khulna district, and the right side is in the Bagerhat district (Figure 1). Plastic pollution is also increasing with the high tourism load and recent developments. Microplastics of a higher concentration could alter the ecosystem and damage the natural balance of the forest, including the food web and ecosystem (Hitchcock, 2022). With all these in mind, the Sundarbans mangrove forest has been chosen as the primary area of this thesis.

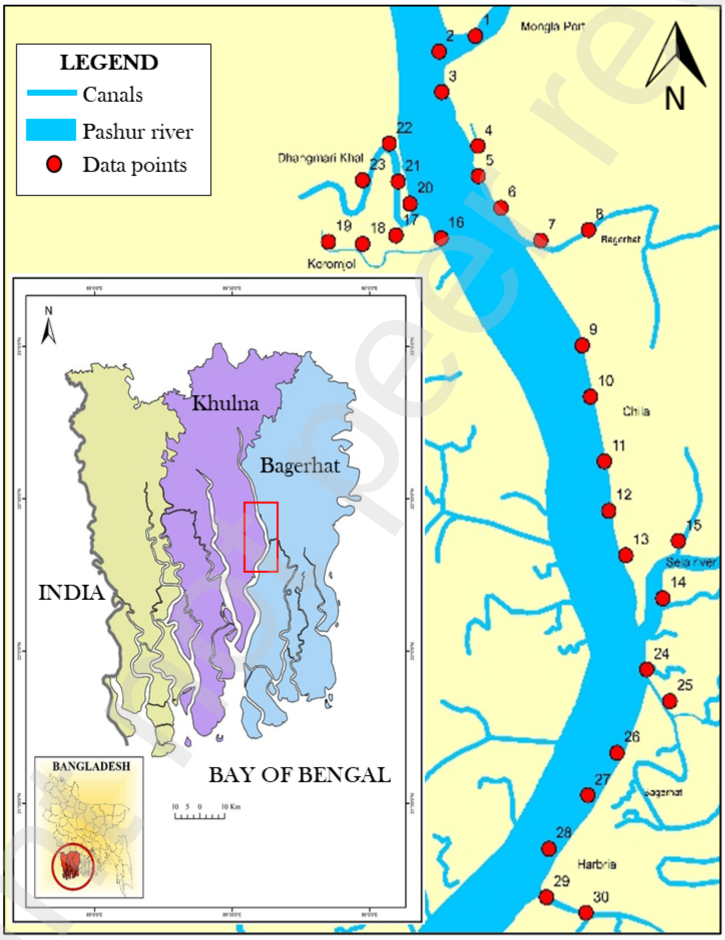

Figure 1. Data collection locations in the Pasur river and its adjacent canals (Bay of Bengal, Bangladesh).

2.2. Sampling and data collection

During the study in mid-February 2022, sediment and water samples were collected from the Pasur river of Mongla city (Shil et al., 2017). Thirty sampling locations from Mongla port to Herbaria were selected beforehand, keeping approximately 1 km distance between each point (Figure 1). A record of the GPS location, time, and name of the local place with a short description of the area was kept during the sample collection. All samples were collected during the daytime for two days, facing both high and low-tide situations. Sixteen samples were collected from the mainstream river, while 14 samples were taken from adjacent canals. Fish samples were collected from Mongla Bazar, located on the opposite side of Mongla port. An inventory was kept for each fish species collected with their local name, scientific name, and feeding zones; afterward, 3-4 individual fish from each sample were weighed and measured for analysis (Table 1).

2.3. Pre-processing, digestion, and filtration

2.3.1. Water

Pre-preparation of water samples was studied from different literature (Laermanns et al., 2021; McCormick et al., 2016; Scherer et al., 2020; Vermaire et al., 2017). One hundred milliliters of water were kept in 150 mL beakers, and 5 mL of concentrated nitric acid (68%) was added. The solution was kept aside for seven days at room temperature. Afterward, the samples were filtered using nylon filter paper with a 0.45 μm mesh size. The filter papers were air-dried for 24 hours for visual observation in glass Petri dishes.

2.3.2. Sediment

Pre-processing and preparation of sediment samples were studied from recent literature (Afrin et al., 2020; Cordova et al., 2021; Garcés-Ordóñez et al., 2019; Horton et al., 2017; Laermanns et al., 2021; Mai et al., 2018; Mohamed Nor & Obbard, 2014; Zhou et al., 2020; Zuo et al., 2020). The sediment samples were dried at 65^0 C for 24 hours in a drying oven. A mortar pestle and sieve shaker were used to separate fine-grained particles with a mesh size of 75 μm. Each sample was shaken for 3 min in a sieve shaker. Twenty milliliters of hydrogen peroxide solution (at 30%) was added to each gram sample and digested in the oven at 80^oC for four hours. For density separation, 3 g ZnCl was added to the beaker and kept aside for 48 hours. Afterward, the samples were filtered using a vacuum filtration pump using 0.45 μm mesh-size nylon filter paper. The filter papers were air-dried for 24 hours before visual observation

Table 1. Attributes of collected fish samples in Mongla Bazar, located on the opposite side of Mongla port (Bangladesh).

Local name	Specie	Family	Status (IUCN Red List)	Environment: climate zone and depth range	No. of individual
Ilish	*Tenualosa ilisha*	Clupeidae	Least concern (Freyhof, 2014)	Brackish and pelagic-neritic	3
Bhetki	*Lates calcarifer*	Latidae	Least concern (Pal & Morgan, 2019)	Brackish and demersal	3
Poa	*Otolithoides pama*	Sciaenidae	Data deficient (Hasan et al., 2020)	Brackish and benthopelagic	4
Tengra	*Mystus vittatus*	Bagridae	Least concern (Ng, 2010)	Brackish and demersal	3
Payra	*Scatophagus argus*	Scatophagidae	Least concern (Collen et al., 2019)	Brackish and reef-associated	3
Loitta	*Harpadon nehereus*	Synodontidae	Near threatened (Russel et al., 2019)	Brackish and benthopelagic	4
Chemo	*Pseudapocryptes elongatu*	Oxudercidae	Least concern (Jenkins & Kullander, 2009)	Brackish and demersal	3
Bele	*Awaous grammepomu*	Gobiidae	Least concern (Larson, 2019)	Brackish and benthopelagic	3

Note - IUCN Red List: International Union for Conservation of Nature's Red List of Threatened Species (https://www.iucnredlist.org/about/background-history).

2.3.3. Fish

Pre-processing of fish samples was studied from previous research (Cole et al., 2014; Daniel et al., 2020; Dehaut et al., 2016; Parvin et al., 2021; Sarker et al., 2019; Selvam et al., 2021). Fish samples were washed with ethanol and cut using stainless steel equipment to extract the gastrointestinal tract (GIT) and muscle tissues; afterward, each sample was weighed and refrigerated at -20°C. Alkali digestion was applied for digesting fish samples (Daniel et al., 2020; Dehaut et al., 2016; Tanaka & Takada, 2016). Ten milliliters of KOH solution (at 10%) was added to each beaker per gram of fish sample. The samples were incubated at 50°C for four days in a shaker incubator. Upon digestion, the samples were filtered using 0.45 µm mesh-sized nylon filter paper. The filter papers were air-dried in glass Petri dishes for 24 hours until visual observation.

2.4. Visual observation and spatial distribution

The water, sediment, and fish samples were analyzed under a digital fluorescence microscope (Motic B410E, Germany) using 10x zoom, for visual identification of MP particles. The particles were classified into five shapes (fragment, fiber, foam, film, pellet), three sizes (1-5 mm, 0.5-1 mm, less than 0.5 mm), and nine colors (violet, red, blue, brown, black, yellow, orange, grey, white, transparent) (Garcés-Ordóñez et al., 2020; Hossain et al., 2020; Jabeen et al., 2017; Parvin et al., 2021; Tanaka & Takada, 2016; Zhou et al., 2020).

2.5. Quality control

Water and sediment samples were collected in marked bottles and airtight bags, respectively, and the openings were sealed. All collection materials were washed with ethanol and distilled water before collecting. Fish samples were weighted and measured at the earliest convenience, and GIT and muscles were dissected with stainless steel equipment. Fish bodies and dissecting equipment were washed with ethanol and distilled water before dissection to avoid contamination (Hossain et al., 2020; J. Li et al., 2016; Parvin et al., 2021). Further, the samples were correctly marked and kept frozen until analysis. While measuring, digestion, and filtration, samples were handled in a glass beaker and Petri dishes.

2.6. Fourier Transform Infrared Spectroscopy (FT-IR) and Scanning Electron Microscopy (SEM)

Selected samples were analyzed in FT-IR to identify MP polymers using an FT-IR spectrometer (PerkinElmer). The transmission mode was applied, and wavenumbers were kept at 400-4000 cm^{-1} (Daniel et al., 2020; Garcés-Ordóñez et al., 2019; Hossain et al., 2020; Parvin et al., 2021). The resulting peaks were matched to standards from other literature, and most matched peaks were accepted to be the specific polymer type (Afrin et al., 2020; Jung et al., 2018; Selvam et al., 2021). Some samples were selected for high-resolution SEM analysis for elemental composition and topography detection by taking photographs. Information on surface topography, morphology, and composition of the surface of MPs can be acquired through an electron beam of SEM (Akhtar et al., 2018; Parvin et al., 2021). In this study, Trinocular Stereo Microscope with Stemi 508 model was used. A built-in camera 'Axiocam 105' was used to compute images of plastic particles. Exposure and white balance were kept in 'auto' mode.

2.7. Data analysis

The statistical analysis of the abundance of MPs was shown using data analysis and visual representation using GraphPad Prism software version 9.0 and ArcMap 10.3. Google Earth was used to extract the locations of sampling sites. Using the sampling data and interpolation command, a spatial distribution of MPs in water and sediment was prepared to illustrate the occurrence of the pollutant.

3. RESULTS

In this study, we observed that the water and sediment samples showed varying levels of plastic particulate contamination (Figure 2A and 2C, respectively). On average, 2.66×10^3 plastic particles/L and 1.57×10^5 particles/kg were found in water (Figure 2B) and sediment samples (Figure 2D), respectively, which may originate from various sources, including terrestrial sources of household wastes, marine litters, tourism, and industrial waste. Furthermore, domestic wastes are an important contributor to mangrove forests (Deng et al., 2021; Garcés-Ordóñez et al., 2019; Naji et al., 2017). As shown in Figure 3, more MP contamination was observed near Mongla port, Mongla-Chila boat line, and Chila bazar, suggesting that tourism and fishing activities contribute to the number of MPs in the adjacent sediment and waters, like previous reports that also identified higher levels of MP contamination in populated areas (Garcés-Ordóñez et al., 2019; R. Li et al., 2020; Zhou et al., 2020; Zuo et al., 2020).

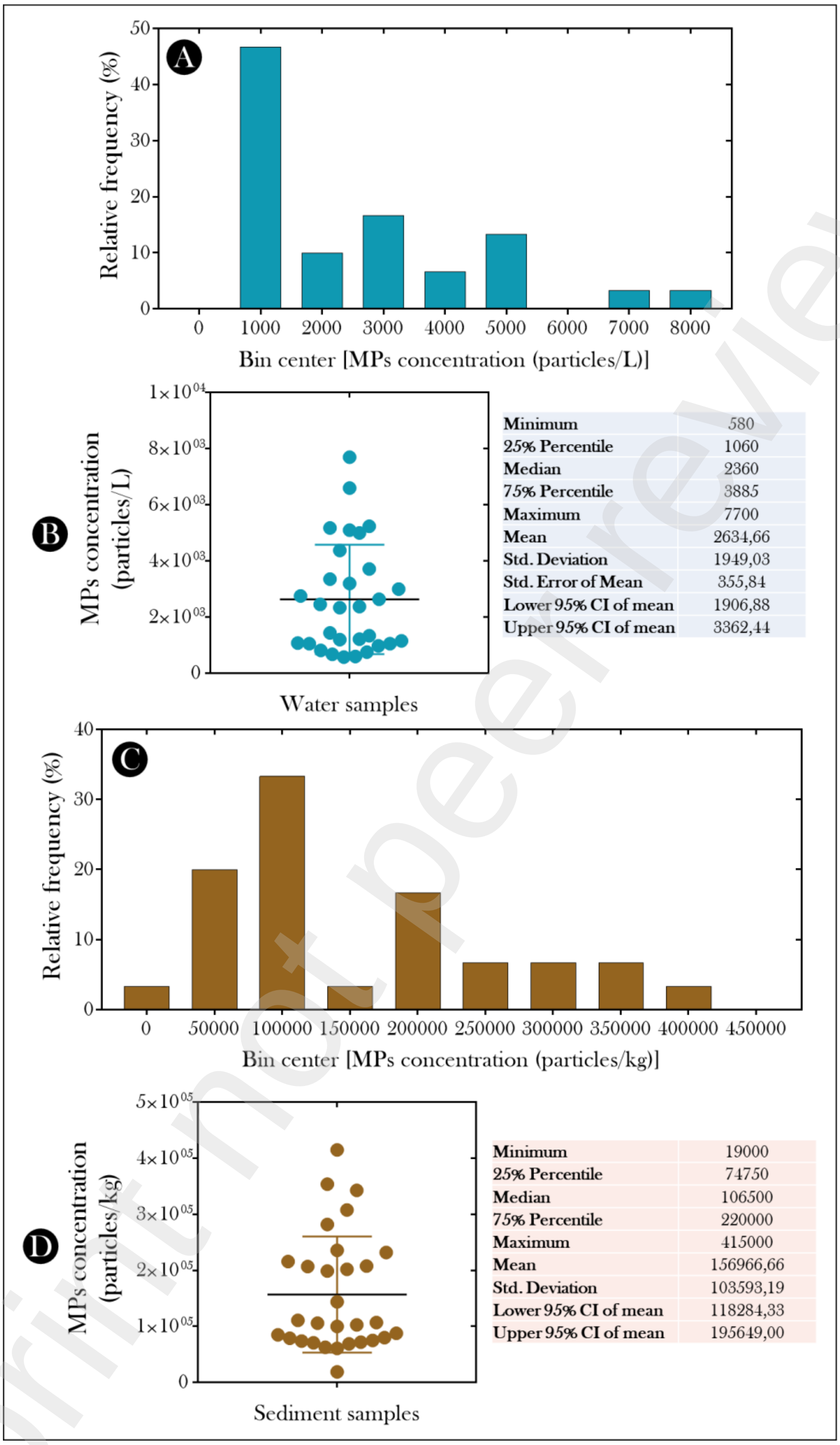

Figure 2. Distribution histogram of plastic particle contamination levels in (A) water and (C) sediment samples (Pasur river, Mongla, Bangladesh). (C-D) Scatter plot and summary of descriptive statistics of concentrations recorded in water and sediment samples, respectively.

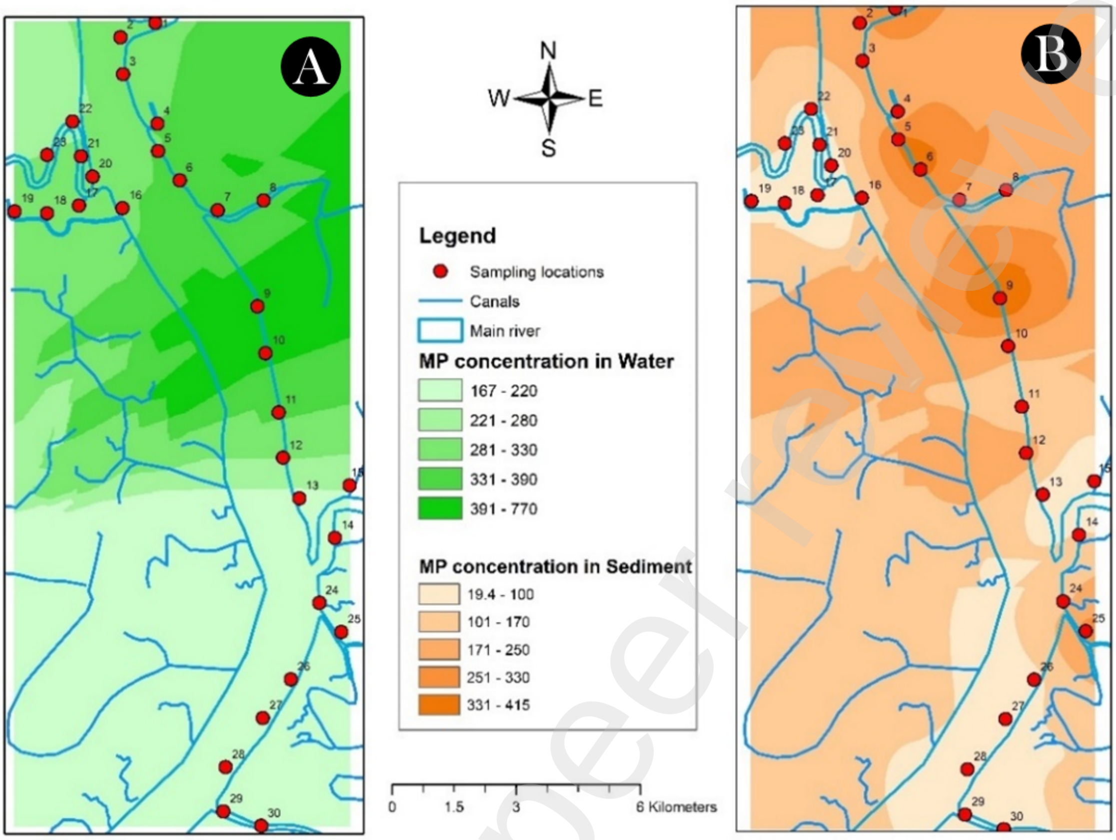

Figure 3. Spatial distribution of microplastics in (A) water and (B) sediment from the study area [Pasur river and its adjacent canals (Bay of Bengal, Bangladesh].

The abundance of MPs in both sediment and water showed a decreasing trend starting from Mongla port toward the Herbaria ecotourism center. The highest number of MPs in water was found at the 6th sampling location, 7.7 x 10^3 particles/L, beside the riverbank of Mongla-Chila road, forwarding toward Chila bazar. The second highest number was found at point 16th, 5.18 x 10^3 particles/L near Karamjal, and the lowest MP contamination was recorded in water at Dhangmari Khal (at point 21st, comprising only 5.8 x 10^2 particles/L) (Figure 4A). Already the major MP number in sediments was present in Chila, point 9, with 4.15 x 10^5 particles/kg, and second highest at point 6, with 3.54 x 10^5 particles/kg (Figure 4B). The 6th sampling point is common for both water and sediments with greater MP contamination levels. On the other hand, sampling points 21-22 are lower in MPs for both water and sediments. The lowest number of particles in sediments are present in sampling point 15, with 1.9 x 10^4 particles/kg only, near Sela River (Figure 4). The abundance of microplastics is lower for both water and sediments near herbaria (Figures 3 and 4).

A relationship between the profusion of MPs between water and sediments shows a decreasing pattern from the northern part of the river toward the southern part (Figure 3). A similarity in the way of increase and decrease can be observed from the curve, which means that areas with greater MPs in water are also greater in number in the case of sediments, and vice versa for the areas with a lower number of MPs (Figure 4). The population density is also a driver in the number of MPs found. Points a few kilometers south of Mongla port, where Chila is located, are seen to have a greater number of MPs both in water and sediment samples. This might result from extreme fishing activities and improper disposal of waste and boat gear.

The spatial distribution of MPs with five classes in water and sediments (Figure 3) shows similarity with the distribution pattern observed in Figure 4; the northern portion of the study area is more polluted with plastics than the southern portion. Most Sundarbans' villages are near Mongla port, Karamjal, and Chila. The spread of microplastics in water is comparatively lower in the points with limited access to people (points 24 to 30) (Figure 4).

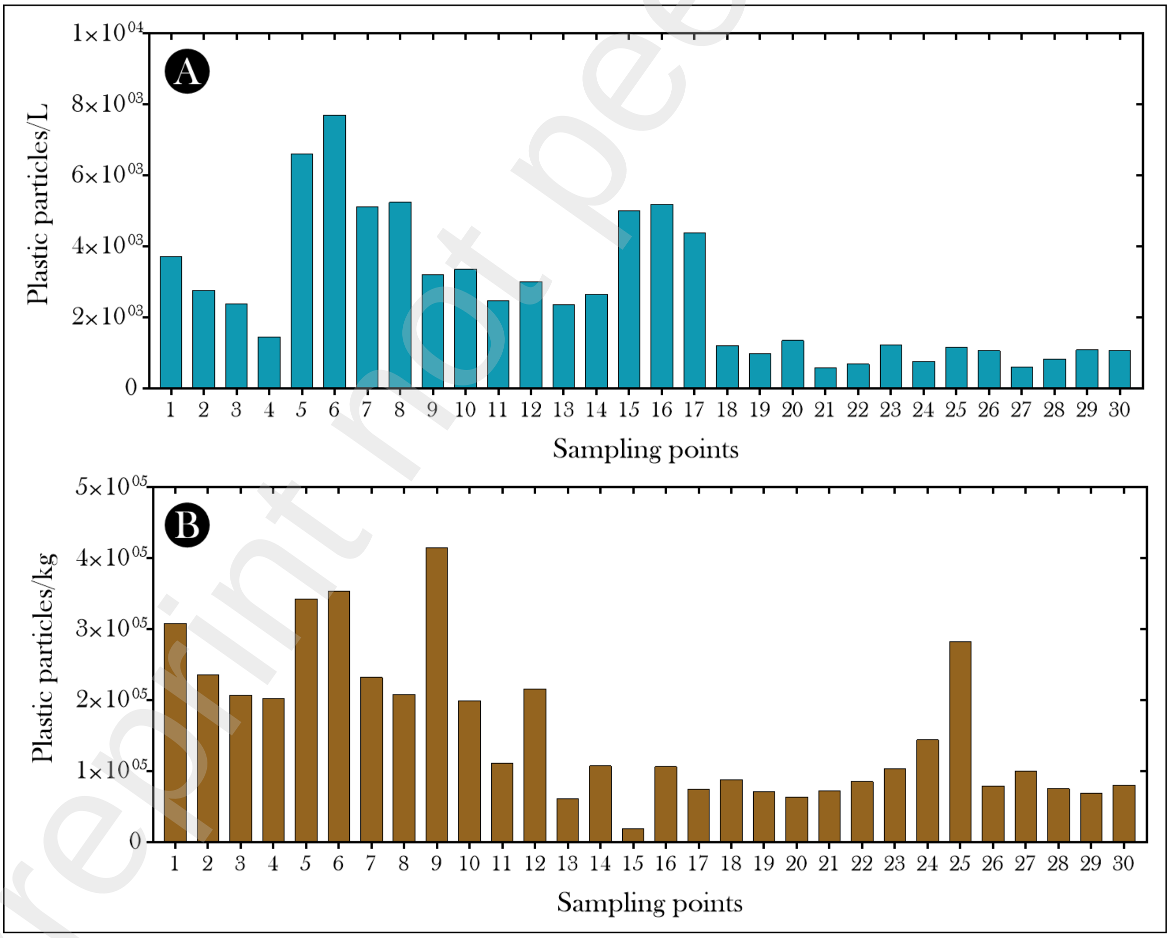

Figure 4. Microplastic abundance in all analyzed (A) water and (B) sediment samples [Pasur river and its adjacent canals (Bay of Bengal, Bangladesh].

MPs were also observed in all analyzed fish samples, considering 3-4 samples/species. Results show a higher number of MPs in the animals' GIT (10.41 ± 7.43 particles/g – median ± SEM), concerning the average concentration recorded in the muscles (4.68 ± 1.85 particles/g – median ± SEM) (higher difference at 50%) (Figure 5A). *O. pama* and *H. nehereus* were the species that showed the highest MPs accumulation in the GIT (Figure 5B). In the muscles, the highest MP levels were observed in *T. ilisha* and *L. calcarifer* (Figure 5C).

The fish species were divided into different feeding zones according to their food habit. The fish from the benthopelagic zone is mostly contaminated with MPs (Parvin et al., 2021), which was confirmed in our study (Figure 6A). Although the MP concentrations in the GIT did not differ significantly in fish when we performed the analysis considering the feeding zone of the animals, we noticed that the evaluated benthopelagic species [especially *Otolithoides pama* and *Harpadon nehereus* (Table 1)] showed MPs accumulation in the GIT, on average 80.57% higher than that observed in the other species (Figure 6A). In addition, expressive MP concentration in demersal fish was identified, which confirms previous studies reporting that the ultimate sink for MPs in water is the benthic and demersal zones (Goldberg, 1997; Pauly et al., 1998; Woodall et al., 2014). A similar pattern was observed when we analyzed the MP concentrations in the muscles of the animals (Figure 6B), which suggests that the uptake of MPs via oral ingestion is a preponderant factor for the absorption of these pollutants and accumulation in the muscles. Overall, we observed a statistically significant correlation between the MP concentrations in the animals' GIT and muscles, as well as a linear increase in the presence of MPs in the muscle as there is a greater uptake of MPs via oral ingestion, thus confirming this hypothesis (Figure 5D).

The presence of high MP contamination in *O. pama* and *H. nehereus*, in particular, constitutes a worrying result since *O. pama* [earlier known as *Pama pama* (*Sciaenoides pama*)] and *H. nehereus* (the most famous member of this genus is the Bombay duck), forms an important sciaenid fishery in the Asiatic estuarine systems (Liang & Pauly, 2017; Gao et al., 2018; Bhakta et al. 2019ab; Bhakta et al., 2022). Therefore, the consumption of these animals represents a potential route of human MP contamination.

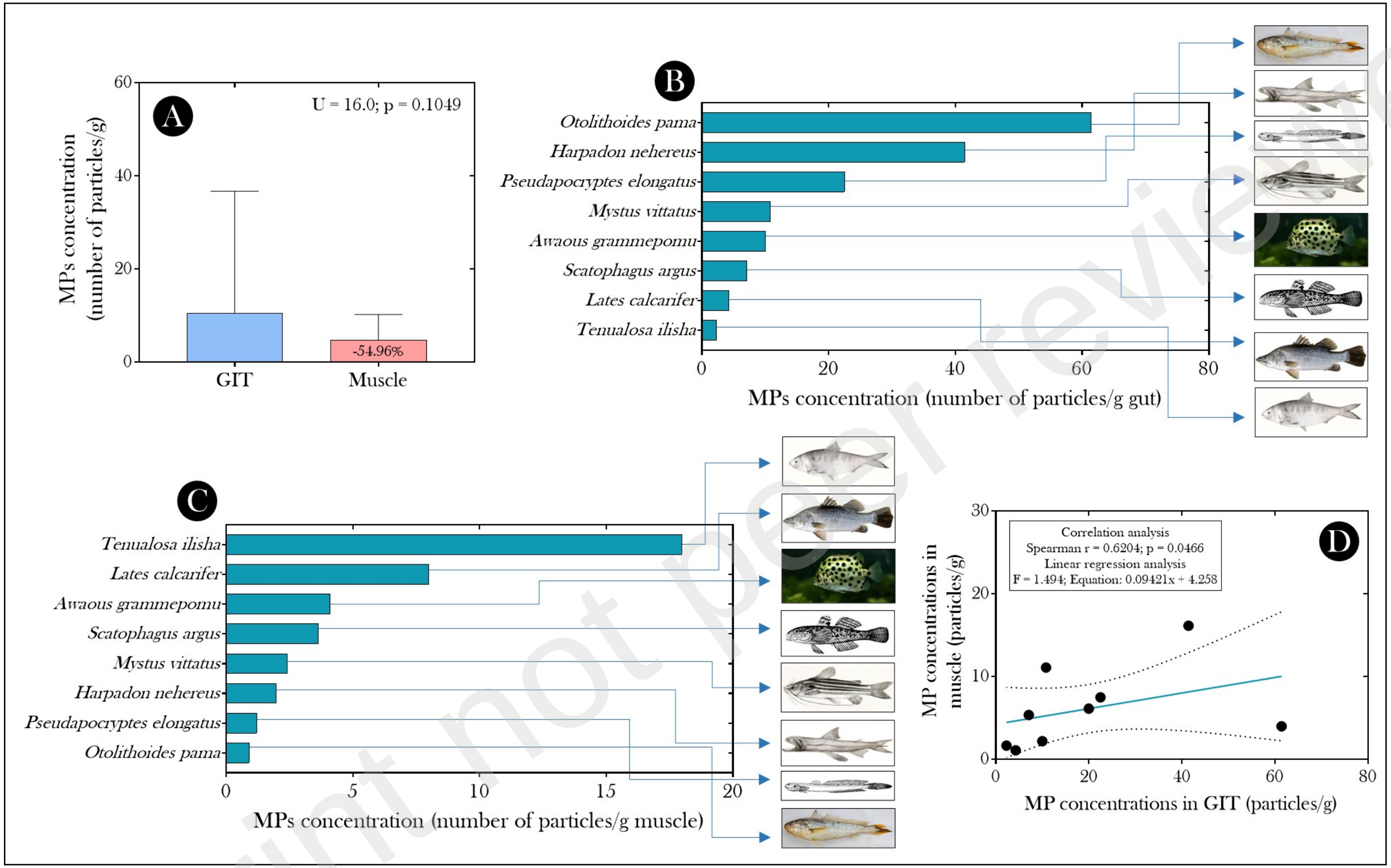

Figure 5. Microplastic concentrations in the gastrointestinal tract (GIT) and muscle samples of fish collected in the Pasur river of Mongla City (Bangladesh). (A) Mean of MP concentrations in GIT *vs*. muscle; (B and C) MP concentrations in GIT and muscle samples, respectively, of the different fish species. (D) Correlation and linear regression analysis between MP concentrations in GIT and muscles. In "A", non-parametric data are presented by the median and interquartile range, and the summary of the statistical analysis is shown at the top of the graph.

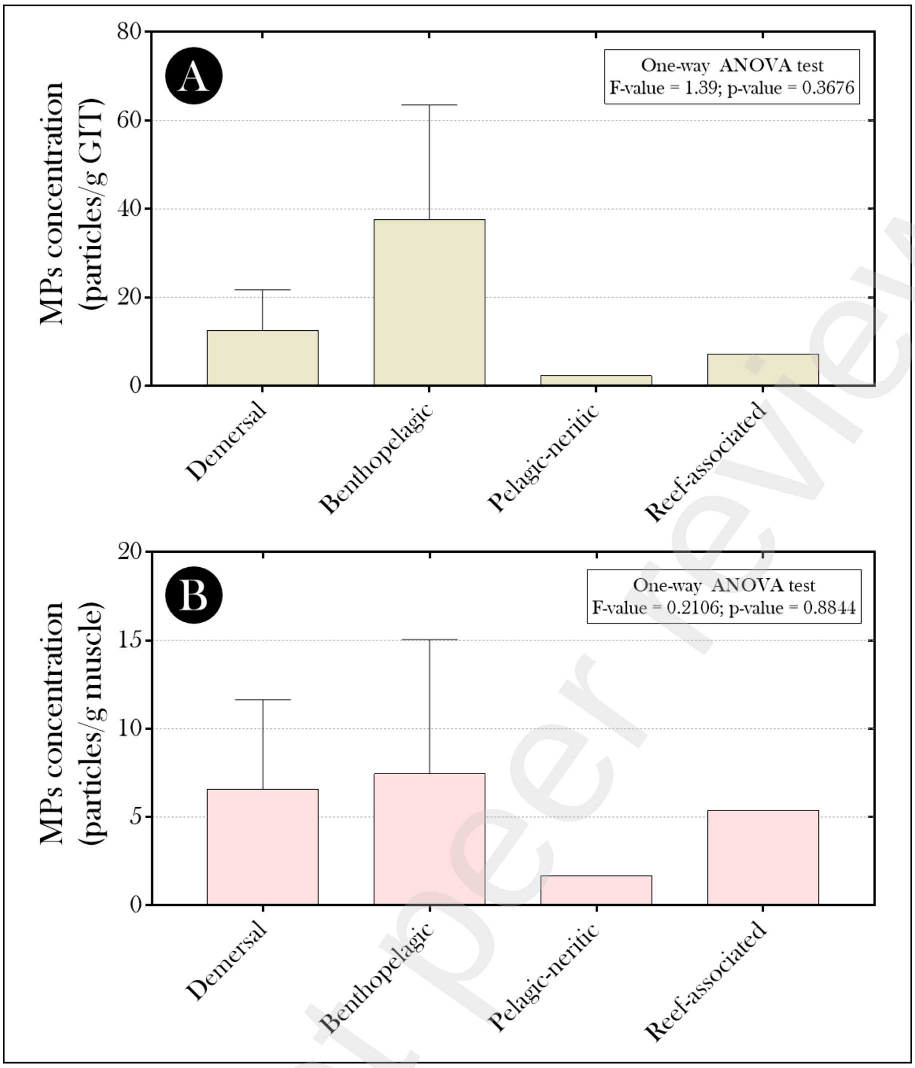

Figure 6. Microplastic (MP) concentrations in (A) gastrointestinal tract (GIT) and (B) muscle of fish separated by habitat type (demersal, benthopelagic, pelagic-neritic, and reef-associated) [Pasur river of Mongla City (Bangladesh)]. Parametric data are presented by the mean + standard deviation, and summaries of statistical analyzes are shown at the top of the graphs.

Regarding the characterization of the MPs identified in our study, we observed that most of the particles found were secondary type, as they do not have any symmetrical shapes, unlike primary particles (Galgani et al., 2015). MPs were differentiated among five forms in this study, like Zhou et al. (2016), with the fragments dominant in the water and sediment samples (Figure 7A-B, respectively). On the other hand, the MP types most abundant in the GIT and muscle samples were the fibers and fragments (Figure 7C-D, respectively). While fragments were more frequent in sediment samples than in water samples (Figure 8A), fibers were more abundant in water samples (Figure 8A). In the biological samples, the differences between the types of MPs in the GIT and muscle samples were not observed (Figure 8B).

Similar research also found abundant fragments in sediments (Horton et al., 2017; Selvam et al., 2021; Zuo et al., 2020). Fragment particles occur due to the breakdown of plastic particles (Cole et al., 2011). Some secondary MPs of asymmetrical shape are released from packaging materials such as water bottles, juice bottles, milk cans, garbage bags, polybags, etc. (Wang et al., 2019). Pellets or granules generally come from the presence of fragments to prove that the particles found are of secondary origin (Lehtiniemi et al., 2018). It is reported that microorganisms living in the mangrove can degrade plastics into fragment particles (Deng et al., 2021). Many studies found an abundance of fiber and fragments in water (Aliabad et al., 2019; Nabizadeh et al., 2019).

The abundance of fiber particles in fish GIT was also reported by other studies (Daniel et al., 2020; Garcés-Ordóñez et al., 2020; Karlsson et al., 2017; R. Li et al., 2020; Parvin et al., 2021). These particles may come from extreme fishing activities, an everyday livelihood in the Mongla district, because of fishing nets, nylon nets, and gill nets (Garcés-Ordóñez et al., 2020; R. Li et al., 2020). Fibers in GIT may also come from textiles and clothes, sewage water from cloth washing, etc. (Browne et al., 2011; Park et al., 2020). Other sources of fiber found in fish GIT can be from household wastewater and textile wastes (Hossain et al., 2020).

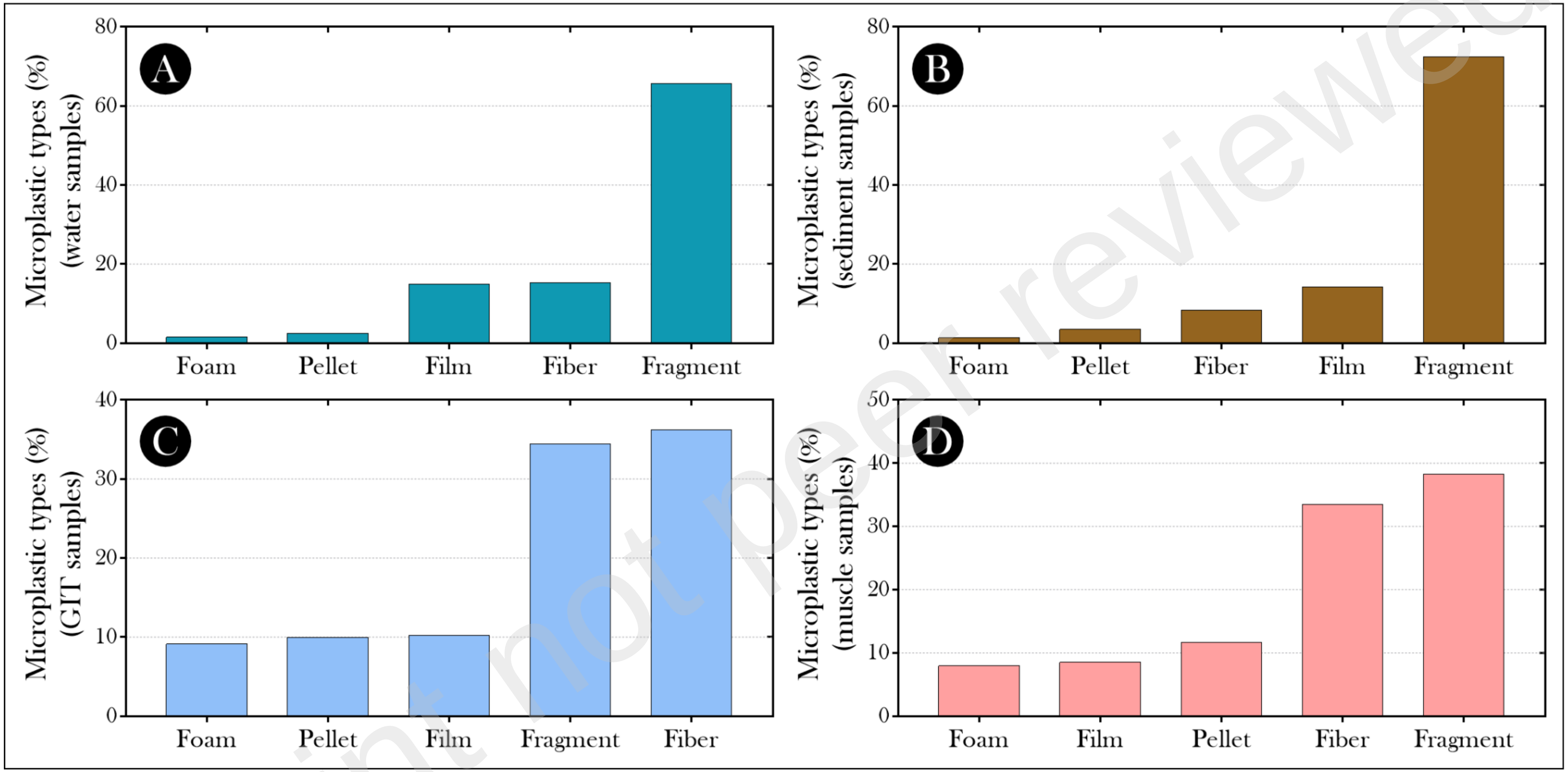

Figure 7. Microplastic types (%) identified in the present study in (A) water, (B) sediment, (C) gastrointestinal tract (GIT), and (D) muscle samples.

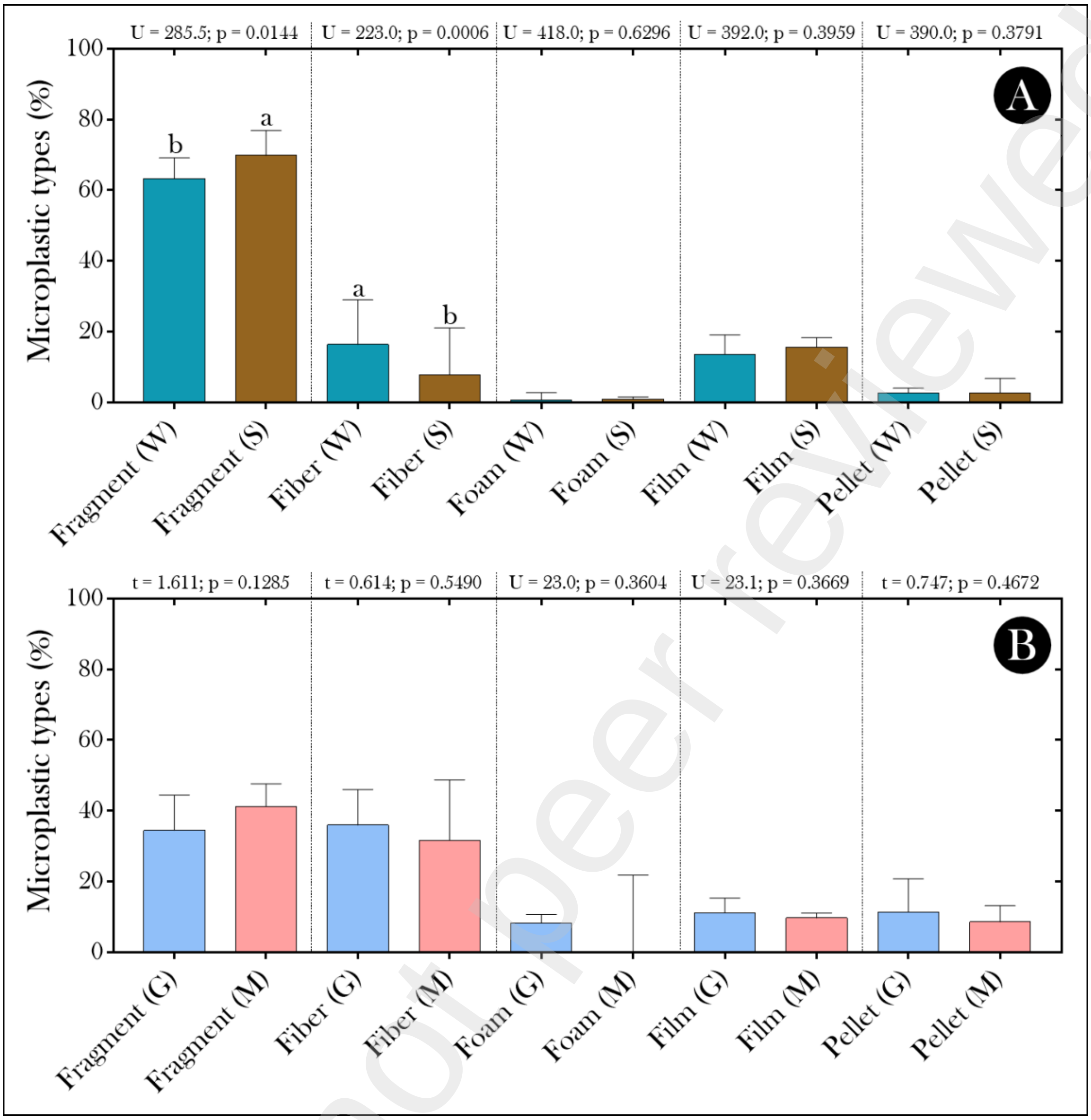

Figure 8. Microplastic types (%) in the different samples analyzed in our study. (A) Water (W) and sediment (S) samples and (B) gastrointestinal tract (GIT) and muscle (M) samples. Parametric data are presented by the mean + standard deviation, whereas non-parametric data are presented by the median and interquartile range. Summaries of statistical analysis are shown at the top of the graphs.

Microplastics were diversified among the samples, and ten color schemes were observed (Figure 9A). Water samples showed the most diversified color combinations among the water, sediment, and fish samples, with more violet, red, blue, and orange colored particles than the others. Although in all samples, black and brown were dominant, ranging between 23-39% and 18-23% particles, respectively. The yellow color was found at the lowest percentage, less than 2% in the samples. Sediment samples had the least diversified plastic particles according to color, with most of the particles being black or brown (Figure 9A). Most sediment samples were brown, although transparent films and white-ish colored pellets were seen.

The black color-dominated particles were also found by other researchers (Hossain et al., 2020; Zuo et al., 2020). Several studies have differentiated plastic particles to be 'colored' and 'non-colored'; while some researchers found white and transparent colors to be dominant among MPs, others have seen red and blue colors to be prevalent (Deng et al., 2021; J. Li et al., 2018; R. Li et al., 2019, 2020; Mohamed Nor & Obbard, 2014). The source of the colored particles may come from the coloring materials of fishing gears and vessels and packaging (Aliabad et al., 2019; R. Li et al., 2020). Fishing activities are common occupations of the people in Mongla. From dingy boats to engine boats and speed boats, varieties of colors are used; colors from fishing gears are a possible source of colored particles. The colored particles are likely to be ingested by marine biota as it resembles food particles for fishes; thus, attraction by color is a cause of ingestion (Abayomi et al., 2017; Mohamed Nor & Obbard, 2014; Rakib et al., 2022).

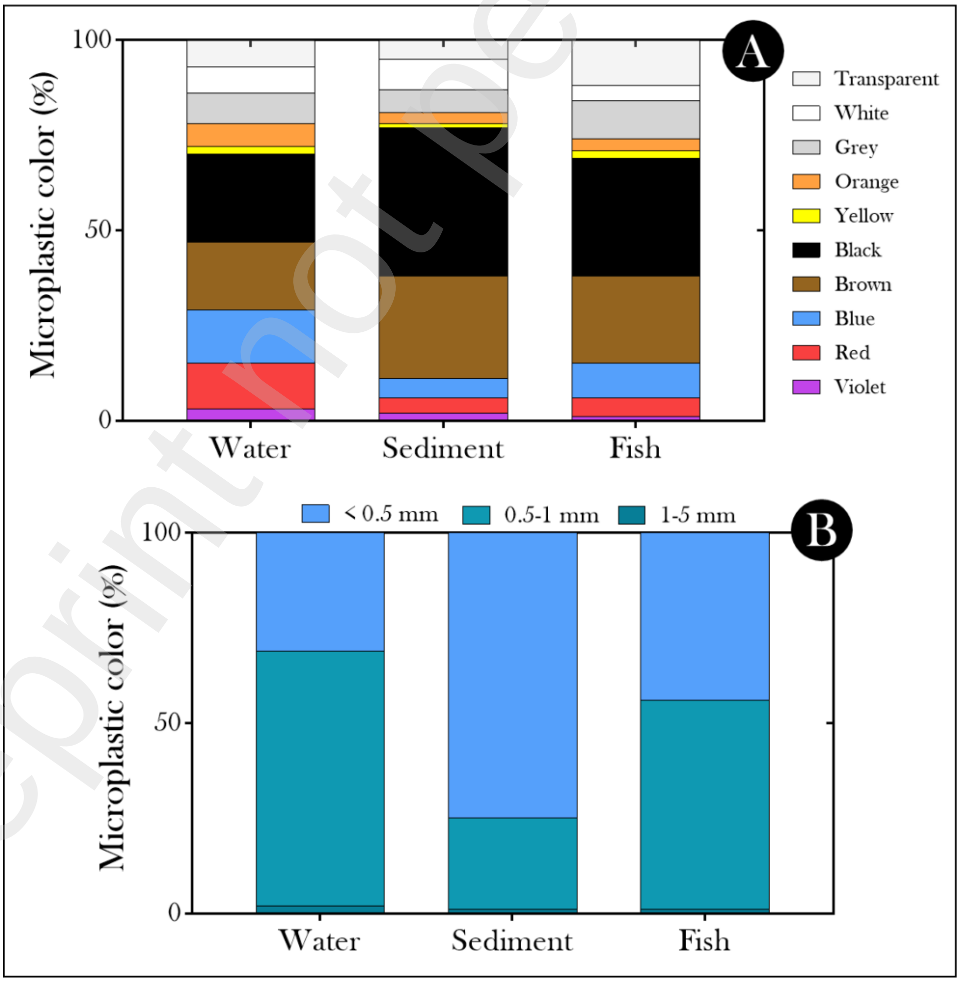

Figure 9. Microplastic (A) color and (B) size percentages identified in the water, sediment, and fish samples analyzed in the present study.

Furthermore, MPs were found among three size ranges (Figure 9B). Most particles in water and fish samples, 67% and 55%, respectively, were found to be in ranges 0.5-1 mm; but in sediment samples, about 75% of particles were of size ranges below 0.5 mm. Larger particles of 1-5 mm sizes were scarce, about 1-2%, in all three samples. These particles are visible to the naked eye, and most of the observed filter paper was clear, indicating the scarcity of larger particles. Related studies show similar results in the abundance of MPs ranging below 1 mm in size (Hamid et al., 2020; J. Li et al., 2018; R. Li et al., 2020; Naji et al., 2019; Q. Wang et al., 2020; Zhou et al., 2020; Zuo et al., 2020). The smaller particles are more likely to be uptake by a marine organism (Mohamed Nor & Obbard, 2014). The small size also depicts the particle as a secondary MP, which occurs through the breakdown of primary plastic particles. Microscopic analysis shows vibrant colors and various shapes of microplastics present in the studied samples (Figure 10).

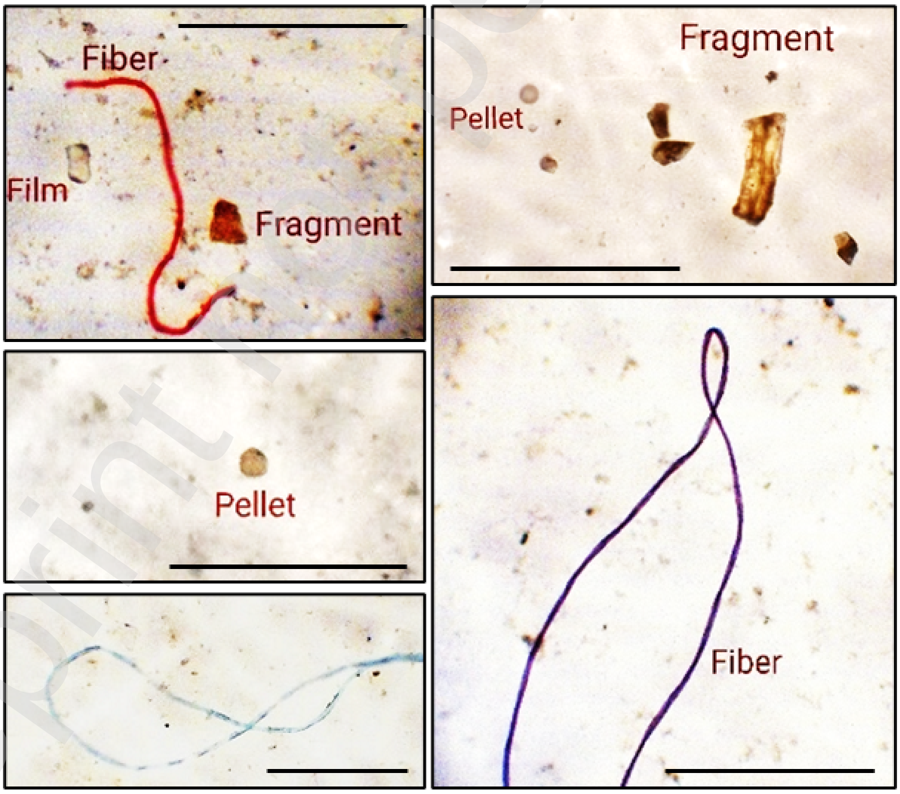

Figure 10. Representative photomicrographs of the types of microplastics identified in the present study. Barr scale = 0.1 mm.

Regarding the identification of polymers in the analyzed samples, the results of the analysis via FT-IR revealed the presence of seven polymeric types [polyamide (PA), polystyrene (PS), polyethylene (PE), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), and polyvinylchloride (PVC)], by comparing the spectra obtained in our study (Figures 11A, 12A, 13A, and 14A) with those available in the literature (Chércoles Asensio et al ., 2009; Daniel et al., 2020; Jung et al., 2018; Nishikida & Coates, 2003; Noda et al., 2007; Selvam et al., 2021). While in the GIT and muscle samples, the percentages of the polymeric types did not differ (Figures 11B and 12B, respectively), in the water and sediment samples, PA was the most abundant polymer in these samples (Figures 13B and 14B, respectively). Furthermore, we did not notice significant differences between the percentages of each polymeric type between the different samples analyzed (Figures 15 and 16), which confirms the relationship between the MPs available in water and sediments and those ingested by the animals.

The polymer's PP, PE, and PS abundance, in particular, can be due to the location of aquaculture around the sampling areas, as the aquaculture can contribute to these polymers (J. Li et al., 2018; Q. Wang et al., 2020). The abundance of HDPE in fish can be a consequence of the usage of HDPE in daily activities, including packaging of bags, bottles of milk, detergents, any other food or juice products, pipes, etc. (Parvin et al., 2021).

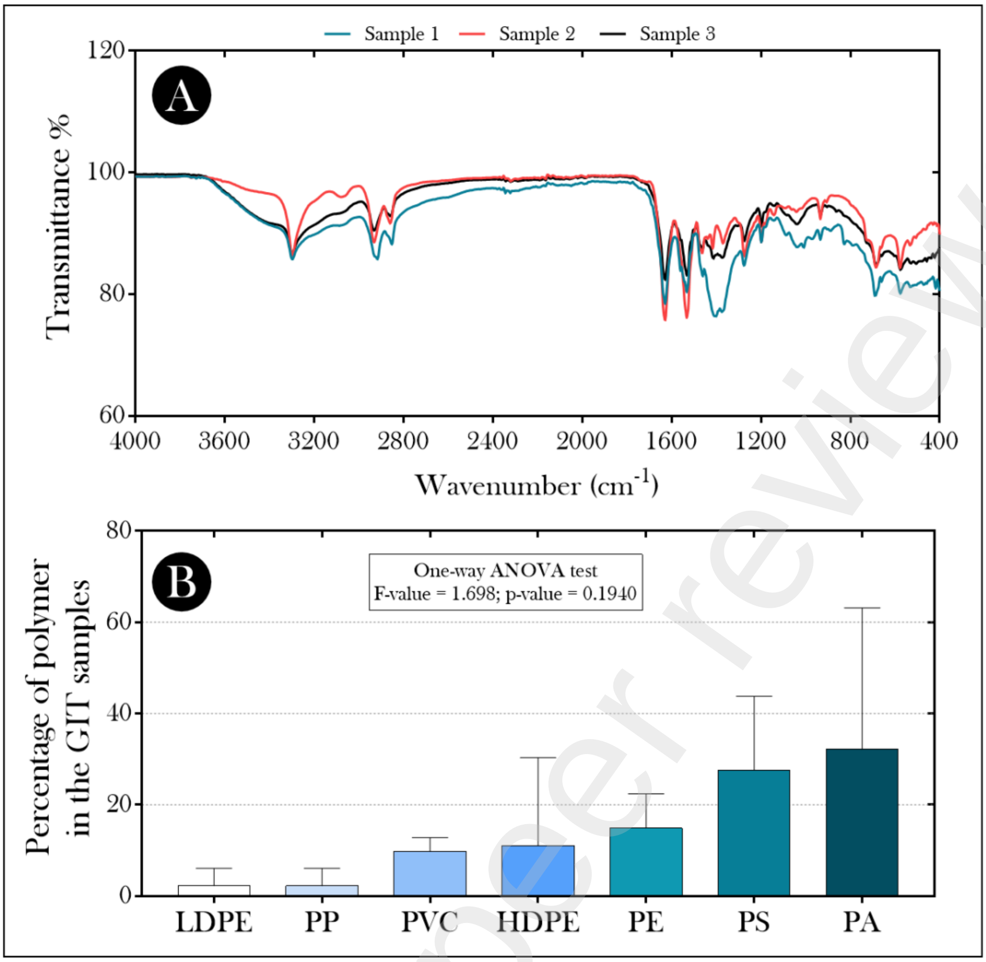

Figure 11. (A) Representative FT-IR spectra and (B) percentage of polymers identified in the gastrointestinal tract (GIT) samples of fish [Pasur river of Mongla City (Bangladesh)]. In “B”, parametric data are presented by the mean + standard deviation, and the summary of statistical analysis is shown at the top of the graph. Note: polyamide (PA), polystyrene (PS), polyethylene (PE), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), and polyvinylchloride (PVC).

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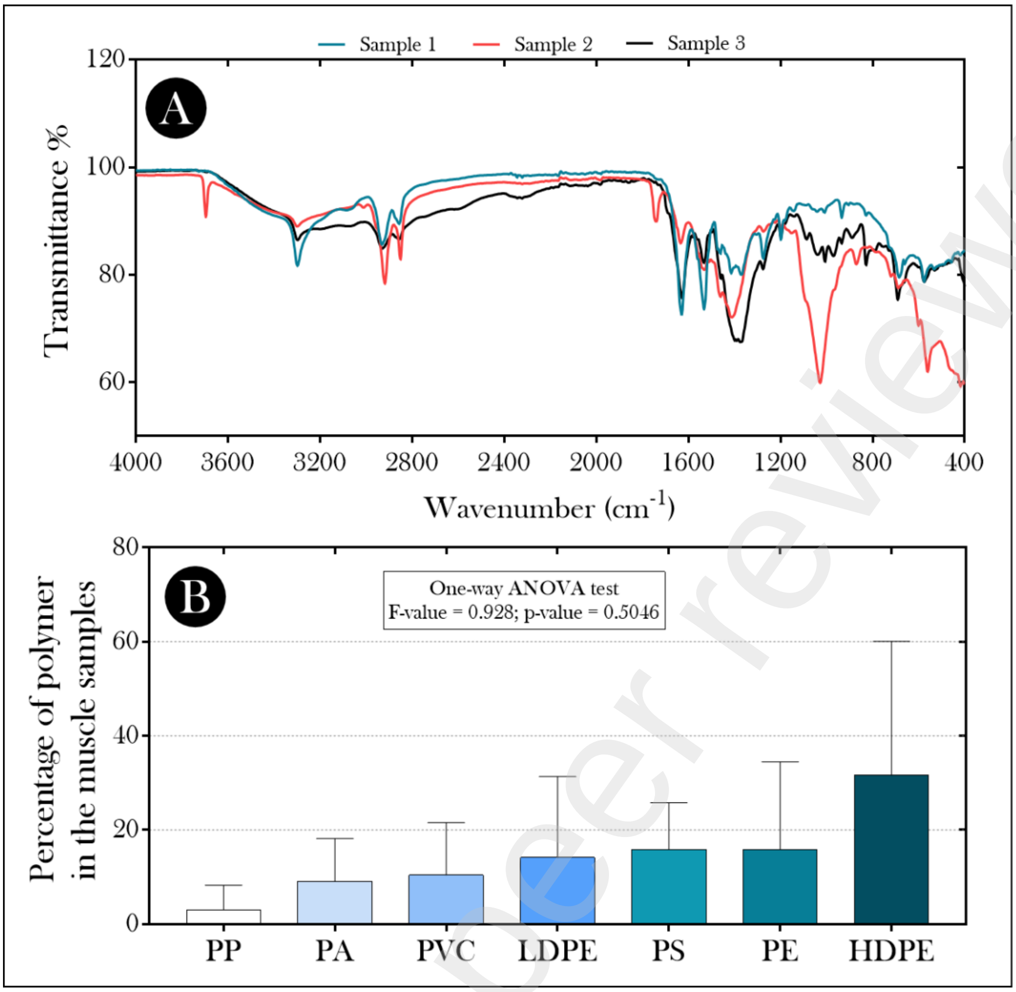

Figure 12. (A) Representative FT-IR spectra and (B) percentage of polymers identified in the muscle samples of fish [Pasur river of Mongla City (Bangladesh)]. In "B", parametric data are presented by the mean + standard deviation, and the summary of statistical analysis is shown at the top of the graph. Note: polyamide (PA), polystyrene (PS), polyethylene (PE), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), and polyvinylchloride (PVC).

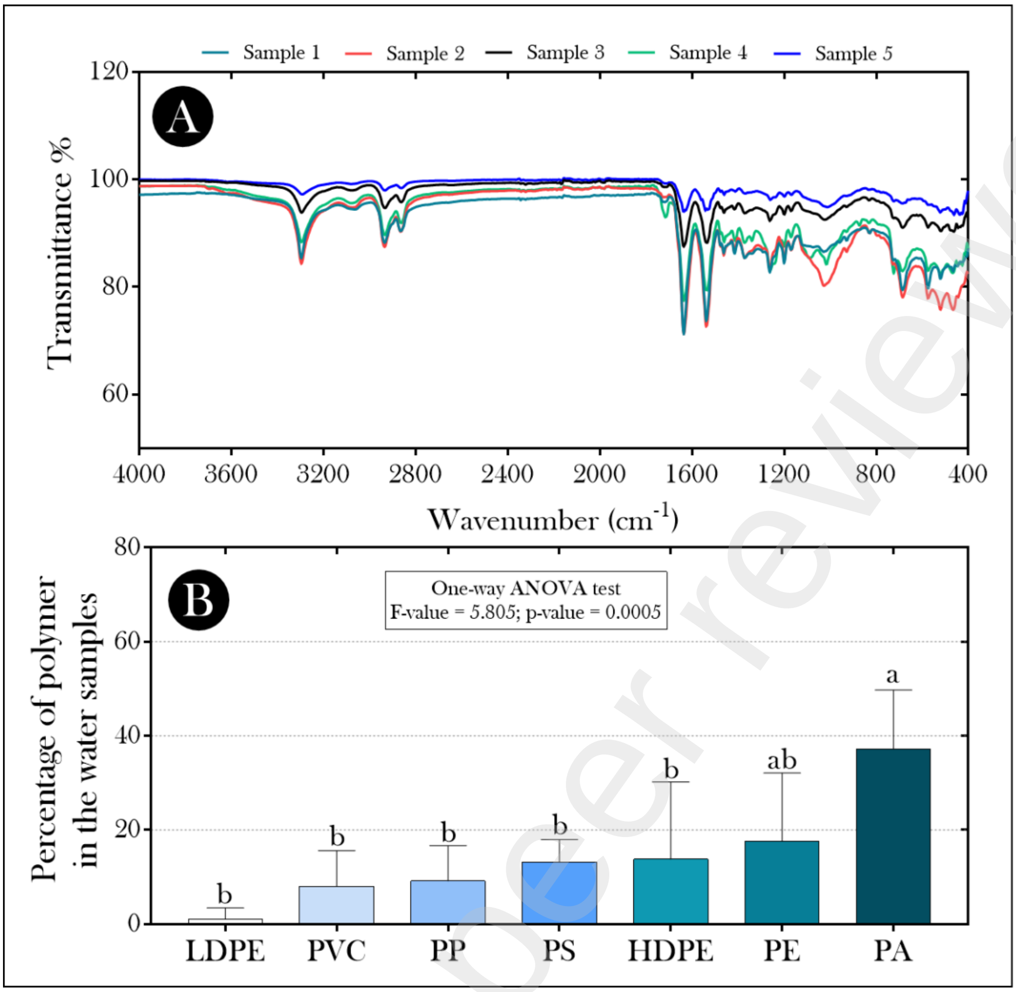

Figure 13. (A) Representative FT-IR spectra and (B) percentage of polymers identified in the water samples. In “B”, parametric data are presented by the mean + standard deviation, and the summary of statistical analysis is shown at the top of the graph. Distinct lowercase letters indicate significant differences. Note: polyamide (PA), polystyrene (PS), polyethylene (PE), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), and polyvinylchloride (PVC).

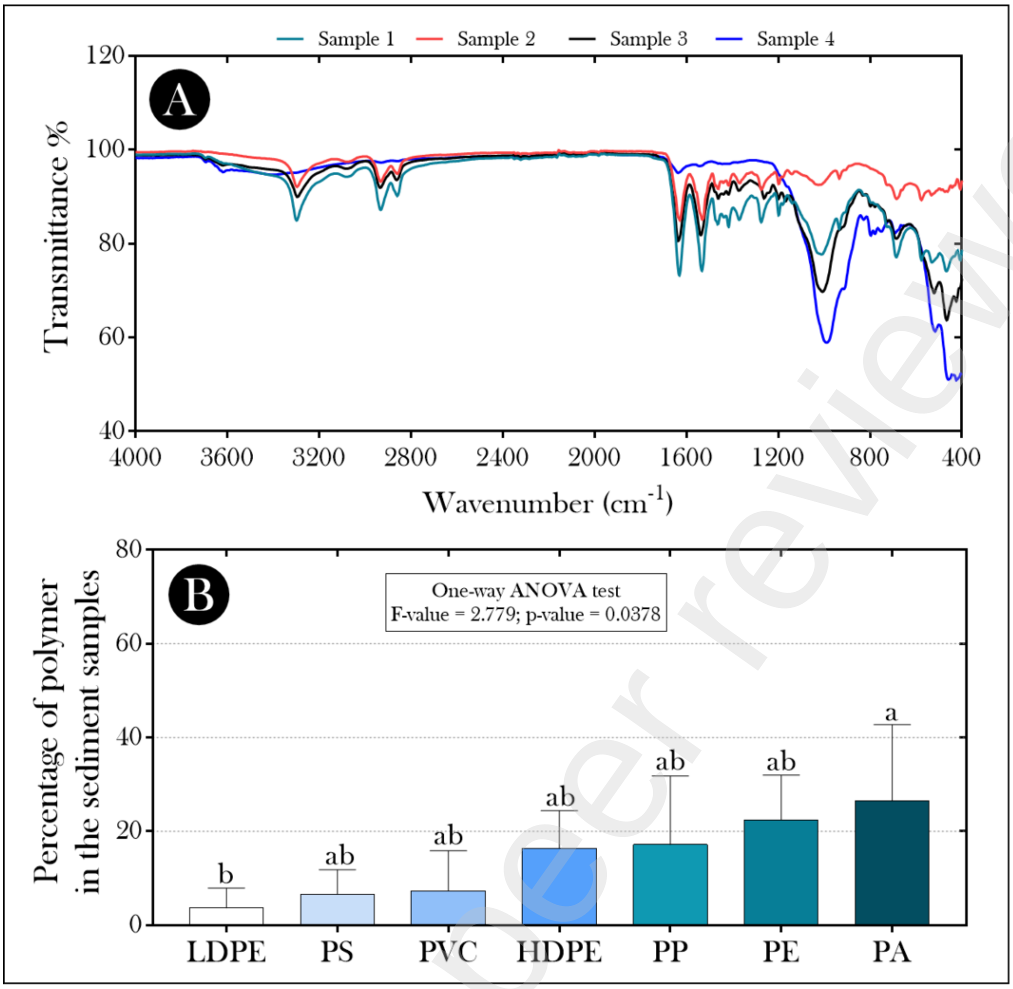

Figure 14. (A) Representative FT-IR spectra and (B) percentage of polymers identified in the sediment samples. In "B", parametric data are presented by the mean + standard deviation, and the summary of statistical analysis is shown at the top of the graph. Distinct lowercase letters indicate significant differences. Note: polyamide (PA), polystyrene (PS), polyethylene (PE), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), and polyvinylchloride (PVC).

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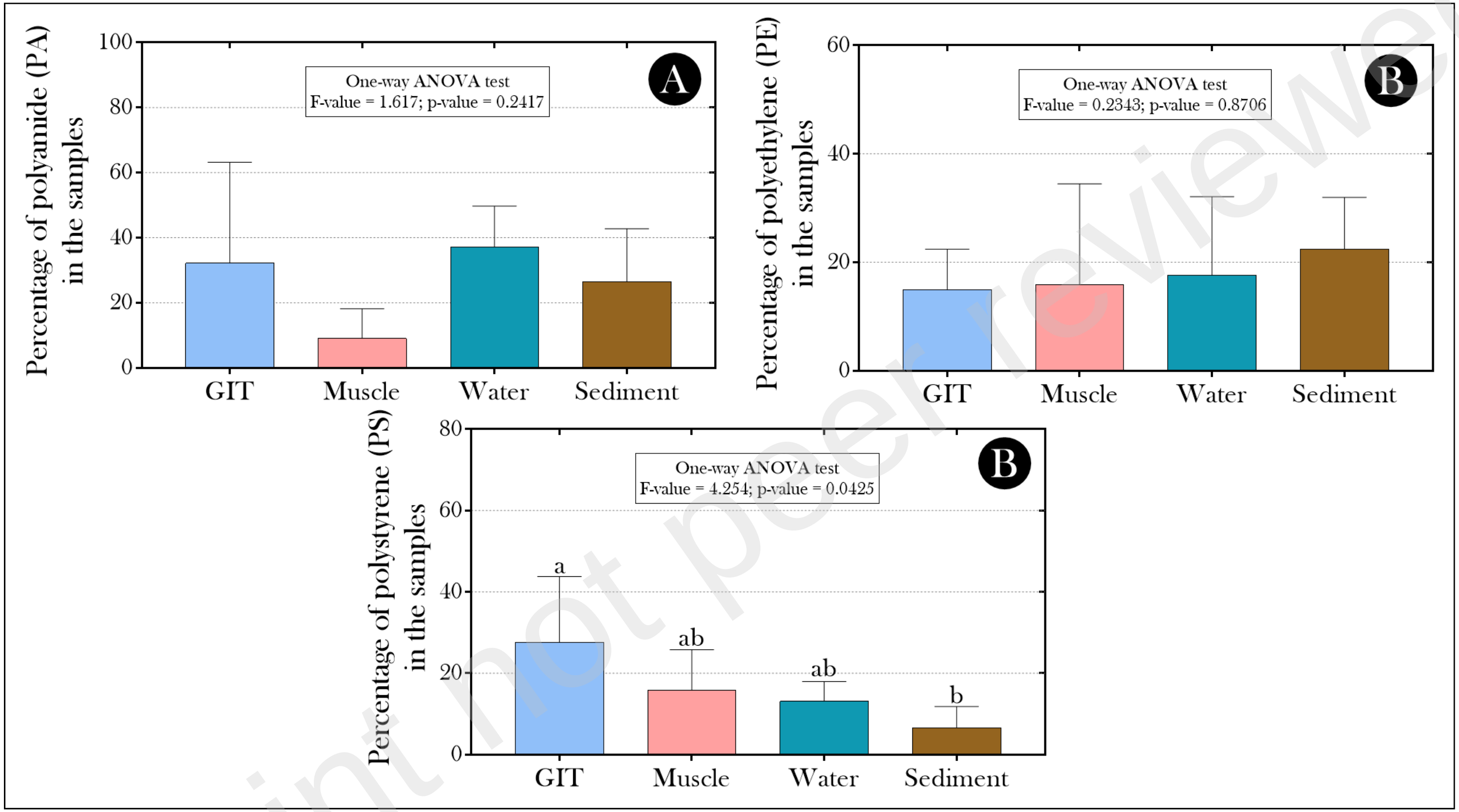

Figure 15. Percentage of (A) polyamide, (B) polyethylene, and (C) polystyrene identified via FT-IR analysis in the different samples analyzed in the present study. Parametric data are presented by the mean + standard deviation, and the statistical analysis summaries are shown at the top of the graphs.

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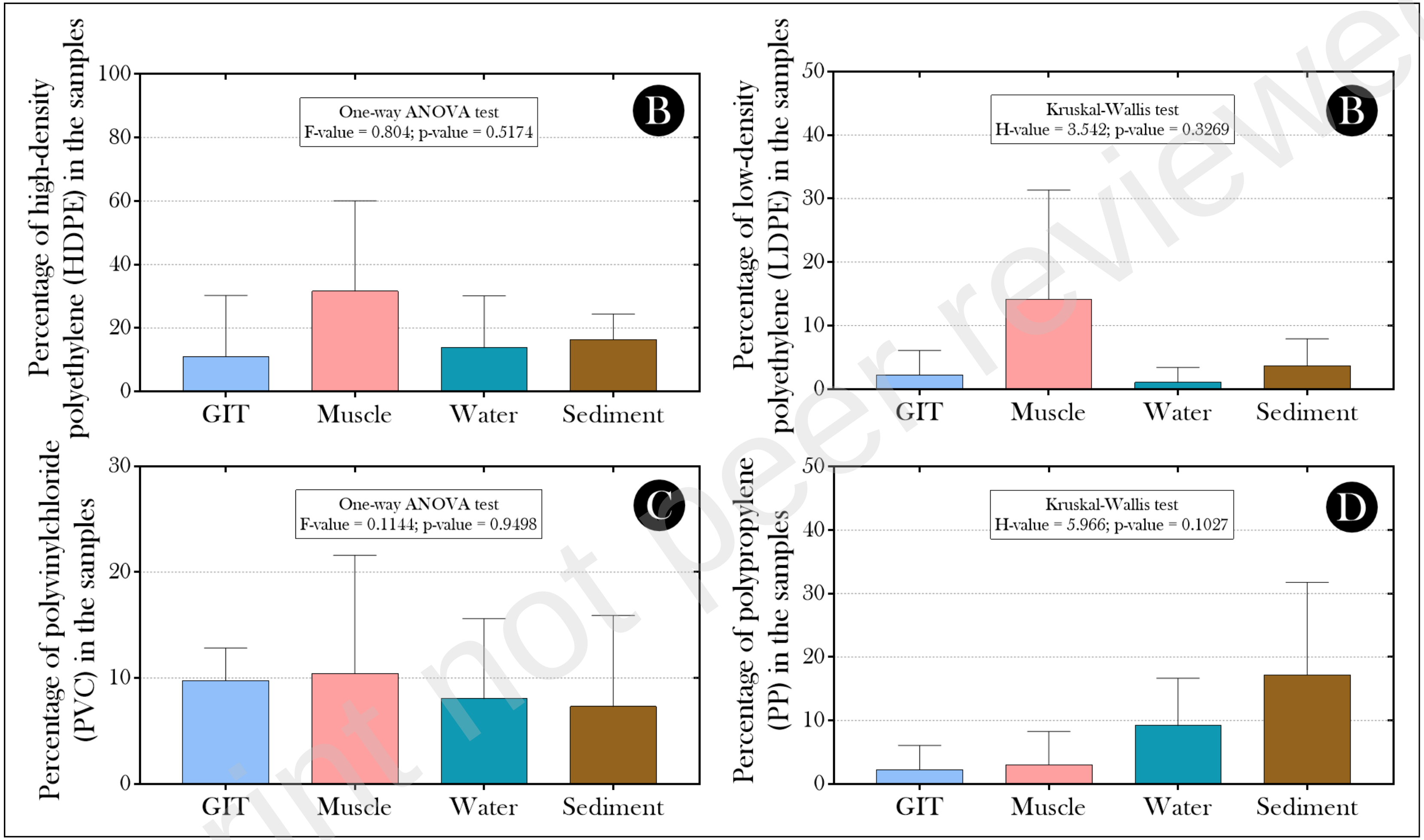

Figure 16. Percentage of (A) high-density polyethylene, (B) low-density polyethylene, (C) polyvinylchloride, and (C) polypropylene identified via FT-IR analysis in the different samples analyzed in the present study. Parametric data are presented by the mean + standard deviation, and the statistical analysis summaries are shown at the top of the graphs.

Different exposures to the environment may have an impact on the structural morphology and additive content of microplastics. The chemical and morphological characteristics can be identified through scanning electron microscopy (Fries et al., 2013). Some samples were selected for SEM analysis, although it is challenging to identify the sources of fiber and fragments through the images (Parvin et al., 2021). SEM images showed several fractures, cracks, flakes, and scratches on the surface of MPs. Some images showed particles adhering to the surface of MPs (Figure 17). MPs not only remain in the environment for extended periods than other pollutants but also absorb other harmful inorganic and organic pollutants like PAHs, pathogens, and heavy metals on their surface. Its larger surface is one reason for this absorbance, leading to toxicity (Rochman et al., 2013; Schrank et al., 2019; Yang et al., 2014). Flakes may result from the particle's oxidative weathering (Parvin et al., 2021). The features observed in the polymers prove that these plastics have gone through mechanical degradation, oxidative weathering, and aging (Wagner et al., 2014).

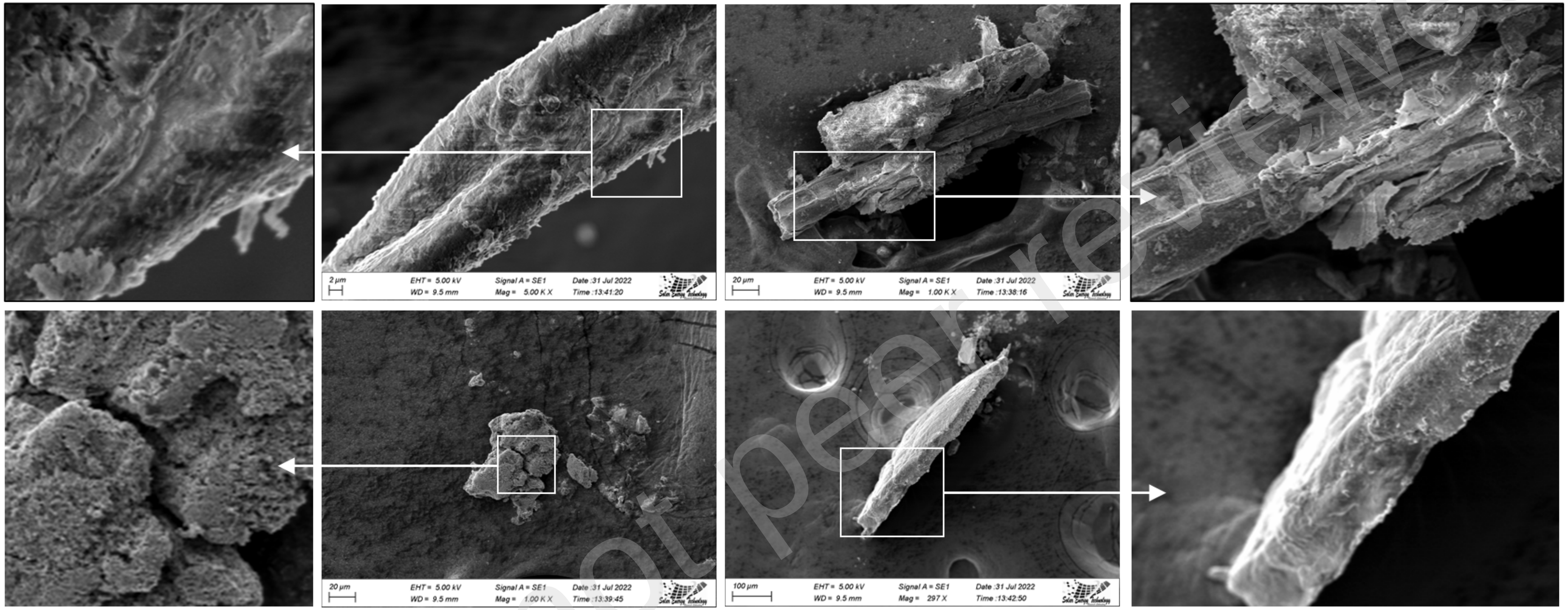

Figure 17. Representative photo electron micrographs of microplastics identified in the different samples analyzed in the present study, at different magnifications.

4. CONCLUSION

MP pollution is getting profuse attention at present in the world. Starting from sediment to human blood, it has announced its presence in every possible environment. Holding the ability to alter environmental processes in both terrestrial and aquatic settings, this pollutant is omnipresent. The present study is the first to report the presence of microplastics in the mangrove forest of Bangladesh and has found that the Sundarbans is contaminated with MPs in water, sediment, and fish body at a more significant amount than any other study described. 100% of the analyzed samples showed the presence of MPs, with sediments mainly being contaminated. Fish feeding from the benthic zone of water also showed a greater number of microplastics in their GIT than other fish species. It is also possible to bioaccumulate through fish muscle and may end up in the human digestive system through the food chain. MP contamination on the river, sediment, and fish pose a greater risk to the ecology and wildlife of Sundarbans, as well as the inhabitants. Further research on the spatial and temporal distribution of MPs along mangrove rivers is needed to understand the occurrences of microplastics more precisely and provide better mitigation measures to control pollution.

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6. DECLARATION OF COMPETING INTEREST

We certify that the study's findings were not compromised by any known ethical or financial conflicts of interest. We verified that all named authors had read, assessed, and approved the article to see if there were more writers who matched the criteria but were not mentioned. We also confirm that the authors' names appear in the article in the order in which they were approved by one another. The integrity of the work has undergone a thorough inspection.

7. ETHICAL ASPECTS

All experimental procedures adhered to the ethical standards for using animals in research, and careful precautions were taken to lessen the suffering of the animals and their exposure to outside sources of stress, pain, and discomfort. The number of animals employed in the current study is within the acceptable range to provide reliable scientific results. The authors of this paper do not cite any of their human studies.

8. DATA AVAILABILITY

The data used to support the findings of this study are available from the corresponding author upon request.

9. CREDIT AUTHOR STATEMENT

Nowshin Nawar: conceptualization, sample collection, analysis, and manuscript preparation. **Md. Mostafizur Rahman**: conceptualization, sample collection, analysis, manuscript preparation, supervision of the study. **Shumayta Marzia**: sample collection and analysis. **Mir Mohammad Ali**: sample collection, manuscript review, and editing. **Md. Ahedul Akbor**: SEM analysis and revision of the manuscript. **Md. Abu Bakar Siddique**: SEM analysis and improvement of the manuscript. **Mst Afifa Khatun**: FTIR analysis. **Md. Shajalal**: FTIR analysis. **Roksana Huque**: FTIR analysis. **Guilherme Malafaia**: analysis, interpretation of results, and draft manuscript preparation. All authors reviewed the results and approved the final version of the manuscript.

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