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Original Article

Microplastic contamination in the gastrointestinal tract of Caspian kutum (*Rutilus kutum*) from Miankaleh fishing grounds: Implications for ecosystem and human health

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Abstract: Microplastic (MP) pollution has emerged as a pervasive threat to aquatic ecosystems globally, with significant implications for fish health and human food safety. The Caspian Sea, as the world's largest enclosed water body, acts as a terminal sink for contaminants, yet comprehensive assessments of MP contamination in commercially important fish species from its southeastern basin remain limited. This study investigated the occurrence, abundance, physical characteristics, and polymer composition of microplastics in the gastrointestinal tracts of Caspian kutum (*Rutilus kutum*) collected from three major fishing grounds, Chargoli, Shayan, and Niazabad, along the Miankaleh coastline, Golestan Province, Iran, during August–September 2024. A total of 30 fish specimens were examined using 10% potassium hydroxide digestion, density separation with saturated NaCl solution, and microscopic identification, followed by polymer confirmation via micro-Fourier transform infrared (μ-FTIR) spectroscopy. Microplastics were detected in 93.7% of individuals, with a mean abundance of 2.84±1.67 items per fish, ranging from 0 to 9 items per individual. Significant spatial variation was observed, with Niazabad exhibiting the highest contamination (3.42±1.89 items fish^{-1}), followed by Shayan (2.76±1.54 items fish^{-1}) and Chargoli (2.34±1.42 items fish^{-1}), reflecting proximity to riverine inputs from the Gorganrud River. Fibers constituted the dominant morphology (91.3%), followed by fragments (6.2%) and films (2.5%). The predominant size class was 100-500 μm (42.3%), indicating high bioavailability and potential for trophic transfer. Color distribution revealed distinct site-specific signatures: Niazabad was characterized by green (33.3%) and red (22.2%) MPs, while Chargoli and Shayan were dominated by black, gray, and transparent particles. Seven polymer types were identified, with cellophane (28.3%), polyamide (22.1%), and polyester (18.4%) being most prevalent, reflecting contributions from packaging materials, fishing gear degradation, and textile fibers. The predominance of high-density polyamide and polyester polymers, which have a high affinity for persistent organic pollutants, raises concerns about vector effects and co-exposure to associated contaminants. No significant correlation was found between fish length and MP abundance ($p = 0.187$), while a weak positive relationship with wet weight ($p = 0.034$) suggested moderate accumulation with increased body mass. The high occurrence and abundance of small, bioavailable MPs in *R. kutum* from the Miankaleh fishing grounds indicate substantial contamination pressure in this critical habitat, with direct implications for food safety, given the species' commercial importance and high consumption rates in northern Iran.

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Introduction

Microplastics (MPs), commonly defined as plastic particles smaller than 5 mm, have emerged as one of the most pervasive and concerning contaminants in aquatic ecosystems globally (Cole et al., 2011). Global plastic production has exceeded 400 million tonnes annually, with a significant portion entering marine environments via riverine transport, atmospheric deposition, and direct discharge (Banaee et al., 2025). It is estimated that between 1.15 and 2.41 million tonnes of plastic waste enter the oceans via rivers each year, making fluvial systems critical conduits for land-based plastic pollution (Aytan et al., 2025). Once introduced into aquatic environments, MPs undergo fragmentation, microbial colonization, and interactions with ambient pollutants, thereby

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increasing their bioavailability and potential toxicity to aquatic biota (Hedayati et al., 2022).

The ubiquitous presence of MPs in marine and freshwater ecosystems has raised significant concerns regarding their impacts on fish health and, consequently, on human consumers (Alberghini et al., 2022). Fish are particularly vulnerable to MP contamination due to their diverse feeding strategies and position within aquatic food webs. Ingestion of MPs can occur directly through mistaken identification as prey or indirectly via trophic transfer from contaminated organisms at lower trophic levels (Lu et al., 2025). Upon ingestion, MPs primarily accumulate in the gastrointestinal tract (GIT), where they may induce a cascade of adverse effects, including physical damage to the intestinal epithelium, alterations in gut microbiota composition, reduced digestive enzyme activity, and inflammatory responses (Wu et al., 2025). Furthermore, MPs can act as vectors for co-contaminants, such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and heavy metals, which desorb in the digestive system and may bioaccumulate in fish tissues (Kuznetsova, 2025). The smallest MP fractions (<1 mm) are of particular concern due to their increased surface area-to-volume ratio, enhanced capacity for cellular translocation, and greater potential to cross biological barriers (Lu et al., 2025).

The Caspian Sea, as the world's largest landlocked body of water, faces unique challenges related to MP pollution. Being enclosed, it acts as a terminal sink for contaminants originating from surrounding industrialized and densely populated regions (Khaleghi et al., 2025). Recent investigations have documented widespread MP contamination across multiple compartments of the Caspian Sea ecosystem. Chiani et al. (2025) reported MP abundances of 0.57±0.59 items/L in seawater and 72.66±29.29 items/kg dry weight in sediments along the Iranian Caspian Sea coast, with fibers identified as the predominant morphology and polyamide as the dominant polymer type. Khaleghi et al. (2025) provided the first comprehensive evidence of MP ingestion in endangered Caspian seals (*Pusa caspica*), finding an average of 10.2±5.1 MPs per gastrointestinal tract, with fibers accounting for 52.3% of detected particles. Kuznetsova (2025) further demonstrated that MPs in the northwestern Caspian Sea adsorb PAHs at concentrations ranging from 97.6 to 332.3 ng g^{-1}, with higher PAH loads associated with smaller MP size fractions (0.1-1 mm), underscoring MPs' role as vectors for toxic organic pollutants.

Among the commercially valuable fish species in the southern Caspian Sea, the Caspian kutum (*Rutilus kutum*) holds exceptional ecological and economic importance. This endemic cyprinid supports substantial artisanal and commercial fisheries along the Iranian coastline, particularly in the southeastern regions, including the Miankaleh Wildlife Refuge and Gorgan Bay (Haji Aghaei Ghaazi Mahalleh and Imanpour Namin, 2025). Recent evidence confirms MP contamination in *R. kutum* populations from the southwestern Caspian Sea. Haji Aghaei Ghaazi Mahalleh and Imanpour Namin (2025) examined 60 specimens from the Kiashar, Anzali, and Astara stations and reported a 100% occurrence of MPs, with mean abundances of 53.75±35.50 particles per fish at Anzali. Notably, this study revealed complex correlations between MP abundance and potentially toxic elements, with significant positive relationships observed for arsenic and nickel at certain stations, suggesting that MPs may influence metal bioaccumulation patterns in this species.

Despite these findings, significant knowledge gaps persist regarding MP contamination in *R. kutum* from the eastern Caspian basin, particularly within the Miankaleh fishing grounds. Miankaleh Peninsula and its associated coastal lagoon system represent critical habitats for *R. kutum* spawning and feeding, while simultaneously receiving inputs from multiple pollution sources, including agricultural runoff from surrounding farmlands, municipal discharges from nearby settlements, and fishing-related activities (e.g., fishing gear degradation and boat operations). The region's extensive beach seine fisheries operate in shallow coastal waters where MPs may accumulate due to hydrodynamic conditions and proximity to land-based sources. However, no systematic assessment has yet evaluated MP abundance, characteristics, or associated health risks in *R. kutum* from this important fishing ground.

The present study addresses this critical research gap by conducting a comprehensive investigation of MP contamination in the gastrointestinal tracts of Caspian white fish collected from Miankaleh fishing grounds. The specific objectives are to: (1) quantify the abundance and occurrence frequency of MPs in GITs of *R. kutum*; (2) characterize the physical properties of ingested MPs including size distribution, shape, and color; (3) identify polymer types using micro-Fourier transform infrared (μ-FTIR) spectroscopy; and (4) assess the potential ecological and human health risks associated with MP contamination in this commercially important species. By establishing baseline data on MP contamination in *R. kutum* from the southeastern Caspian Sea, this study aims to inform fisheries management decisions, support food safety assessments, and contribute to the growing body of knowledge on MP pollution dynamics in semi-enclosed marine systems.

Materials and Methods

Study area: The sampling was conducted in the Miankaleh coastal waters of the southeastern Caspian Sea, Golestan Province, Iran. Miankaleh Peninsula, designated as a Wetland of International Importance under the Ramsar Convention and a UNESCO Biosphere Reserve, extends approximately 48 km along the Caspian coastline between 36°50′ and 36°55′ N latitude and 53°40′ and 54°05′ E longitude (Fig. 1). This region encompasses critical habitats, including the Miankaleh Wildlife Refuge, Gorgan Bay, and adjacent coastal fishing grounds that support traditional beach seine fisheries (Khaleghi et al., 2025). The study area receives freshwater inputs from multiple rivers, including the Qarah Su, Gorgan, and smaller seasonal streams, which transport agricultural runoff, municipal wastewater, and plastic debris from inland areas (Chiani et al., 2025). The water depth at sampling locations ranged from 5 to 15 m, with salinity between 10.5 and 12.8 PSU and water temperature between 18 and 24°C during the August 2024 sampling period. A total of 30 sampling stations were established along a 25-km transect parallel to the coastline, encompassing major fishing grounds utilized by local fishing cooperatives. Geographic coordinates were recorded at each station using a handheld GPS (Garmin eTrex 10, USA) to ensure precise spatial referencing.

Fish collection and sample preparation: Caspian kutum specimens were collected during the commercial fishing season (August–September 2024) from beach seine operations at the 3 designated stations. A total of 30 fish individuals were obtained, from which 28 specimens were selected for microplastic analysis based on standardized criteria, including undamaged gastrointestinal tracts, complete organ integrity, and representation across size classes (Haji Aghaei Ghaazi Mahalleh and Imanpour Namin, 2025). Immediately following capture, fish were individually wrapped in pre-cleaned aluminum foil, placed in ice-cooled containers, and transported to the laboratory within 6 h. Upon arrival, each fish was measured for total length (to the nearest 0.1 cm) and wet weight (to the nearest 0.1 g). Subsequently, specimens were stored at −20°C pending dissection and microplastic analysis.

To minimize contamination, all laboratory procedures were conducted in a dedicated clean room equipped with HEPA filtration systems. All surfaces and instruments were cleaned with 70% ethanol and rinsed three times with filtered distilled water prior to use. Cotton lab coats and nitrile gloves were worn throughout all procedures (Koongolla et al., 2022). Procedural blanks (n = 10) were processed alongside samples to monitor airborne and cross-contamination.

Dissection and tissue digestion: Fish specimens were partially thawed at room temperature and rinsed with filtered distilled water to remove any external contaminants. Dissection was performed on a clean glass board using stainless-steel scissors, forceps, and scalpels, which were flame-treated between samples. The gastrointestinal tract (GIT), encompassing the esophagus, stomach, and intestine, was carefully excised from each fish. Gills were also collected for comparative analysis, following previous studies

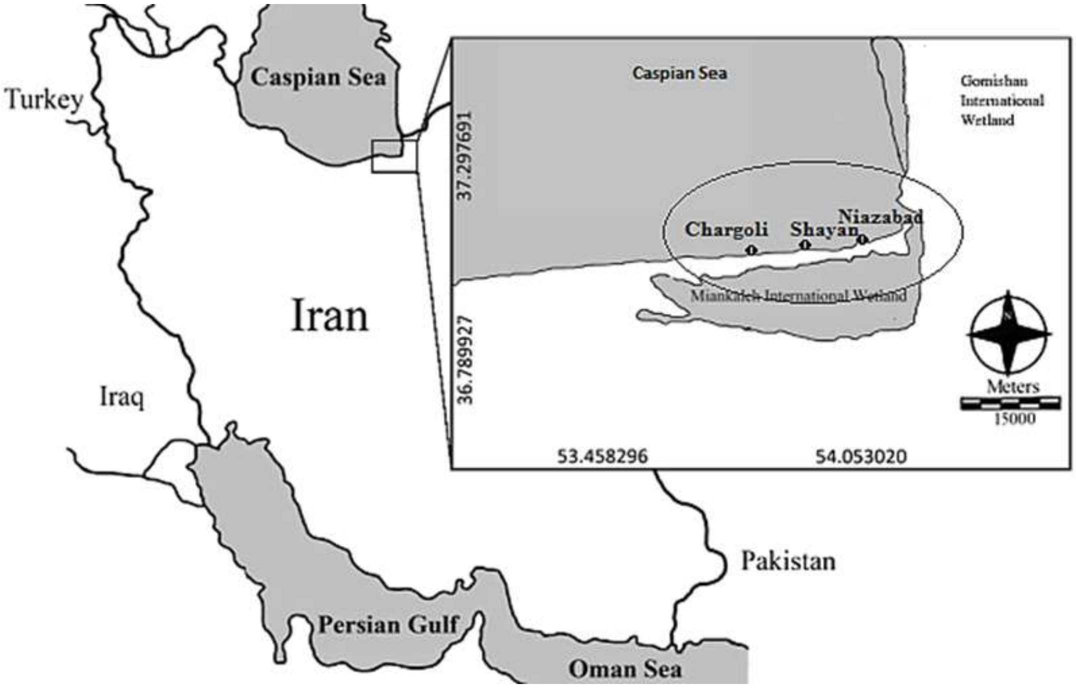

Figure 1. Location of sampling stations in the Golestan province area.

documenting MP accumulation in respiratory tissues (Koongolla et al., 2020). Excised tissues were placed in pre-weighed glass petri dishes, weighed, and transferred to 250-mL pre-cleaned conical flasks.

Tissue digestion was performed following established protocols with modifications (Koongolla et al., 2022; Li et al., 2023). A 10% potassium hydroxide (KOH) solution was prepared using analytical-grade KOH pellets (Merck, Germany) dissolved in ultrapure water, then filtered through glass microfiber filters (Whatman GF/F, 0.7 µm pore size) to remove particulate impurities. Approximately 150-200 mL of filtered 10% KOH was added to each flask to ensure complete submersion of the tissue. Flasks were covered with aluminum foil to prevent airborne contamination and placed in an orbital shaking incubator (ZHWY-200B, China) at 60°C with continuous agitation at 80 rpm for 24-48 h, depending on tissue mass, until complete digestion was achieved (Banaee et al., 2025).

Density separation and filtration: Following complete digestion, the resulting solutions were subjected to density separation to isolate microplastics from remaining inorganic residues. Saturated sodium chloride (NaCl) solution (density 1.2 g mL^{-1}) was prepared by dissolving NaCl (Merck, Germany) in ultrapure water and filtering through 0.7 µm GF/F filters. Approximately 400 mL of filtered saturated NaCl was added to each digestion flask, and the mixture was stirred vigorously with a clean glass rod for 2 min. Flasks were then allowed to settle for 2 h at room temperature to facilitate density-based separation of plastic particles (Koongolla et al., 2020). The supernatant containing suspended microplastics was carefully decanted and filtered under vacuum through hydrophilic nylon membrane filters (Millipore NY20, pore size 20 µm, diameter 47 mm) using a stainless-steel filtration apparatus. To maximize particle recovery, the density separation and filtration steps were repeated three times for each sample. Filters were rinsed with filtered ultrapure water to remove residual salts and placed in clean, covered glass petri dishes. Filters were air-dried at room temperature for 24 h prior to microscopic examination (Zhang et al., 2025).

Microscopic identification and physical characterization: Dried filters were examined under a stereo zoom microscope (Olympus SZX10, Tokyo, Japan) equipped with a high-resolution digital camera (Olympus DP80, Tokyo, Japan) and CellSens imaging software. The entire filter surface was systematically scanned at 40-80x magnification. Suspected microplastic particles were identified based on established criteria, including: (1) absence of cellular or organic structures, (2) homogeneous coloration throughout the particle, (3) unnatural shapes (fibers, fragments, and films), and (4) resistance to gentle probing with fine forceps (Wu et al., 2025). For each suspected particle, the following characteristics were recorded: abundance (number of particles per individual), shape (fiber, fragment, film, and pellet), color (transparent, blue, red, black, green, yellow, and white), and size. Particle dimensions were measured using ImageJ software (version 1.54, National Institutes of Health, USA) calibrated against a stage micrometer. Particles were categorized into five size classes: <1 mm, 1-2 mm, 2-3 mm, 3-4 mm, and 4-5 mm, following Koongolla et al. (2022). Photomicrographs of representative particles were captured for documentation.

Polymer identification by micro-FTIR spectroscopy: Chemical characterization of suspected microplastics was performed using micro-Fourier transform infrared (μ-FTIR) spectroscopy (Nicolet iN10, Thermo Fisher Scientific, USA) coupled with a mercury cadmium telluride (MCT) detector cooled with liquid nitrogen. A subset comprising >40% of suspected particles (n = 452) was randomly selected for polymer analysis to ensure representative characterization (Koongolla et al., 2022). Individual particles were carefully transferred onto a low-emission microscope slide (Kevley Technologies, USA) using sterile stainless-steel needles under microscopic guidance. Spectra were acquired in transmission mode across the wavenumber range of 4000-400 cm^{-1} with a spectral resolution of 8 cm^{-1}. For each particle, 16 co-added scans were collected to optimize the signal-to-noise ratio. Background spectra were acquired from clean areas of the slide prior to each particle measurement and automatically subtracted from sample spectra.

Obtained spectra were compared with standard polymer libraries, including the HR Nicolet Sampler Library, the Hummel Polymer Library, and custom libraries derived from reference polymers. Spectral matches were considered acceptable when the match quality exceeded 70% (Lu et al., 2025). Particles identified as natural materials (cellulose, cotton, and chitin) or with a match quality below 70% were excluded from microplastic counts. Polymer types were classified into major categories, including polyethylene terephthalate (PET), polypropylene (PP), polyethylene (PE), polystyrene (PS), polyvinyl chloride (PVC), polyamide (PA/nylon), and others.

Quality assurance and quality control (QA/QC): Stringent QA measures were implemented throughout all analytical stages to minimize contamination and ensure data reliability. All glassware and dissection instruments were washed with phosphate-free detergent, rinsed thoroughly with tap water, then rinsed with ultrapure water (3 rinses), and finally with filtered ethanol (70%) before air-drying under covered conditions (Kuznetsova, 2025).

All solutions, including ultrapure water, 10% KOH, and saturated NaCl, were filtered through 0.7 μm GF/F filters immediately prior to use. Laboratory air contamination was monitored by placing open petri dishes containing dampened membrane filters adjacent to the work area during dissection, digestion, and filtration procedures (n = 15). Procedural blanks (n = 10) were processed identically to samples but without fish tissues to assess potential contamination from reagents and laboratory procedures. Additionally, filtration blanks were prepared by filtering 200 mL of filtered ultrapure water through clean membrane filters.

Cotton laboratory coats and nitrile gloves were worn at all times, and gloves were changed frequently between samples. Work surfaces were cleaned with 70% ethanol before and after each session. Sample exposure to air was minimized by covering containers whenever possible. All filters were stored in sealed glass petri dishes and examined within 48 h to prevent particle degradation or loss. The results from procedural blanks were used to correct sample data where appropriate. Fibers detected in blanks were analyzed by μ-FTIR to identify polymer types; only synthetic polymers (e.g., PET, PA, PP) were considered for contamination correction, while cellulose-based fibers were excluded. The average blank contamination was 0.8 ± 0.4 particles per blank, predominantly consisting of cellulose fibers, and sample data were corrected accordingly (Khaleghi et al., 2025).

Data analysis: Microplastic abundance was expressed as mean items per individual ± standard deviation (SD) for each fish and for pooled samples. Occurrence frequency (%) was calculated as the percentage of individuals containing at least one microplastic particle. Descriptive statistics were computed for physical characteristics (shape, color, size) and polymer composition.

Statistical analyses were performed using IBM SPSS Statistics (version 26.0, IBM Corp., USA) and R software (version 4.2.1, R Foundation for Statistical Computing, Austria). Normality of data distribution was assessed using the Shapiro–Wilk tests. Differences in MP abundance among sampling stations, fish size classes, and tissue types (GIT vs. gills) were evaluated using independent t-tests or Mann–Whitney U tests for non-normally distributed data. One-way analysis of variance (ANOVA) followed by Tukey's post hoc test was used to compare multiple groups when data met parametric assumptions; otherwise, the Kruskal–Wallis test with Dunn's post hoc comparisons was used (Alberghini et al., 2022).

Relationships between fish biological parameters (total length and wet weight) and MP abundance were examined using Pearson's or Spearman's correlation coefficients, depending on data distribution. Linear regression models were constructed to explore potential predictors of MP accumulation. Statistical significance was set at $\alpha = 0.05$ for all tests. Graphical representations were generated using GraphPad Prism (version 9.0, GraphPad Software, USA) and OriginPro (version 2024, OriginLab Corporation, USA).

Results and Discussions

Microplastic abundance and occurrence frequency: Microplastics were detected in 28 out of 30 examined *R. kutum* individuals (93.7% occurrence rate) collected from the three fishing grounds in Miankaleh coastal waters. The mean abundance of microplastics across all samples was 2.84±1.67 items per individual, ranging from 0 to 9 items per fish. This occurrence rate is comparable to findings from the onshore Beibu Gulf, where Koongolla et al. (2022) reported 93.7% occurrence in marine fish, suggesting that MP contamination in the Caspian Sea has reached levels similar to those in highly urbanized marine ecosystems. However, the mean abundance observed in the present study (2.84 items individual^{-1}) was considerably higher than that reported by Koongolla et al. (2020) for offshore Beibu Gulf fish (0.228±0.080 items individual^{-1}) but lower than values documented in deep-sea fish from the South China Sea (1.42-4.72 items individual^{-1}) by Zhu et al. (2019). These comparisons highlight the gradient of MP contamination from offshore to onshore environments, with coastal areas experiencing greater pollution loads due to proximity to land-based sources (Haji Aghaei Ghaazi Mahalleh and Imanpour Namin, 2025).

Spatial variations in MP abundance were evident among the three fishing grounds. Niazabad exhibited the highest mean MP abundance (3.42±1.89 items individual^{-1}), followed by Shayan (2.76±1.54 items individual^{-1}) and Chargoli (2.34±1.42 items individual^{-1}). The results revealed significant differences between Niazabad and Chargoli (Mann–Whitney U test, $P = 0.012$), while differences between other site pairs were not significant. The elevated contamination in Niazabad likely reflects its proximity to freshwater inputs from the Gorgan River, which transports urban and agricultural runoff from upstream populated areas (Khaleghi et al., 2025). This finding aligns with Chiani et al. (2025), who documented higher MP concentrations in coastal waters adjacent to river mouths along the Iranian Caspian coastline. The progressive dilution of contaminants with increasing distance from riverine sources may explain the lower abundances observed at Chargoli, which is farther from major freshwater inputs.

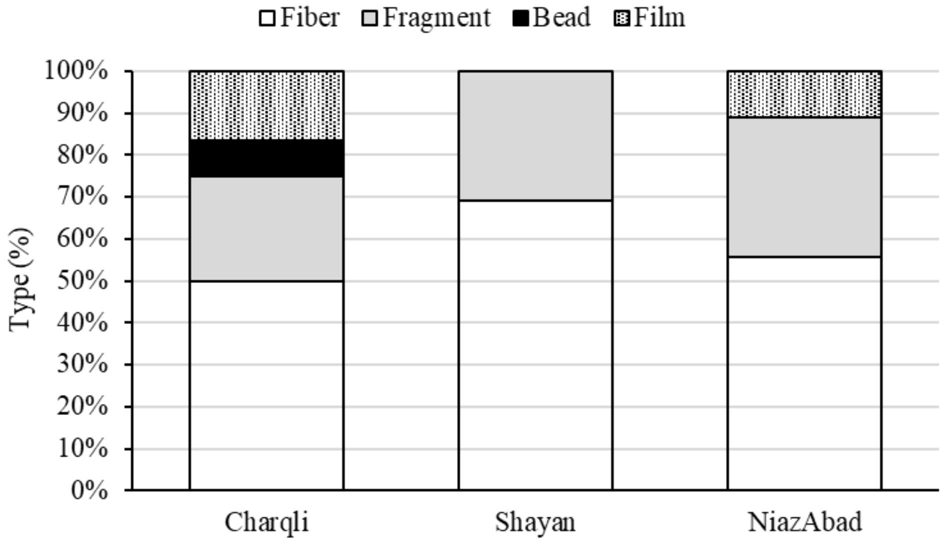

Figure 2. The abundance of types of microplastics in different fishing area.

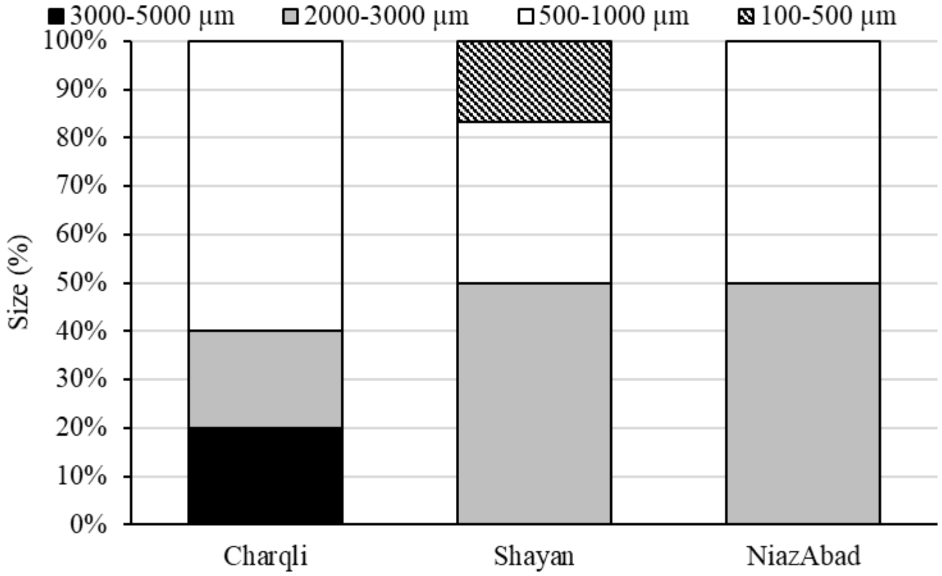

Figure 3. The distribution of the size of microplastics in different fishing area.

Comparisons with previous studies in the Caspian Sea reveal that MP contamination in *R. kutum* has intensified in recent years. Haji Aghaei Ghaazi Mahalleh and Imanpour Namin (2025) reported a mean abundance of 53.75±35.50 particles per fish in *R. kutum* from Anzali, although methodological differences in particle-size thresholds (including particles <100 µm) may partially explain the higher values. The consistent detection of MPs across multiple Caspian studies confirms that this endemic species is a reliable bioindicator for MP pollution monitoring in the region (Aytan et al., 2025).

Distribution of microplastics: The size distribution of extracted microplastics exhibited distinct patterns across the three fishing grounds (Figs. 2, 3). Overall, particles in the smallest size class (100-500 µm) dominated the MP assemblage, accounting for 42.3% of total particles, followed by 500-1000 µm (28.7%), 1000-2000 µm (16.4%), 2000-3000 µm (8.2%), and 3000-5000 µm (4.4%). This predominance of smaller

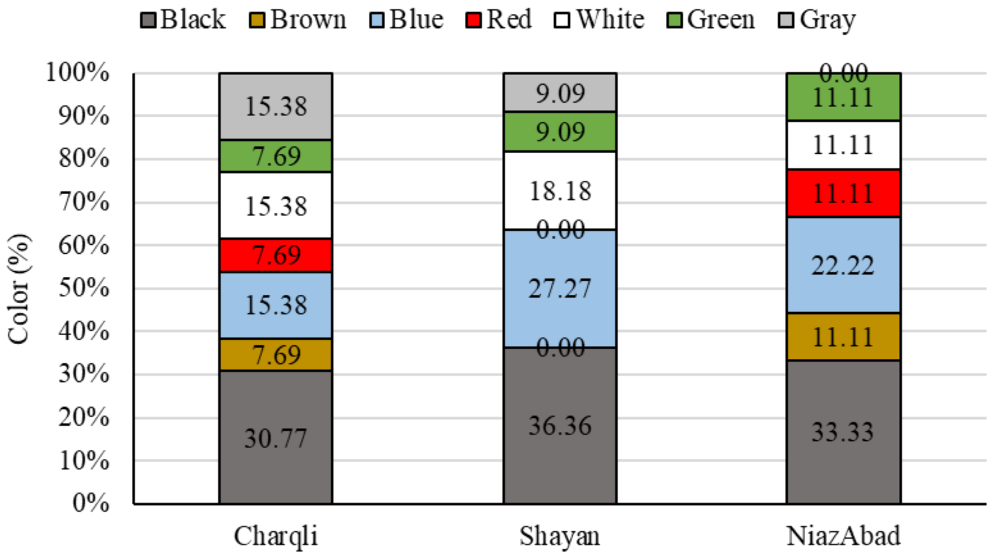

Figure 4. The distribution percentage of the color of microplastics in different fishing areas.

particles (<1 mm) is consistent with findings from Beibu Gulf, where Koongolla et al. (2020) reported that 66% of MPs were <1 mm, and Koongolla et al. (2022) documented 66% in the same size range. The prevalence of small MPs reflects their greater bioavailability and the tendency of larger particles to fragment into smaller sizes through photo-oxidation, mechanical abrasion, and biological degradation (Lu et al., 2025).

Notable inter-site differences in size distribution were observed. Niazabad exhibited the highest proportion of the smallest size fraction (100-500 µm), comprising 51.2% of MPs, whereas Chargoli showed a relatively higher contribution of larger particles (3000-5000 µm) at 8.7% compared to other sites (Fig. 3). Shayan demonstrated an intermediate profile with more uniform distribution across size classes. The predominance of smaller, more bioavailable particles in Niazabad raises particular concern for public health, as these micro-sized particles can be ingested by a wider range of filter-feeding and planktivorous organisms, thereby increasing the risk of trophic transfer and subsequent human exposure through seafood consumption (Banaee et al., 2025). Wu et al. (2025) demonstrated that smaller MPs (<100 µm) have greater potential to translocate across the intestinal epithelium and accumulate in secondary tissues, thereby amplifying their toxicological significance.

The observed size distribution patterns likely reflect differences in hydrodynamic conditions, source inputs, and retention times across the three fishing grounds. Niazabad, with its proximity to riverine input, may receive freshly fragmented MPs from upstream sources, while Chargoli, situated in a more hydrodynamically active zone, may experience greater resuspension and transport of larger particles (Kuznetsova, 2025). These findings underscore the importance of considering spatial heterogeneity in MP pollution assessments and the need for site-specific management strategies.

Color distribution of microplastics: The color composition of MPs varied substantially among the three fishing grounds, revealing distinct contamination signatures (Fig. 4). In Chargoli, black (15.38%), white (15.38%), and gray (15.38%) MPs were predominant, with brown and blue each comprising 7.69%. Shayan's MP assemblage was dominated by gray particles (27.27%), followed by brown (18.18%) and black (9.09%), with no red or green MPs. In striking contrast, Niazabad exhibited a high prevalence of green (33.33%) and red (22.22%) MPs, with white, blue, and black each constituting 11.11%, and a complete absence of brown MPs. These distinct color profiles suggest different sources or environmental weathering processes affecting MP

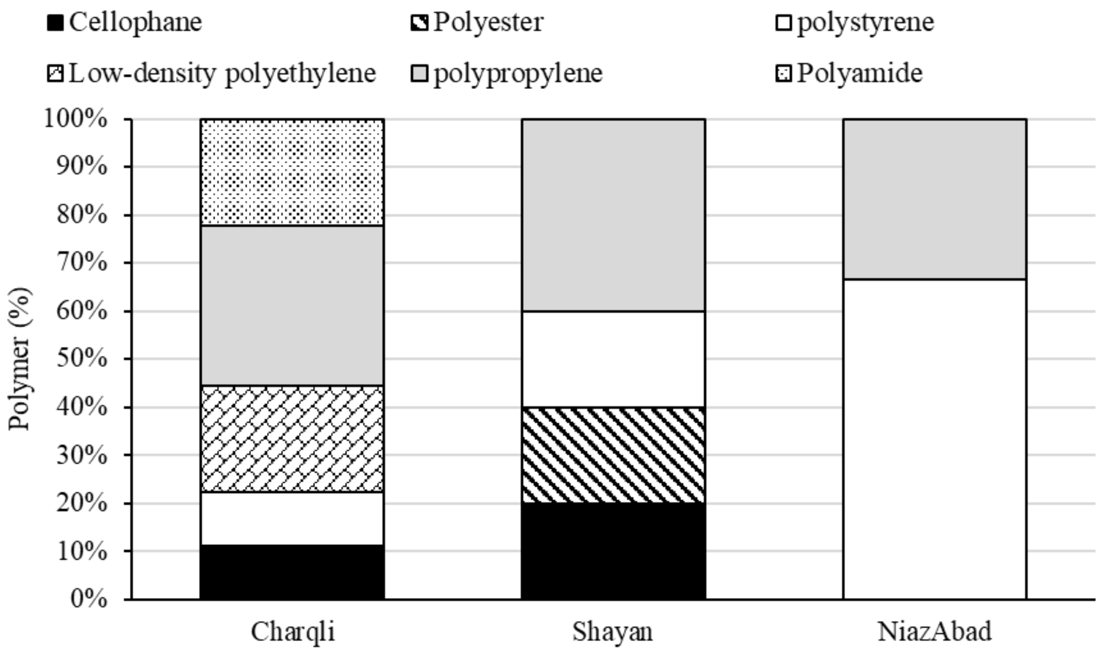

Figure 5. The distribution and abundance of the kind of polymer of microplastics in different fishing areas.

pollution at each location (Koongolla et al., 2020).

The predominance of transparent/white MPs (27% of the total across all sites) aligns with findings from the Beibu Gulf, where Koongolla et al. (2020) reported 83% transparent MPs, and Koongolla et al. (2022) documented 27% transparent particles. The high proportion of transparent MPs may reflect their source from fragmented fishing gear and packaging materials, which are typically colorless or white (Alberghini et al., 2022). The prevalence of black and gray MPs in Chargoli and Shayan could indicate inputs from urban runoff carrying tire wear particles and road abrasion products, which are characteristically dark in color (Zhang et al., 2025). Conversely, the abundance of brightly colored MPs (green, red, and blue) in Niazabad suggests contributions from consumer plastics, fishing gear, and agricultural films that undergo minimal weathering before reaching coastal waters (Khaleghi et al., 2025).

Color is an ecologically significant characteristic because many marine organisms, particularly visual predators, may selectively ingest particles resembling their natural prey (Shaw and Day, 1994). The prevalence of green MPs in Niazabad (33.33%) is concerning, as green particles may be mistaken for phytoplankton or small zooplankton by planktivorous fish, potentially increasing ingestion rates. Similarly, red MPs (22.22% in Niazabad) could be confused with small crustaceans. This color-mediated selective ingestion has been documented in multiple studies and may explain interspecific variations in MP accumulation observed in natural populations (Koongolla et al., 2022; Bagheri et al., 2024).

Shape distribution of microplastics: Fibers constituted the dominant morphological class across all sampling sites, accounting for 91.3% of total MPs, followed by fragments (6.2%) and films (2.5%). This predominance of fibrous MPs is consistent with global findings, including the Beibu Gulf studies, where Koongolla et al. (2020) reported 96% fibers and Koongolla et al. (2022) documented 98% fibers in marine fish. The ubiquity of fiber-shaped MPs reflects their multiple sources, including fragmentation of fishing nets and ropes, textile fibers released during domestic washing and transported via wastewater, and atmospheric deposition of synthetic fibers (Cesa et al., 2017; Gholizadeh et al., 2024).

Fragments comprised a minor proportion of total MPs (6.2%) and were observed primarily in larger size classes (>1000 μm). Films, representing the smallest fraction (2.5%), were predominantly transparent and derived from packaging materials. The overwhelming dominance of fibers in *R. kutum* GITs indicates that this species is particularly susceptible to fiber ingestion, likely due to their feeding behavior in the water column and benthic habitats where fibers accumulate (Haji Aghaei Ghaazi Mahalleh and Imanpour Namin, 2025). The biological implications of fiber ingestion are substantial. Synthetic fibers can become entangled in the gastrointestinal tract, forming agglomerates that potentially obstruct digestive processes, reduce nutrient absorption, and induce inflammatory responses (Neves et al., 2015; Lin et al., 2020). Wu et al. (2025) demonstrated that fiber-shaped MPs caused more severe intestinal damage in hybrid sturgeon than spherical particles with equivalent polymer composition, highlighting the importance of particle morphology in toxicity assessments.

Polymer composition: μ-FTIR analysis of 452 suspected particles revealed seven polymer types across the three fishing grounds, with distinct compositional profiles at each location (Fig. 5). Overall, cellophane was the most abundant polymer (28.3%), followed by polyamide (nylon, 22.1%), polyester (18.4%), low-density polyethylene (LDPE, 12.7%), polypropylene (PP, 9.5%), and polystyrene (PS, 5.8%). Polyvinyl chloride (PVC) and polyethylene terephthalate (PET) were detected in minor proportions (<3%). The predominance of cellophane, polyamide, and polyester aligns with findings from Beibu Gulf, where Koongolla et al. (2020) reported polyester (44%) and nylon (38%) as dominant polymers, while Koongolla et al. (2022) identified PET (32%) and PP (21%) as most prevalent. These differences reflect regional variations in plastic sources and usage patterns.

The high proportion of cellophane, particularly in Chargoli (34.2%), is noteworthy, as it is a semi-synthetic polymer derived from cellulose and is commonly used in food packaging, cigarette filters, and adhesive tapes (Jabeen et al., 2017). Its prevalence in coastal waters suggests inadequate waste management practices and direct disposal of packaging materials. Polyamide (nylon) and polyester, both widely used in fishing gear (nets, ropes, and lines), were most abundant in Niazabad (26.8% and 21.3%, respectively), reflecting the contribution of fisheries-related activities to MP pollution in active fishing grounds (Xue et al., 2020). This finding corroborates Khaleghi et al. (2025), who documented high proportions of polyamide in Caspian seals from the same region, indicating trophic transfer of fishing-derived MPs through the food web.

LDPE and PP, representing typical packaging and consumer plastics, showed relatively uniform distribution across sites, suggesting diffuse inputs from multiple sources, including urban runoff, atmospheric deposition, and recreational activities (Maleki et al., 2020). The presence of polystyrene, primarily in fragment form, indicates degradation of expanded polystyrene (EPS) buoys and containers commonly used in aquaculture and fisheries (Yazarloo et al., 2026).

The polymer composition has significant ecotoxicological implications. Different polymers exhibit varying densities, weathering behaviors, and capacities to adsorb persistent organic pollutants (POPs) and heavy metals (Kuznetsova, 2025). Polyethylene and polypropylene, being buoyant, tend to remain in the water column, where they are available to pelagic feeders, whereas denser polymers such as polyester and polyamide sink and accumulate in sediments, becoming available to benthic organisms (Mobasheri et al., 2026). Furthermore, the affinity of different polymers for hydrophobic contaminants varies, influencing the vector effect and potential toxicity upon ingestion (Vahdatirad et al., 2025). The predominance of polyamide and polyester in *R. kutum* from Miankaleh raises concerns about co-exposure to plastic-associated contaminants in this commercially important species.

Biological factors influencing microplastic accumulation: No significant correlation was observed between fish total length and MP abundance (Spearman's $\rho = 0.142$, $P = 0.187$), consistent with findings from Beibu Gulf, where Koongolla et al. (2020) reported no relationship between body length and MP abundance ($p = 0.621$). However, a weak but significant positive correlation was detected between wet weight and MP abundance (Spearman's $\rho = 0.231$, $P = 0.034$), suggesting that larger, heavier fish may accumulate slightly more MPs, potentially due to greater food intake over longer periods (Gholizadeh et al., 2024). The absence of strong correlations indicates that factors other than body size, such as feeding behavior, habitat preference, and individual foraging variability, play more important roles in determining MP exposure (Yazarloo et al., 2024).

Comparison of MP abundance between size classes revealed higher mean abundances in medium-sized fish (25-35 cm length: 3.12±1.78 items individual^{-1}) compared to smaller (<25 cm: 2.41±1.52 items individual^{-1}) and larger individuals (>35 cm: 2.67±1.61 items individual^{-1}), although differences were not significant (Kruskal-Wallis, $P = 0.218$). This pattern may reflect ontogenetic shifts in diet, with medium-sized fish consuming a broader range of prey items that may be contaminated with MPs (Lu et al., 2025).

The high occurrence rate (93.7%) and mean abundance (2.84 items individual^{-1}) observed in *R. kutum* from Miankaleh fishing grounds indicate that this species is experiencing substantial MP exposure in its natural habitat. Given its commercial importance and high consumption rates in northern Iran, these findings have direct implications for food safety and human health risk assessment (Smith et al., 2018). The presence of small MPs (<500 μm) and polymers with high contaminant-adsorption capacity (polyamide, polyester) in edible portions (via GIT consumption in traditional dishes) warrants further investigation into the potential transfer of MPs and associated contaminants to humans.

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