

Article

Microplastic Pollution in Commercially Important Seafood from Chandipur, Bay of Bengal, East Coast of India: A Detailed Risk Analysis

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Abstract

Microplastic (MP) pollution in marine ecosystems is a matter of concern worldwide, as their ingestion and accumulation in marine fauna pose a significant health risk associated with MP pollution. This detailed study is the first of its kind in the Chandipur coastal waters, Bay of Bengal to comprehensively evaluate MP pollution, and associated pollution load in commonly consumed edible fish and shrimp species. Samples of *Harpadon* sp., *Setipinna taty*, *Coilia dussumieri*, *Johnius belangerii*, *Pampus* sp., *Arius arius*, and *Penaeus monodon* were collected from Chandipur, Odisha, East coast of India and examined using wet peroxide oxidation, followed by FTIR spectroscopy. A relatively higher concentration of MPs was observed in the muscle tissues ($4628 \pm 11,702$ particles/g of tissue) compared to the gastrointestinal tract (GIT) (4296 ± 9687 particles/g of tissue). The abundance of MPs was maximum in *Coilia dussumieri* and minimum in *Arius arius*. Comparatively higher retention of MPs ($11,309 \pm 15,448$ particles/g of tissue) was obtained in the monsoon season than in the pre- and post-monsoon. Microscopic examination revealed the presence of mostly fiber- and fragment-type MPs, in addition to black fibers. The commonly encountered size class was 1–50 μm with 63.4%. FTIR analysis revealed eighteen different types of MPs and polyvinyl chloride (PVC), polyethylene terephthalate (PET), and cellulose acetate (CA) with occurrence percentage between 91.6 and 100%, whereas polyamide (PA) was the most uncommon and least found in all the samples. The Polymer Hazard Index (PHI) revealed the presence of extremely hazardous polymers such as polyurethane (PU), PVC, and PET in tissues, and Pollution Load Index (PLI) values indicate low pollution levels.

Keywords: MPs; fish; shrimp; Chandipur; FTIR; PHI; PLI



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1. Introduction

Plastics have gained importance because of their light weight, high durability, and cost-effectiveness. With extensive use in commercial, medical, household, industry, and municipal activities and the improper disposal of plastics, they are making their way into aquatic ecosystems. According to an announcement from the Press Information Bureau (PIB), citing the Central Pollution Control Board (CPCB) annual reports, India generated 4.14 million tons of plastic waste in 2022–2023 [1]. Global annual use of microplastics has increased the load to over 150 million tons with fiber type MPs dominating in water,

sediment, fish, and shellfish samples [2,3]. These plastics can form MPs whose size is <5 mm, through mechanical, photo-chemical, and biological degradation. The degraded forms of plastics are known as secondary type whereas the manufactured ones are called primary type of MPs [4]. The first detection of plastic debris in the ocean was reported during the 1970s [5]. The most commonly encountered forms of MPs in water bodies are polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) [6,7].

The MPs in water channels can flow on the surface, get washed to the shore, sink and accumulate at the bottom through surface fouling and colonization, or can be ingested by aquatic organisms [8,9]. Being bio-inert, the MP particles get stored in the alimentary canal. The blockage of the alimentary canal might result in delayed ovulation, reduced reproductive health, and impaired locomotion leading to drowning, low growth rate, decreased hormonal activities, and enzyme blockage resulting in the absorption of toxins in aquatic organisms [10,11]. Such recurring events ultimately lead to their death, thereby releasing the MPs into the water bodies, making them available for ingestion by other aquatic organisms. Through food chain contamination, the microplastic particles can get transferred from the prey to the predator, contaminating the whole ecosystem [12].

MPs can serve as carriers of persistent organic pollutants (POPs) like polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and poly-brominated diphenyl ethers (PBDEs) which adhere to the MPs and can enter aquatic life, creating different health hazards [7]. Trophic transfer of MPs leads to their accumulation in the liver, spleen, placenta, breast milk, lungs, and even in the brain [13,14]. Bioaccumulation of MPs has been documented by many researchers, and they observed that fish were found to bioaccumulate MPs more than crustaceans and even mollusks [15]. Microplastic accumulation is governed by many factors and is dependent on the habitat and position of the species at the trophic level; generally, organisms at higher trophic levels are often found with a high abundance of MPs [15]. Hence, the bioconcentration of MPs in fish and shellfish is a rising threat to human health due to the risk of biomagnification.

Odisha has a long coastline of 574.7 km and is rich in aquatic fauna suitable for commercial consumption. Among its key locations, Chandipur has recently gained prominence as an important fish landing center which is going to be developed as a fishing harbor in the near future. As per the report of the Directorate of Fisheries, Government of Odisha, India for the year 2023–2024, the marine fish production for Balasore was around 47,820 MT which is the third highest in the State. With the increase in fish production and export of seafood, more landing facilities are required, which will eventually increase the microplastic load in aquatic systems. Given the high dependency on aquatic resources due to livelihood returns, nutritional fulfillment, and the production of nutraceuticals for improving human health, it is expected that microplastic pollution is bound to increase.

Although several studies have reported the abundance of MPs in vertebrate and invertebrate organisms across the Bay of Bengal [16–20], no detailed prior work has addressed the microplastic (MP) pollution in commercially available and commonly consumed fish and shrimp samples at Chandipur, Bay of Bengal, India. The present study provides a first assessment of microplastic pollution in commercially important seafood at Chandipur, Bay of Bengal. In addition, the current study aims to characterize microplastics (MPs) in the gastrointestinal tracts (GIT) and muscle tissues of Bombil, Hairfin anchovy, Goldspotted grenadier anchovy, Croaker, Pomfret, Sea catfish, and Tiger prawn across three seasons from the Chandipur coast (Bay of Bengal), and to assess their associated ecological risks. The ecological risks were evaluated by calculating the Pollution Load Index (PLI) and the Polymer Hazard Index (PHI). The PLI assesses the level of MP contamination by examining MP concentrations relative to a baseline, whereas the PHI estimates potential ecological

risks by evaluating the hazard scores of different polymer types. These findings provide valuable baseline data on MP contamination in aquatic organisms across different feeding zones, as well as the associated risks of consuming seafood from the Chandipur coast (central Bay of Bengal), ultimately improving our understanding of MP distribution, seasonal variations, and their associated risks in edible seafood.

2. Materials and Methodology

2.1. Chemicals

Sodium chloride (NaCl, AR, HIMEDIA, Mumbai, India), Potassium hydroxide (KOH, AR, HIMEDIA, Mumbai, India), Hydrogen peroxide (H_2O_2 , AR, 30%, Merck, Darmstadt, Germany), Ferrous sulphate heptahydrate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, extrapure AR, 99.5%, SRL-97868, Mumbai, India), Sulphuric acid (H_2SO_4 , AR, 95%, Merck, Darmstadt, Germany), Potassium bromide (KBr, SRL-13873, 99.5%, Mumbai, India), Acetone (extra pure AR, SRL-0129135, Mumbai, India), and Nile Red (NR, SRL-47353, Mumbai, India) were used for the present study.

2.2. Study Site and Collection of Organisms

The sampling site is an important fishing hub with a temporary fish landing center that handles more than 2213 fishing vessels and trawlers operating in the coastal waters. These vessels contribute to microplastic (MPs) pollution through the wear and tear of fishing gears, plastic packaging, and trawler activities. Additionally, Chandipur receives a large number of tourists, which results in plastic littering. The coastal waters also receive inputs from upstream waterways and industrial outlets, which introduce a substantial number of MPs into the water. Furthermore, the waters are impacted by mismanaged solid waste from near-shore human settlements. Besides fishing, tourism, and settlements, the study area is influenced by the local fish-feed industry. Notably, the region is also known as Wheeler Island. Sampling was carried out along a designated stretch of the Chandipur coast with geographical coordinates $21^\circ 29.663' \text{ N}$ and $87^\circ 10.234' \text{ E}$ (P1) to $21^\circ 26.713' \text{ N}$ and $87^\circ 05.288' \text{ E}$ (P2) (in Figure 1) using commercial fishing trawler fitted with an automated winch system to release and haul the nets. The selection of samples was based on their ecological and commercial importance, consumption, nutritional value, local abundance, and their feeding habit and habitat. The fish and prawn samples ($n = 3$ in duplicate for each species) were collected in pre-monsoon, monsoon, and post-monsoon season to understand variation if any, in the distribution of MPs. For collection, both motorized gill net and multiday trawl net with towing speed between 2.5 and 3 knots and duration 120 min were used for each haul. Samples after collection were transported to the laboratory in an ice box for further processing.

2.3. Tissue Processing and Microplastic Extraction

Refrigerated samples were thawed at room temperature and washed with distilled water; total length and weight using electronic balance (Citizen, Model CY220, Mumbai, India) of each sample were recorded. The gastrointestinal tract (GIT) and muscle tissues were dissected and weighed. The dissected tissues underwent alkaline digestion by 30 mL of 4 M Potassium hydroxide (KOH) solution for 5 g of tissue. This was followed by the addition of 5 mL 30% Hydrogen peroxide (H_2O_2) and incubated for 12 h at 25°C [21]. Further wet peroxide oxidation (WPO) using 20 mL of H_2O_2 and Fe (II) solution was used to digest the organic matter using a magnetic stirrer with hot plate (REMI, Model 5MLH, Mumbai, India). The 0.05 M Fe (II) solution was prepared by dissolving 7.5 g of $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ in 500 mL distilled water and 3 mL of concentrated H_2SO_4 . The solution was then subjected to density separation using 6 g of Sodium chloride (NaCl) [22]. The microplastic solution

obtained from density separation was passed through sieves ranging from 1 μm to 5 mm to separate MPs. The sieves were continuously rinsed with distilled water to avoid adhesion of MPs on the surface of the sieves, and collected in a Petri dish. The extracted MPs were dried and mounted on glass slides, followed by gravimetric analysis, microscopic examination, and FTIR analysis.

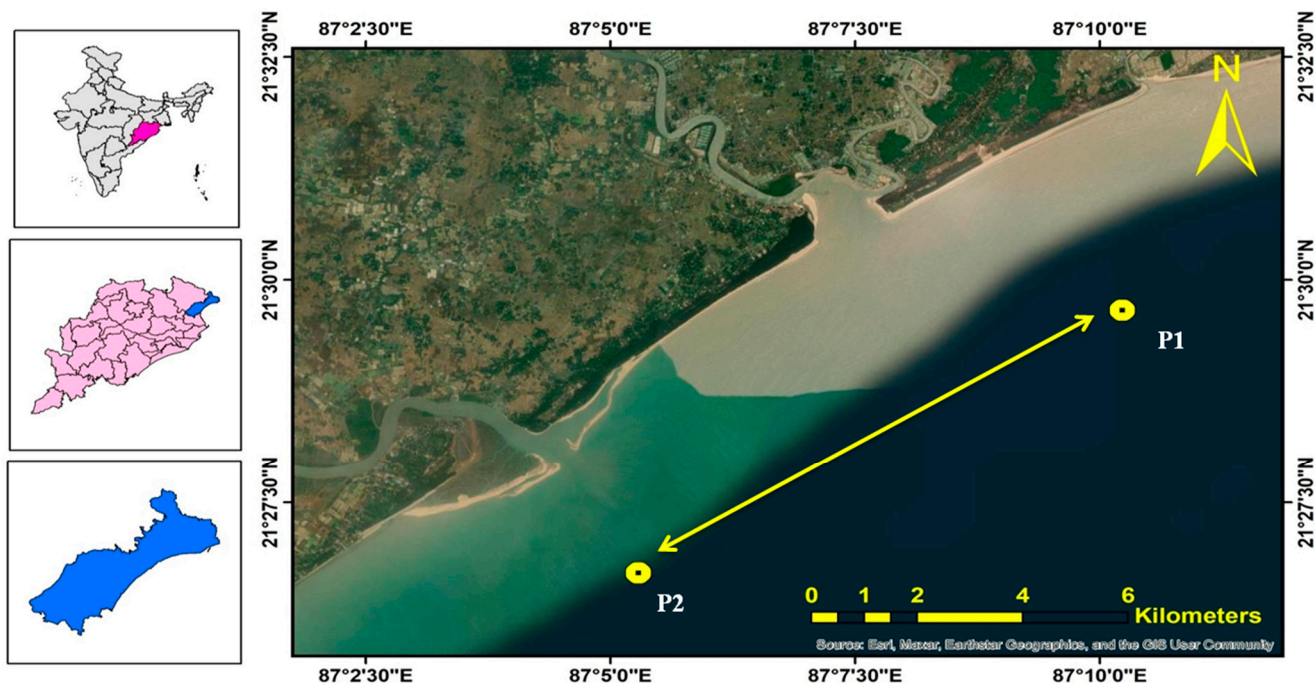


Figure 1. Location of the sampling sites for collection of organisms with $n = 4$, for each species from P1 to P2. India Map (Gray); Odisha Map (Pink); Balasore Map (Blue).

2.4. MP Visualization and Characterization

The dried slides were examined under a Nikon microscope (Tokyo, Japan) equipped with a camera at $10\times$ magnification for the visualization of MPs, to classify the MPs according to their shape and color. The fluorescent dye, Nile Red (NR) was used for identifying MPs based on the basic principle that the dye (NR) stains plastic fragments, causing them to emit fluorescence upon irradiation [23] at excitation and emission wavelengths of 515 nm and 638 nm respectively. The slides were stained with 1 ng/mL of Nile Red (SRL-47353) working solution and analyzed under a fluorescent microscope (Leica, DMi8, Wetzlar, Germany). The NR solution was prepared by diluting 1 mg/mL stock solution with Acetone. The dried samples were placed on the top of double-sided adhesive carbon tape on a sample holder, which was then plasma-coated and an ultra-structure study was carried out using a Scanning electron microscope (Gemini SEM 300, Zeiss, Jena, Germany). Fourier-Transformed Infrared Spectroscopy (FTIR) is an absorption-based technique that measures the transmitted radiation from the sample following the illumination of IR rays to provide a chemical fingerprint of the same. The KBr pellets were prepared using dried samples and examined in FTIR spectroscopy (Thermo scientific, Nicolet-iS5, Waltham, MA, USA) to characterize polymers according to their chemical nature.

2.5. Statistical Analysis—Potential Risk Assessment

All statistical and graphical studies were conducted using Origin pro 2024b, GraphPad Prism 5.01, and MS Excel. The sampling points were plotted using ArcGIS 10.8.2 and Sankey diagram with Sankey MATIC (<http://sankeymatic.com/>). The graphical abstract was made with Inkscape version 1.4.2 and Microsoft PowerPoint version 2408. Prior

to analysis, data normality was tested using the Shapiro–Wilk test at a 0.05 significance level. Since the null hypothesis was rejected, indicating that the data were not normally distributed, differences among seasons were analyzed using the Kruskal–Wallis test. This was followed by Dunn’s Multiple Comparison Test, applying Bonferroni and Bartlett’s corrections. Statistical significance was considered at $p < 0.05$.

2.6. Polymer Hazard Index (PHI)

The potential risk of MPs in the tissue samples based on seasons was calculated using PHI considering concentration, polymer type and their hazard score [24,25]. PHI was calculated using the following formula:

$$PHI = \sum P_n \times S_n \quad (1)$$

where P_n is the percentage of polymer types and S_n is the hazard score. The scores were calculated following the standard method given by Lithner et al. [25]. The calculated scores were compared with the reference Table S1 for assigning the hazard category.

2.7. Pollution Load Index (PLI)

The PLI was calculated to assess the level of microplastic pollution in different fish and prawn species collected during sampling spread over three seasons. PLI was calculated referring to Tomlinson et al. [26] and Ranjani et al. [27]. PLI is described as the square root of concentration factor (CF_i) of MPs, which is given as:

$$CF_i = \frac{C_i}{C_{oi}} \quad (2)$$

$$PLI = \sqrt{CF_i} \quad (3)$$

where C_i is microplastic concentration in each species, and C_{oi} is the background microplastic concentration (particles/g of tissue), which is the lowest concentration detected across three seasons.

2.8. Quality Control and Quality Assurance

All laboratory equipment used during the experiment was thoroughly cleaned, rinsed three times with distilled water, dried in an oven, and covered when not in use to reduce contamination. Cotton lab coats and non-shedding gloves were worn throughout the experimental period, from collection to analysis. Samples were collected in clean, closed containers and handled carefully to minimize external contamination. Prepared reagents were stored in Borosil glass containers to avoid airborne contamination, and work surfaces were wiped and cleaned with alcohol. Minor dissecting equipment, such as scissors and scalpels, was also cleaned with alcohol. Samples were analyzed in a laboratory with restricted air circulation to minimize airborne contamination.

During the processing of each batch, three procedural blanks and instrument blanks were run to account for any possible contamination. The blank samples were prepared in the same manner as the tissue samples; the blank set contained all the reagents used during digestion but no tissue material. Instrument blanks for FTIR were analyzed using KBr pellets without extracted microplastics (MPs). Results from the blank sets recorded 0–1 colored fibers; these were not deducted from the sample counts due to their minimal presence.

3. Results and Discussion

3.1. Identification of Collected Organisms

The four organisms collected for each species during the pre-monsoon, monsoon, and post-monsoon periods were identified as *Harpadon* sp. Lesueur, 1825 (Bombil), *Setipinna taty* Valenciennes, 1848 (Hairfin anchovy), *Coilia dussumieri* Valenciennes, 1848 (Goldspotted grenadier anchovy), *Johnius belangerii* Cuvier, 1830 (Croaker), *Pampus* sp. Bonaparte, 1834 (Pomfret), *Arius arius* Hamilton, 1822 (Sea cat fish), and *Penaeus monodon* Fabricius, 1798 (Tiger prawn) through morphological characterization (Figure 2). Among these, *Pampus* sp. was not encountered during the pre-monsoon, and *Harpadon* sp. was not found during the post-monsoon collection. Identification of the samples was carried out by the Zoological Survey of India (ZSI), Gopalpur, Odisha.



Figure 2. Organisms collected across three seasons ((a) *Arius arius*, (b) *Setipinna taty*, (c) *Coilia dussumieri*, (d) *Johnius belangerii*, (e) *Penaeus monodon*, (f) *Pampus* sp., and (g) *Harpadon* sp.).

3.2. Abundance of MPs

MPs were found in all tissue types with the highest concentration in monsoon followed by pre- and post-monsoon. The average distribution was 481 ± 587 particles/g of tissue in pre-monsoon, $11,309 \pm 15,448$ particles/g of tissue in monsoon, and 453 ± 568 particles/g of tissue in post-monsoon season. The MP concentration ranged between 53–1725 particles/g of tissue in pre-monsoon, 327–64,960 particles/g of tissue in monsoon, and 43–1938 particles/g of tissue in post-monsoon season for muscle tissue whereas for the GIT it ranged from 32–2035 particles/g of tissue, 84–46,235 20–2207 particles/g of tissue, and particles/g of tissue in pre-monsoon, monsoon, and post-monsoon respectively (Figure 3a,b). Throughout the seasons, *C. dussumieri* showed the highest accumulation of microplastics in the GIT and comparatively lower in muscle whereas this was opposite in the case of *A. arius*. All the collected species showed higher concentrations of MPs in their GIT during the monsoon season, while in the post-monsoon season, muscle tissue showed higher retention than the digestive tract. During the pre-monsoon period, the accumulation of MPs was high in the muscle tissue of *J. belangerii*, and low in *S. taty*. Microplastic concentration in muscle

tissue differed significantly among seasons. The Kruskal–Wallis test indicated significant seasonal effect both in muscle ($H_{(2)} = 13.56$, $p = 0.0011$) and GIT ($H_{(2)} = 7.46$, $p = 0.0240$). Dunn’s post hoc test revealed significant difference for pre-monsoon vs. monsoon and monsoon vs. post-monsoon in muscle tissue whereas in GIT significant difference was observed between monsoon and post-monsoon only. Additionally, Bartlett’s test showed a significant difference in variances for muscle and GIT ($p < 0.001$), and Bonferroni’s multiple-comparison test suggested a significant difference between monsoon vs. post-monsoon, and pre-monsoon in both the tissues.

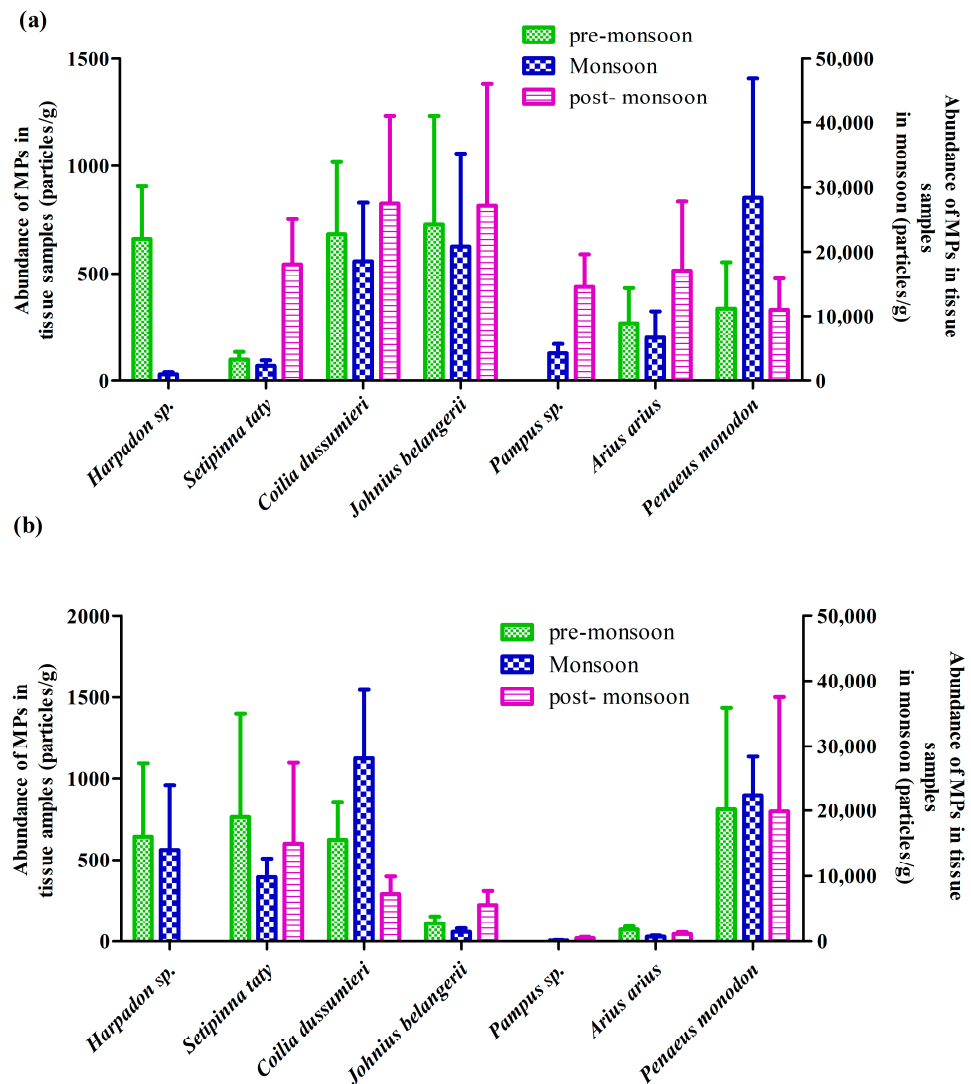


Figure 3. Graph representing abundance of MPs extracted from the muscle (a) and GIT tissue (b) in particles/g.

Microplastic accumulation in aquatic fauna might increase due to direct ingestion, changes in the seasonal pattern, gut structure, ingestion of the contaminated prey, and abundance of MPs in their habitat [28,29]. Monsoon plays an important role in the input, transport, distribution, and fate of microplastics (MPs) in aquatic systems. Intense rainfall leads to surface runoff, riverine discharge, and floods, increasing the MP load through the mobilization of land-based plastic debris. In addition, enhanced water turbulence causes the resuspension of MPs from sediments. Heavy inflows of water also change salinity levels, which leads to MP aggregation and biofouling, ultimately making these particles available for consumption. Hence, the high accumulation in tissues during the monsoon period is due to monsoon-driven hydrological processes that affect the abundance, nature,

and distribution of MPs in the water [30]. MPs tend to remain on the surface due to their hydrophobic and highly buoyant nature. Biofouling by microorganisms such as bacteria and algae increases the density of MPs by colonizing, resulting in their sinking to the bottom. This process promotes consumption of MPs by bottom feeders like *Harpadon* sp., *J. belangerii*, and *P. monodon* as compared to water column dwellers [31]. However, the highest MP concentration was observed in *C. dussumieri* despite it being a pelagic feeder, mostly because of its feeding habit. *C. dussumieri* feeds on active feeders like ostracods, prawn larvae, and young fish. These active feeders are intermediate consumers of plankton, frequently ingesting MPs, which indirectly increases the MPs' load in *C. dussumieri*. This trophic transfer leads to higher deposition of MPs in high trophic level organisms over time [32]. Similarly, a comparatively higher retention of MPs was recorded in the GIT of *P. monodon* during the monsoon season, which might be due to the denser MPs present in the sediment [29]. Higher MP retention observed in muscle tissue than in the GIT is due to differences in ingestion and translocation. MPs in GIT may be periodically excreted, resulting in lower concentration. MP particles can directly be absorbed through gills rather than entering the digestive systems [33]. In addition, small MP particles can easily cross intestinal walls as well as gills and enter muscle tissues [34]. Furthermore, prolonged exposure may lead to retention of smaller MP particles in tissue, and larger MPs in the GIT might be excreted.

3.3. Morphology of MPs

Examination of the samples under a compound microscope revealed the prevalence of fiber-shaped MPs in the GIT and muscle of each species. The total MPs were categorized into 3 groups: 1–50 μm , 50–100 μm , and 100–150 μm , and are depicted in Figure 4. In the present study, the most commonly identified MP size class was 1–50 μm with 63.4%, followed by 50–100 μm (26%), and 100–150 μm (4.3%). Eight different colors of fibers were observed in our study (Figure 5A–H) and black color was dominant (80–86%) with the least number of yellow-colored fibers (0–0.9%) in all the seasons (Figure 5I). Furthermore, a considerable deviation was observed in the color pattern distribution of the fiber type of microplastic during three seasons in the sampled tissues. Hence, no significant correlations can be established between the distribution of colored MPs accumulated during pre-monsoon, monsoon, and post-monsoon. The black color dominated over others with 85.8% in pre-monsoon, 80.1% in monsoon, and 86.1% during post-monsoon seasons, followed by transparent colored MPs.

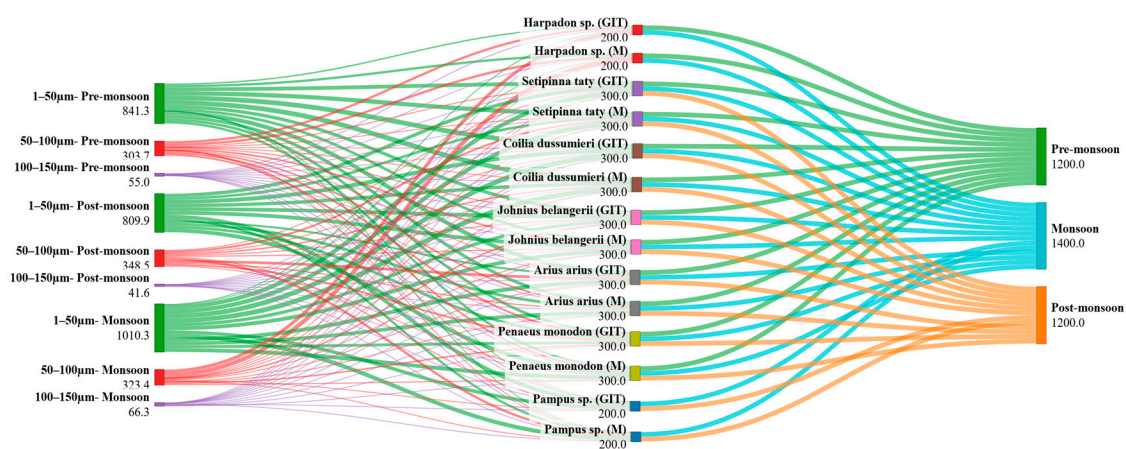


Figure 4. Size diversity of MPs represented by Sankey diagram created by using SankeyMATIC (<http://sankeymatic.com/>).

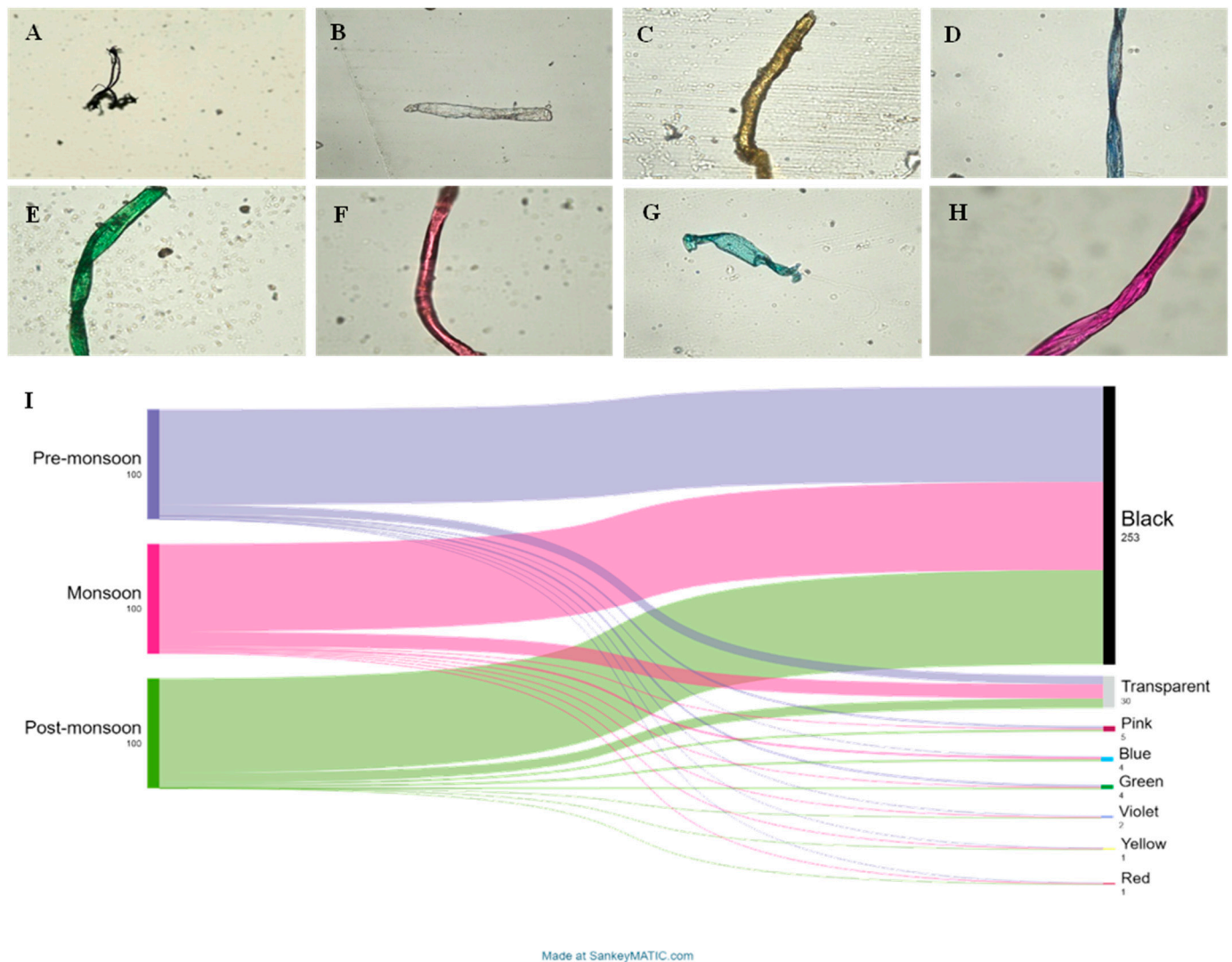


Figure 5. Compound microscope images of different colors of microplastic fibers extracted from tissue samples ((A) black, (B) transparent, (C) yellow, (D) blue, (E) green, (F) red, (G) shade of blue, (H) pink) and (I) shows percentage occurrence of different colors found in tissue samples.

Fibers are small-sized and their strength and softness along with non-deformability make them more suitable to accumulate in faunal tissue [35]. Similar results have been observed by Ding et al. [36] in fish and bivalve samples collected from the markets in Qingdao and Dongying, and Abbasi et al. [29] in fish and prawn samples in the Musa estuary, Persian Gulf. The high dominance of fibers may be due to their one-dimensional nature [37].

In the present investigation, the observed maximum size of MPs was 150 μm and similar results have been reported in fresh and processed seafood from Germany with dominance of MPs (97%) < 150 μm [38]. The incidence of smaller sized MPs was expected as these particles were preferable as they camouflage with planktons, which results in ingestion by aquatic organisms [37,39]. The availability of smaller MPs was possible due to the hydrodynamic actions which degrade larger particles through photo-chlorination, mechanical action, and biodegradation [40,41]. These particles may move across the intestinal barrier through intracellular or paracellular endocytosis [42]. Small sized MPs poses highest health risks [40]. Hossain et al. [43] reported dominance of <0.5 μm (97.74%) MPs in *Scomberomorus guttatus* from a large subtropical estuary. Similarly, Alfaro-Núñez et al. [44] reported abundance of 150–500 μm size MPs in the Tropical Eastern Pacific and Galápagos,

Daniel et al. [45] reported prevalence of size 100–200 μm in edible shellfish tissues, and Daniel et al. [46] reported in Kerala that the dominant size was 200–400 μm .

The present study highlights the abundance of black-colored MPs across three seasons. The abundance of microplastics depends on the color and type of MPs, and it shows differential accumulation trends for different animal species [2,3]. Eryaşar et al. [47] detected black color MPs in the gastrointestinal tract of 11 commercial fish samples, and Borges-Ramirez et al. [48] also reported predominance of black-colored MPs in the gastrointestinal tract of tropical fish (44.8%). Our findings are also supported by the work of Mc Neish et al. [28], Ory et al. [49], and Atamanalp et al. [50] who reported dominance of black color. Generally, planktons are transparent or yellow in color but have black patches on their surface which is preferred by juvenile fish, hence supporting the probable occurrence and dominance of black-colored microplastic presence in the tissues [51]. Similar results with black colored fiber form of MPs have been reported by Shukhairi et al. [52] in *Holothuria scabra* (sea cucumber) from Pulau Jambongan, Sabah. The color of MPs in water or in tissues can indicate the original form released either directly or indirectly into water bodies. Tee-hor et al. [53] reported microplastic pollution in the tissue of Giant Freshwater Prawns *Macrobrachium rosenbergii*, Thailand, and observed the dominance of three colors: blue, black, and red. Additionally, the colors of MPs have always been a significant factor in the internalization of the particles by fish and other vertebrate and invertebrate species. Color defines the source of plastics as follows: dark or black ones are often sourced from several industrial effluents, blue and green arise from fishing nets and related equipment, white and transparent ones arise from plastic bottles and bags whereas the bright colored (yellow, red) MPs have a dye, toy or cosmetic industry source [3].

3.4. Visual Characterization of MPs

The extracted MPs were imaged under a Scanning electron microscope and are shown in Figure 6a–c. For better clarity and comparison, fluorescent images are presented along with bright-field images confirming the presence of hydrophobic MPs (Figure 6). SEM analysis of the MP surface by Zbyszewski et al. [54] and Wang et al. [55] showed similar smooth structure with cracks as observed in our study and it might be due to a relatively mild mechanical weathering, polymeric decay, and oxidative damage. Fluorescence microscopy primarily revealed the presence of fibers, fragments, and films within the gastrointestinal tract (GIT) and muscle tissue. Accumulation in these tissues can cause mechanical injury and damage tissue structure.

3.5. Characterization of MPs

Polymer characterization was done using FTIR, and the generated peaks (Figure S1) were compared to the standard MP peak. Eighteen different types of MPs were observed in the collected samples based on the peak analysis and we found mostly polyurethane (PU), polyethylene terephthalate (PET), polyvinyl chloride (PVC), polystyrene (PS), polypropylene (PP), Nylon, acrylonitrile butadiene styrene (ABS), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyethylene (PE), cellophane, polyamide (PA), polycarbonate (PC), cellulose acetate (CA), poly (methyl methacrylate) (PMMA), ethylene vinyl acetate (EVA), nitrile, and latex. Species and season-wise presence of microplastic types were analyzed based on season and represented in Figure S2, S3, and S4 respectively. Almost all the MPs showed two absorption spectra around $2845\text{--}2925\text{ cm}^{-1}$ corresponding to CH symmetric and asymmetric stretching, whereas N-H stretching and O-H group stretching were found around 3430 cm^{-1} in Nylon and PA. In IR spectra, CH_2 bending at $1400\text{--}1460\text{ cm}^{-1}$ was common for PU, PVC, PS, PP, Nylon, ABS, PE, HDPE, LDPE, PMMA, EVA, nitrile, and Latex. CH_2 rocking found around 750 cm^{-1} was a characteristic peak of

PE, HDPE, LDPE, PP, PVC, PMMA, and EVA. The absorption spectra at $1620\text{--}1660\text{ cm}^{-1}$ and $1050\text{--}1250\text{ cm}^{-1}$ correspond to $\text{C}=\text{O}$, and $\text{C}-\text{O}$ were present in PET, PU, PC, Nylon, PMMA, and EVA. $\text{C}-\text{N}$ stretching ($1533\text{--}1551\text{ cm}^{-1}$) was seen in PU, Nylon, and nitrile, while $\text{C}-\text{Cl}$ stretching ($580\text{--}650\text{ cm}^{-1}$) was the characteristic peak of PVC [56–61]. The percentage occurrence of MPs was calculated by dividing the presence of polymer in each tissue type and total tissue type (12) and presented in Figure 7a. During the pre-monsoon period, the dominant MPs were found to be PET with 100%, PVC and CA with 91.6%, whereas the lowest form was PA with 8.3%. Monsoon season showed a comparatively highest distribution of MP type with percentages varying from 21.4 to 100; PET (100%), PVC (100%), CA (92.8%), and cellophane (92.8%) were dominant types and the occurrence of PA was lowest with 21.4%.

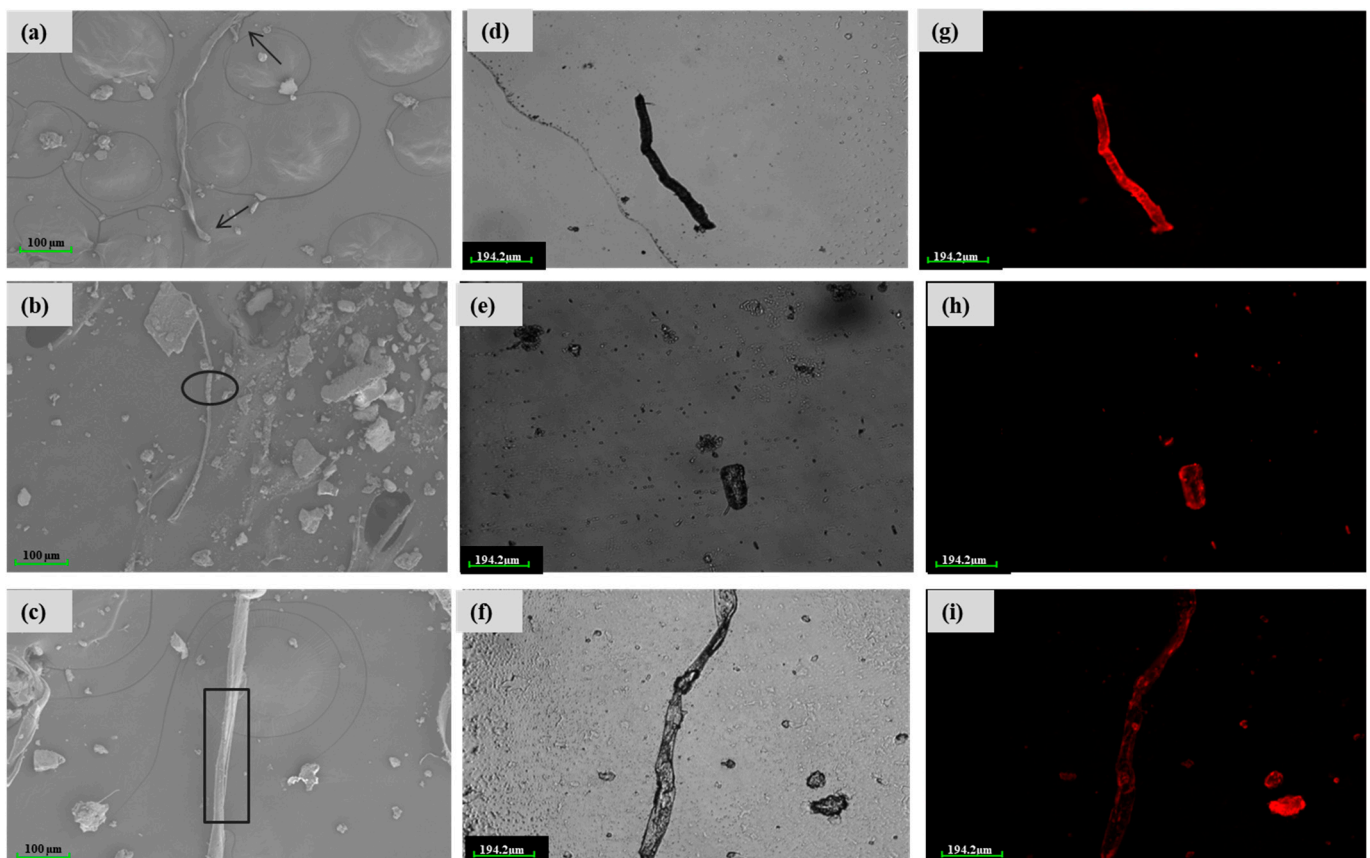


Figure 6. Scanning electron microscope (a–c) and fluorescent microscope images ((d–f) bright field, and (g–i) fluorescence image) of MPs extracted from the tissue samples collected during pre-monsoon (a,d,g), monsoon (b,e,h), and post-monsoon (c,f,i) season. (In SEM images, the symbol “→” indicates weathering, “O” indicates cracks and “□” indicates a smooth surface of MPs.).

The State of Odisha implements a fishing ban for a period of almost two months, and the ban is generally lifted in the second week of June, i.e., close to the monsoon period. Rampant fishing activities are carried out during the monsoon period which might have contributed to a higher MP load in water and edible organisms in the sampling area. Ekalaturrahmah et al. [62] did the identification and quantification of MPs in water, sediment, and shrimp collected from shrimp farming ponds. Their findings revealed the dominance of cellophane, reaching 100%, and the source might be the result of human activities. Similarly, in the case of post-monsoon, highest % was observed for PET (91.6%), PVC (91.6%), and CA (100%), whereas PA was absent (Figure 7a). The possible sources of PET pollution can be plastic bottles or PET bottles, packaging materials, tire wares, effluents from textile industries, and cosmetics [63,64]. The second dominant MP PVC pollution

can be from runoffs of households having PVC pipes, and flooring materials, industrial effluents from plastics manufacturing and textile industries, and effluents from construction sites as well as agricultural lands [65,66]. The major source of CA is cigarette filters and other sources include road markings, marine coatings, synthetic textiles, and personal care products [67]. Although cellophane is a natural polymer derived from cellulose, it still acts as a pollutant because of the additives involved during the formation [68]. It is generally found in wrappings, rubbers, fiberglass, and industrial and agricultural runoffs [69]. The MPs can leach out from different industrial, household, and agricultural products such as PU from foam packaging, adhesives, and coatings, PS from bottles, oil refineries, packaging, and paper mills, PP from resins, nets, and ropes, PC from water jugs, kitchen appliances, PMMA from dental and medical appliances, aquarium tank, and furniture, EVA from coating, footwear, and packaging, and Polyethylene from plastic packaging and bottles [70–75]. The sources of Nylon and nitrile pollution could have been chiefly from textile industries, and ABS can contaminate water bodies through cosmetics [76]. Latex can be found in gloves, tires, city dusts, and industrial effluents [77]. Daniel et al. [45] reported an average abundance of 2.7 ± 12 microplastic particles/kg in edible tissue (wet weight) and 0.07 ± 0.3 microplastic particles per individual from the sampled shellfishes procured from Cochin and Kalamukku fishing harbors. The edible tissues mostly consisted of fragments and were of PP, PE, and PS polymer types.

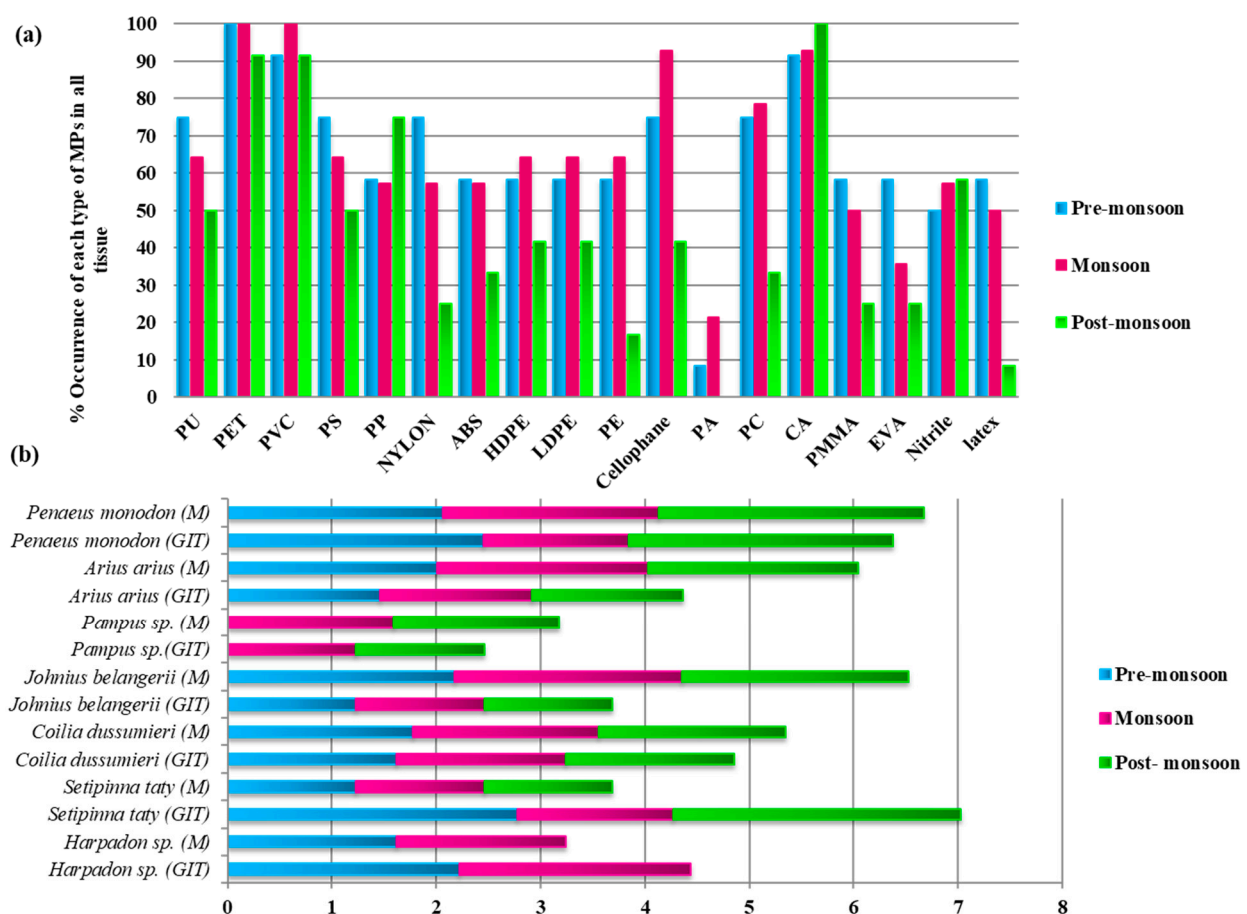


Figure 7. Graph showing (a) % occurrence of 18 different types of MPs analyzed in FTIR in both the tissues and (b) PLI of MPs extracted from tissue samples of *Harpadon sp.*, *S. taty*, *C. dussumieri*, *J. belangerii*, *Pampus sp.*, *A. arius*, and *P. monodon* collected during the pre-monsoon, monsoon, and post-monsoon season.

3.6. Potential Risk Assessment

3.6.1. Polymer Hazard Index

The MPs ingested by marine organisms accumulate in edible tissue parts, which ultimately enter into the human system through the food chain. Hence, it can cause serious health risks to humans as well as marine fauna. MPs are synthetic polymers formed from the polymerization of monomers and some other additives that may be hazardous to our environment. The weathering of these polymers results in the release of those hazardous additives into the water. The hazard ranking model by the United Nations' Globally Harmonized System of Classification and Labelling of Chemicals reported that >50% of chemicals used in the formation of plastics are hazardous [27,28]. The risk assessment of MPs was carried out using the PHI model, and compared with hazard level criteria from Ranjani et al. [27] (Table S1). According to PHI assessment, the MP pollution in fish and prawn samples ranges from hazard level III to V (Table 1). The MPs in tissues show a serious MP pollution trend. PVC and PET have appeared as the most commonly ingested MP type by fish and prawns of the Chandipur region (91–100%), indicating extreme risk and danger to human health respectively. Our findings suggest that ABS, PMMA, and PA (in monsoon) were extremely dangerous polymers despite their occurrence percentage between 21 and 58 PP comes under category III even with 57–75% of presence. Therefore, even if the concentration of MPs is low in water or tissues, their chemical composition can pose significant health risks.

Table 1. The estimated hazard risk assessment of identified polymers from edible fish and prawn samples.

Polymer	Hazard Score ^P	PHI ^q			Hazard Category ^q	Risk Category ^q
		Pre-Monsoon	Monsoon	Post-Monsoon		
PU	738×10^1	553,800	474,685	369,200	V	Extreme danger
PVC	500×10^1	458,425	500,100	458,425		
ABS	655×10^1	382,200	374,400	218,400		
PMMA	102×10^1	59,558	51,050	25,525		
PC	610	45,750	47,928	20,333		
Nylon	50	3750	2857	1250		
PS	30	2250	1928	1500	IV	Danger
PA	50		1071			
		416		NC		
PE	11	641	707	183		
PET	4	400	400	366		
HDPE	11	641	707	458		
LDPE	11	641	707	458	III	High
EVA	9	525	321	225		
PP	1	58	57	75		

^P Hazard score according to Lithner et al. [25]. ^q Signify Ranjani et al. [27]. NC: not classified.

3.6.2. Pollution Load Index

The PLI was calculated to measure the level of microplastic pollution in the tissue samples. It is based on the ratio of the concentration of MPs in each type of tissue and the background value. The background values were determined by comparing MP abundance across three seasons. Based on the PLI, microplastic pollution in each tissue type was calculated (Figure 7b). Although the PLI value of muscle tissues was relatively higher than that of the GIT, the values for all species were <10, indicating Hazard level I (Minor contamination) (Table S1). The PLI values depend upon the microplastic abundance, which

is affected by the rate of industrial development, population density, sea-based activities such as fishing, and trawling, sewage release, and human activities [27,79,80].

3.7. Dietary Intake of MPs Through Fish and Prawn Consumption

The annual per capita fish consumption of the State of Odisha, India was estimated to be 18.33 kg by the Fisheries and Animal Resources Development Department, Govt. of Odisha 2023–2024 [81]. In the present study, the average abundance of MPs in edible fish tissues was calculated to be $4462 \pm 10,696$ particles/g of tissue. Hence, the global per capita intake of MPs is approximately 81.78 ± 19.6 million particles. With an increase in fish consumption and the use of plastics, the MP intake is likely to be elevated in the coming years. However, the intake and transfer of MPs can vary depending on species, area, season, and processing before consumption [45]. In the present study, the results showed the highest concentration of MPs during monsoon season which could have resulted in more intake of dietary MPs. The per capita fish consumption for the year 2022 was 20.7 kg [82], hence it can increase the intake rate to about 92.36 ± 22.14 million particles globally. At the current rate, the dietary intake of MPs per annum can cause serious health concerns to mankind. The mechanism behind the flow, retention, and long-term impact of MPs is not yet explored properly but they can cause oxidative stress, inflammation, immune response, metabolic alterations, cellular and DNA damage, secretion of cytokines, neurotoxicity, endocrine disruption, and cancer [83,84].

3.8. Comparative Analysis of Polymer Composition and Concentration of MPs

The concentration, color, morphological type, and polymer composition of MPs in the fish and prawn groups of the present study were equated with findings across the world and depicted in Table 2. Most of the studies reported the dominance of black-colored fibers and the derivative of PE MPs. The dominant form of MPs in *P. monodon* was found to be PA type in studies reported by Morris et al. [85], and Jayaweera et al. [86], whereas PET, PVC, and CA were observed in the present study instead of PA. Similarly, PP was the dominant form of MPs in *J. Belangerii* reported by Karami et al. [87], but our findings showed the dominance of PET, PVC, and cellophane. The findings of Khattab et al. [88] showed retention of Poly (2, 4, 6-tribromo styrene) (PtBS) and Chloro sulfonated polyethylene (CSPE), whereas in our study, we found the accumulation of PET, CA, Nylon, PVC, and cellophane in *Pampus* sp. Unlike studies on *Harpadon*, which reported PET, PE, PS, PU, and PA as dominant polymers, the present study showed abundance of PET and PVC. In the case of *A. arius*, PE was found to be dominant in previous studies, whereas in the present study, most of the polymers were dominant. The environmental conditions, use of plastics, sewage treatment, and weathering process can be the reasons for the wide variation in concentration and composition of MPs observed during evaluation. The higher occurrence of PET and PVC might be associated with consumption risks, as they are commonly used in packaging materials and may lead to contamination from consumer products or discarded materials. These microplastics can lead to serious health complications in humans through trophic transfer by ingestion of seafood.

The comparative analysis (Table 2) indicates that fish may inadvertently ingest plastics during feeding or respiration. The observed preference for specific microplastic colors may result from the resemblance between plastic debris and natural food sources in the environment [99]. Polyethylene terephthalate (PET) was the most frequently identified polymer in this study, consistent with the findings of Di Giacinto et al. [100], who suggested that the primary sources are plastic food containers, bottles, disposable cups, and cartons. Various food industry products, including edible oil packaging, beverage containers, and foils, contain PET [101]. These items are commonly used by fishermen during extended

deep-sea fishing trips, which may last six to seven days or longer, depending on the duration of the fish catch.

Table 2. Abundance and nature of MPs in different species of fish and prawn reported in studies across the world.

Location	Concerned Species	MPs Abundance	Dominant Color	Dominant Type	Dominant Polymer	References
Northern Bay of Bengal, Bangladesh	<i>Harpadon nehereus</i>	8.72 ± 1.54 MPs/species	White	Fiber	PET, PA	[20]
Gujarat state (Jakhau, Okha, and Jaffrabad) and Maharashtra state (Mumbai), India	<i>Harpadon nehereus</i>	6.98 ± 6.73 MPs/g	Black, Blue	NA	PE, PS, PU	[89]
Patenga beach of the Bay of Bengal, Bangladesh	<i>Harpadon nehereus</i>	98.34 ± 53.1 MPs/species	Blue	Filament	PE	[90]
Yellow Sea, China	<i>Setipinna taty</i>	0.35 MPs/species	NA	Fiber	NA	[91]
South Yellow Sea (Jiangsu section), China	<i>Setipinna taty</i>	0.098 ± 0.022 MPs/species	Black, Blue, Brown	Fibrous	CPE, Rayon, PET, PS, and PE	[92]
Northeast coast of Arabian Sea	<i>Coilia dussumieri</i>	28.84 ± 10.13 MPs/g	Blue	Fiber	NA	[93]
Malaysia	<i>Johnius belangerii</i>	15 MPs/species	NA	Fragment	PP	[87]
Pangandaran Bay, Indonesia	<i>Johnius</i> sp.	193 (total)	NA	Fragment	NA	[94]
Taif market, Saudi Arabia	<i>Pampus argenteus</i>	7 MPs/species	NA	NA	Poly (2, 4, 6-tribromostyrene) (PtBS) and Chlorosulfonated polyethylene (CSPE)	[88]
Yogyakarta Province, Indonesia	<i>Pampus argenteus</i>	139.3 MPs/species	Black	Fiber	NA	[95]
Tamilnadu coast, India	<i>Arius arius</i>	1 MPs/species	Black	Fragment	PE	[96]
Songkhla Lagoon, Thailand	<i>Arius maculatus</i>	1.13–4.00 g (Tissue sample)	Blue, Black, Red	Fiber	PP, rayon, and PET	[97]
Arabian sea	<i>Penaeus monodon</i>	0.74 ± 2 MPs/species	Black, blue	Pellet	PA-6	[85]
Puttalam, Sri Lanka	<i>Penaeus monodon</i>	30.75 ± 9.06 MPs/species	Blue	Fiber	Nylon-6,6	[86]
The west coast of the Arabian Gulf, Saudi Arabia	<i>Penaeus semisulcatus</i>	238 MPs	Gray	Fiber	PET	[98]
Chandipur, Bay of Bengal, East coast of India	<i>Harpadon</i> sp.	796 ± 491 particles/g of tissue	Black	Fiber	PVC, PET, CA	Present study
	<i>Setipinna taty</i>	958 ± 1240 particles/g of tissue				
	<i>Coilia dussumieri</i>	$6690 \pm 11,911$ particles/g of tissue				
	<i>Johnius belangerii</i>	$7445 \pm 16,018$ particles/g of tissue				
	<i>Pampus</i> sp.	2302 ± 2597 particles/g of tissue				
	<i>Arius arius</i>	2456 ± 4746 particles/g of tissue				
	<i>Penaeus monodon</i>	$9694 \pm 21,298$ particles/g of tissue				

NA: not available.

3.9. Limitations

The limitation of the study is that the recovery percentage was not obtained using spiked blank tissue samples. Because the present study depends on wild-caught edible marine fish and prawn samples, it was not feasible to collect the live species and maintain them in laboratory conditions. Hence, it is not possible to analyze identical standardized samples for recovery testing after controlled spiking. The limited sample size ($n = 3$) (in duplicate per species) led to high standard deviations, reflecting substantial inter-individual variation. This variation limits statistical robustness and might not capture the true natural variation and diversity. Furthermore, polymer identification relied exclusively on FTIR, which should be paired with Raman spectroscopy for robust validation. Future studies can incorporate larger sample sizes, broader taxonomic coverage, and complementary analytical techniques to confirm these patterns comprehensively.

4. Conclusions

This study provides quantitative data on the presence of microplastics (MPs) in commonly consumed fish and shrimp species across the pre-monsoon, monsoon, and post-monsoon periods. The PLI and Polymer Hazard Index (PHI) values indicate low level of pollution of the collected fish and prawn samples with MPs. However, the Polymer Hazard Index (PHI) analysis highlights long term health risk, classifying the pollution risk between III to V due to probable accumulation. Therefore, regular consumption of such contaminated fish could pose a serious health risk at different levels of the food chain, particularly for humans who are at the top of the food chain. The species *Coilia dussumieri* showed the highest retention of black-colored fibers in the gastrointestinal tract (GIT) indicating a transfer of MPs to the muscle tissue, which is generally consumed by humans. The accumulation of MPs in the muscle tissue will affect humans through direct consumption as food and the accumulation might reduce the macronutrient profile of the edible prawn as well as fish. The most abundant microplastics (MPs) observed in the present study are between the size of 1 and 50 μm and small particles can be easily retained in the human system upon consumption. Through chemical characterization, PET (polyethylene terephthalate), PVC (polyvinyl chloride), and CA (cellulose acetate) type of polymers were confirmed to be commonly present across all seasons. The source of various forms could be the result of the breakdown of fishing nets, ropes used for releasing nets into the water, plastic bags used for storage, plastic crates used for packaging, and even the release of cloth pieces directly into the water. The present research provides valuable insights into microplastic (MP) pollution in edible and popular seafood, and its potential health risk index, highlighting the urgent need for continuous monitoring and remediation strategies to safeguard both human health and reduce risk to the marine ecosystem. Given the proximity of the Budhabalanga estuary to the study site and localized contaminant burdens, future research must integrate polymer hazard indices, trophic transfer tracking with modeling, and human exposure risk for local consumers. Future directions of this work could include tracing the sources of plastic pollution, specifically quantifying the waste originating from fishing gear and river runoff. Additionally, regular monitoring of edible bivalves, crabs, and fish should be initiated to establish a localized seafood safety baseline. The generated data could then be used to integrate scientific findings into regional policies such as managing land-based runoff, minimizing single-use plastics, and strictly regulating discarded fishing gear to protect aquatic ecosystems.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/microplastics5030140/s1>, Figure S1: Graphs showing Fourier-Transform Infra-red Spectroscopy analysis of MPs extracted from tissue samples (a–f) *Harpadon* sp.,

S. taty, *C. dussumieri*, *J. belangerii*, *A. arius*, and *Penaeus monodon* of pre-monsoon (g–m) *Harpadon* sp., *S. taty*, *C. dussumieri*, *J. belangerii*, *Pampus* sp., *A. arius*, and *P. monodon* of monsoon, and (n–s) *S. taty*, *C. dussumieri*, *J. belangerii*, *Pampus* sp., *A. arius*, and *P. monodon* of post-monsoon sampling period; Figure S2: Graph showing distribution of 18 different types of microplastics analyzed from Fourier-Transform Infra-red Spectroscopy analysis of microplastics extracted in tissue samples of *Harpadon* sp., *Setipinna taty*, *Coilia dussumieri*, *Johnius belangerii*, *Penaeus monodon*, and *Arius arius* collected during pre-monsoon period; Figure S3: Graph showing distribution of 18 different types of microplastics analyzed from Fourier-Transform Infra-red Spectroscopy analysis of microplastics extracted in tissue samples of *Harpadon* sp., *Setipinna taty*, *Coilia dussumieri*, *Johnius belangerii*, *Pampus* sp., *Arius arius*, and *Penaeus monodon* collected from monsoon season; Figure S4: Graph showing distribution of 18 different types of microplastics analyzed from Fourier-Transform Infra-red Spectroscopy analysis of microplastics extracted in tissue samples of *Setipinna taty*, *Coilia dussumieri*, *Johnius belangerii*, *Pampus* sp., *Arius arius*, and *Penaeus monodon* collected from post-monsoon season; Table S1: Hazard level criteria of microplastics.

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Data Availability Statement: Data will be made available on request.

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Conflicts of Interest: The authors declare that there is no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

MPs	microplastics
PE	polyethylene
PP	polypropylene
PS	polystyrene
PET	polyethylene terephthalate
PVC	polyvinyl chloride
PA	polyamide
PU	polyurethane

HDPE	high-density polyethylene
LDPE	low-density polyethylene
ABS	acrylonitrile butadiene styrene
CA	cellulose acetate
PMMA	poly (methyl methacrylate)
EVA	ethylene vinyl acetate
PC	polycarbonate
FTIR	Fourier-transform infrared spectroscopy
SEM	scanning electron microscopy
PHI	Polymer Hazard Index
PLI	Pollution Load Index
POPs	persistent organic pollutants
PCBs	polychlorinated biphenyls
PAHs	polycyclic aromatic hydrocarbon
PBDEs	poly-brominated 70 diphenyl ethers
GIT	Gastro-intestinal tract
µm	micrometer
%	percentage
kg	kilogram
g	gram
ZSI	Zoological survey of India
CF	concentration factor
NR	Nile Red
WPO	wet peroxide oxidation
PtBS	Poly (2, 4, 6-tribromo styrene)
CSPE	Chloro sulfonated polyethylene
DNA	Deoxyribose nucleic acid
PIB	Press Information Bureau
CPCB	Central Pollution Control Board

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