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AQUATIC PLASTIC POLLUTION

Anthropogenic microparticles ingestion patterns in fish across trophic guilds in mangrove estuaries

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Abstract The ingestion of anthropogenic microparticles by fish is an emerging global concern, with significant knowledge gaps in ecosystems such as mangroves. We analyzed the gastrointestinal tract contents of 736 juvenile fish representing 20 species from different trophic guilds across three estuaries, sampled during two seasons (dry and rainy), within the largest mangrove area in South America. A total of 1516 food items were identified, of which 128 (~10%) were classified as anthropogenic particles. Among these particles, 109 were microparticles, 18 were mesoparticles, and one was a macroparticle. Most particles were filaments (84%), predominantly blue and black, across all estuaries and seasons. The occurrence of anthropogenic microparticles averaged 26.07% during the rainy season and 21.25% during the dry season. Fish from all trophic guilds showed ingestion of anthropogenic particles. Our findings reveal the widespread presence of plastic- and textile-derived contamination in juvenile fish, even in remote mangrove ecosystems, highlighting the need for further investigation and mitigation efforts in both impacted and relatively pristine environments.

Keywords Amazon coast · Plastic · Polymer · Marine pollution · Microplastic

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Introduction

Estuarine ecosystems are transitional environments between rivers and the ocean, characterized by the mixing of freshwater and seawater. Estuaries are among the most productive systems in the world because they create a wide range of fish habitats and provide nutrients, protection, and nursery areas for reproduction, in addition to being a source of food for humans (Barletta et al., 2010; Ferreira et al., 2016). Within these environments, mangroves represent one of the dominant ecosystems in tropical and subtropical regions, playing a fundamental ecological and socioeconomic role (Kulkarni et al., 2018). This importance is directly related to their high efficiency in carbon sequestration, which significantly contributes to climate regulation (Dittmar et al., 2006). In addition, their complex root structures promote sediment retention and water filtration, improving environmental quality and supporting biodiversity in adjacent ecosystems. The high productivity and ecological importance of these ecosystems make them particularly susceptible to contamination from human-derived debris, such as plastics, highlighting the need to understand the scale and impacts of this pollution (Kulkarni et al., 2018).

In recent decades, the advancement in the development of new materials has been significant (Koller & Mukherjee, 2022), with the expansion of the plastics industry being a notable highlight. The annual production of plastic goods amounted to 25 million metric tons globally in 1970 and it surpassed 435 million metric tons in 2020, with estimates indicating that this volume could double in the next 20 years (Geyer et al., 2017; Walker & Fequet, 2023; OECD, 2024). Most plastic waste in the environment is "disposable" (i.e., single-use) and is dumped in landfills, where it is frequently blown back to the surface and turned into "debris" (i.e., microplastic), while the remaining plastic waste is improperly discarded into the environment (Schnurr et al., 2018).

Plastic polymers are generally classified by size: nanoplastics (< 1 μm), microplastics (1 μm–5 mm), mesoplastics (5–25 mm), and macroplastics (> 25 mm) (GESAMP, 2019). Additionally, regarding size classification, microplastics (MPs) are divided into two categories: primary or secondary. Primary MPs are defined according to the size at which they were originally produced, whereas secondary MPs result from the fragmentation of larger plastic items, typically originating from plastics that were improperly discarded into the environment (GESAMP, 2019). More broadly, the term "microparticles" encompasses all small particles present in the environment, including both natural and synthetic origins, such as cellulose, which can occur naturally or be industrially produced, while the term "microplastics" specifically refers to particles composed of synthetic plastic polymers. Finally, the term "anthropogenic particles" is used in this study to denote all human-derived particles, including synthetic plastics, textile fibers, and other man-made debris. This distinction clarifies that while all microplastics are anthropogenic, not all anthropogenic particles are plastics.

Mangroves act as natural retention zones for various contaminants, making them particularly vulnerable to the accumulation of microplastics and synthetic fibers (Bayen, 2012). The pathways through which plastics can enter aquatic ecosystems are diverse, including wastewater treatment plants (GESAMP, 2019), washing machines that release large amounts of fibers into the water (Browne, 2015; Karlsson, 2015), sewage sludge containing high concentrations of household waste that is washed into waterways by rainwater (Zubris & Richards, 2005), among others. Additionally, it is worth noting that approximately 18% of the plastic particles found in the oceans are attributed to the fishing industry, which commonly loses and/or improperly discards materials such as ropes, lines, and fishing nets at sea (Andrady, 2011; Barasarathi et al., 2014). However, tropical estuaries are among the habitats most imperiled by plastic pollution due to their proximity to densely populated coastal areas, high inputs of land-based waste, and hydrodynamic conditions that favor the accumulation and retention of debris (Barasarathi et al., 2014; Nor & Obbard, 2014; Medrano et al., 2015; Andrades et al., 2020; Naidoo et al., 2020; De et al., 2023).

After reaching estuaries, plastics have a high potential to be transported to continental shelves and the open ocean (Malli et al., 2022). However, the tidal cycles characteristic of these environments favor the prolonged retention of these materials, which can remain in estuaries for extended periods (Ivar do Sul & Costa, 2013). During this time, plastics are subjected to various degradation processes, both in the different types of sediments where they accumulate and throughout their movement between distinct estuarine microhabitats (Wang et al., 2022). However, despite their ecological relevance, mangroves have historically been underestimated in studies on microplastic pollution (Deng et al., 2021).

Studies indicate that fibers—especially those originating from textiles and fishing gear—are the most common forms of microplastics in these ecosystems (e.g., Carr, 2017; Deng et al., 2021; Acharya et al., 2021). Once retained in the sediment or suspended in the water column, these particles become bioaccessible to aquatic organisms, potentially being ingested and transferred along the food chain (Markic et al., 2018). The persistent presence of these pollutants in critical habitats raises concerns about long-term ecological impacts, such as physiological stress, bioaccumulation, and risks to the food security of human communities that depend on these resources.

The number of marine species interacting with plastic particles has increased by approximately 2.5-fold over the past two decades, from 267 species (Laist, 1997) to 693 species (Gall & Thompson, 2015), with records of 427 fish species ingesting plastic particles (Li et al., 2021). The fish diversity in estuaries forms the basis of a substantial portion of the subsistence diet, serving as a crucial source of protein for many human communities (Paiva & Silva, 2020). Spatial differences among estuaries are expected to influence microparticle ingestion, as factors such as proximity to urban areas, hydrodynamics, and sediment characteristics alter the availability and retention of debris (Ivar do Sul & Costa, 2013; Barasarathi et al., 2014). Seasonal variations may also affect exposure, as rainfall and tidal cycles modify particle transport and habitat conditions (Wang et al., 2022; Deng et al., 2021). In addition, plastic ingestion by fish represents a well-documented environmental concern in estuarine ecosystems, as it can affect feeding behavior, energy balance, and contaminant transfer across trophic levels (Benson et al., 2022; Orose et al., 2023; Nodehi et al., 2024). Studies conducted in temperate and subtropical estuaries have shown a high occurrence of plastic particles in different fish species, indicating the global relevance of this issue (Ferreira et al., 2016; Di et al., 2024; Carty et al., 2025).

During their early life stages, fish species exhibit heightened vulnerability to environmental fluctuations, particularly variations in salinity, temperature, and turbidity (Rodrigues et al., 2019). In addition to these physiological constraints, juveniles may also be more susceptible to plastic ingestion due to limited foraging experience and still-developing sensory and feeding mechanisms (Roch et al., 2020; Li et al., 2021). This combination can increase the likelihood of mistaking plastic particles for prey, especially in turbid environments where visual discrimination is reduced (Ory et al., 2018). Considering that trophic ecology influences exposure routes and feeding mechanisms, the inclusion of fish from distinct trophic guilds enables a comprehensive assessment of potential differences in microparticle ingestion among species with contrasting feeding strategies (Giani et al., 2023; Albertin-Santos et al., 2025).

Our aim was to investigate the ingestion of anthropogenic microparticles by juvenile fish from distinct trophic guilds in three estuaries within the largest mangrove area in South America, in the Brazilian Amazon coast. Gastrointestinal tract contents were analyzed to test the hypotheses: (1) ingestion frequency varies among fish species due to differences in size, morphology, and feeding behavior; (2) fish from different trophic guilds ingest different quantities and types of microparticles, reflecting distinct exposure pathways; (3) the shape, color, and size of ingested particles vary among species and guilds, reflecting feeding strategies and habitat use; and (4) microparticle ingestion differs among estuaries and between dry and rainy seasons, reflecting spatial and temporal variability in environmental exposure. The null hypothesis was that, regardless of species, trophic guild, estuary, or season, anthropogenic microparticles would occur equally across all groups.

Materials and methods

Study area

The study was conducted in three distinct mangrove estuaries, the estuary of the Pará River, the estuary of the Caeté River (both in the Brazilian State of Pará), and the estuary of the Parnaíba Delta (located along the border between the States of Maranhão and Piauí) (Figs. 1 and S1). These estuaries differ markedly in hydrodynamics, salinity gradients, sediment dynamics, and the intensity and sources of anthropogenic pressures, which are detailed below. The months from December to May (rainy season) have the highest

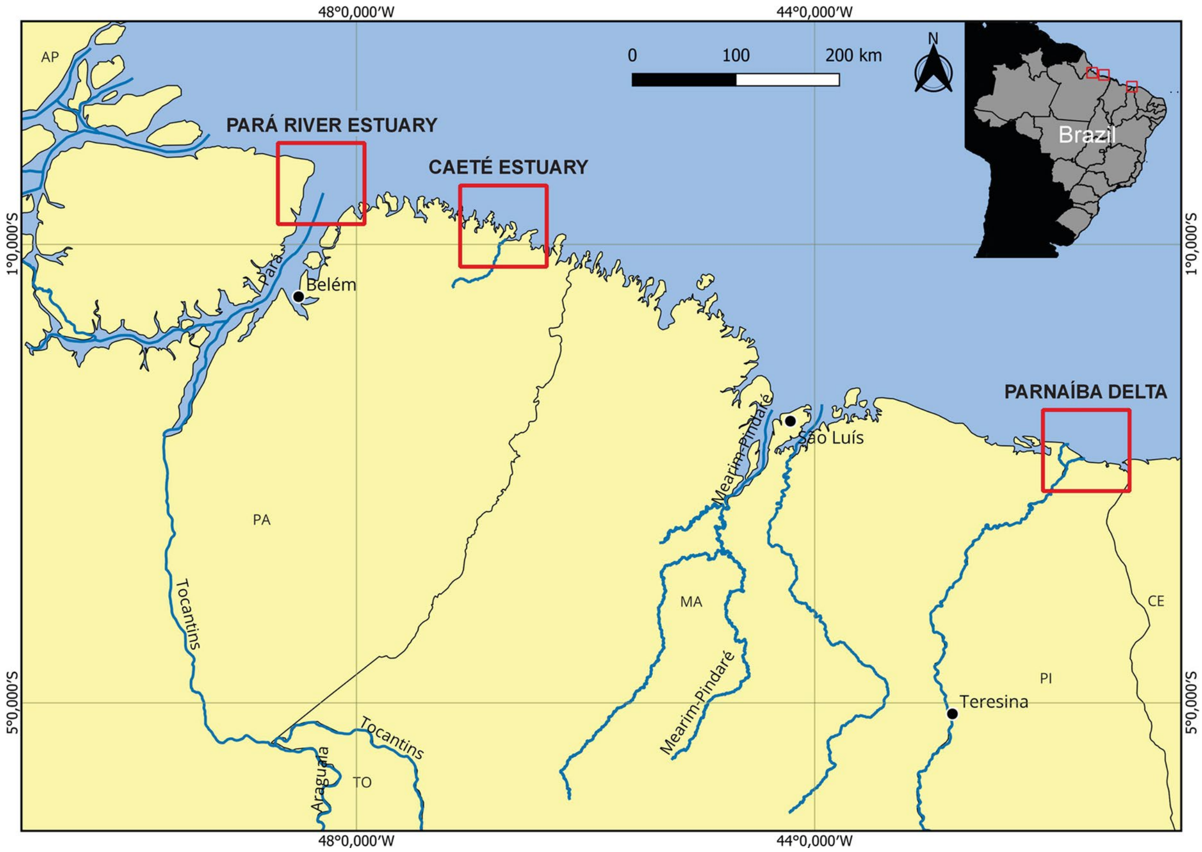

Fig. 1 Location of the study area, including data collection locations in the Pará, Caeté, and Parnaíba estuaries (Brazil)

rainfall rates in the three estuaries, while the months from June to November have the lowest rates (dry season) (Nittrouer et al., 2021). The main plant species found in the region include *Rhizophora racemosa* G. Mey., *Rhizophora mangle* L., *Avicennia germinans* (L) L., *Laguncularia racemosa* (L.) C.F.Gaertn. and *Acrostichum aureum* L. (França & Souza-Filho, 2003).

The Pará River estuary, also known as Marajó Bay (0° 44′ 34″ S 48° 30′ 25″ W) (Fig. 1), has a longitudinal extension of more than 300 km and a mouth extension of approximately 60 km, mostly generated by the discharges of the Amazon River (via the Breves Strait) and Tocantins River (Prestes et al., 2020; Nittrouer et al., 2021), which increase the flow of organic material, dissolved nutrients, and sediments (Nittrouer et al., 2021). By the margins of the estuary are the cities of Soure and Salvaterra, which together have over 48,000 inhabitants (IBGE, 2022). In addition, several cities are indirectly associated with the banks of the Pará River, including Belém and Ananindeua (Santos et al., 2023). The salinity of the Pará River estuary varies between 1.7 and 5.6 psu (Rosário et al., 2016), and the mangrove vegetation is composed of typical species adapted to the brackish and unstable conditions of this coastal environment. Potential sources of plastic pollution in this estuary include domestic sewage and solid waste from nearby urban centers, port activities, and the discharge of materials transported by the Amazon and Tocantins rivers (Souza et al., 2023; Morais et al., 2024).

The Caeté estuary (0° 50′ 25″ S 46° 38′ 20″ W) is in the northeast of Pará, in the municipality of Bragança, which is home to approximately 123,000 inhabitants (IBGE, 2022). The main river extends 100 km from Ponta do Maiaú to the mouth of the Atlantic Ocean, which is approximately 11.5 km long (Barletta et al., 1998). The Caeté estuary exhibits highly dynamic sediment movement associated with macrotides, resulting in zones of erosion and vegetation deposition (Cohen & Lara, 2003), while salinity ranges from 5.1 to 26.5 (Rosa Filho et al., 2006). Plastic inputs in the Caeté estuary mainly originate from fishing activities, tourism, and domestic waste from urban and rural communities along the riverbanks (Mendes et al., 2024).,

The Parnaíba Delta (2° 45′ 49″ S 41° 50′ 21″ W) is located between the states of Maranhão and Piauí, with the municipalities of Parnaíba, Ilha Grande, Luiz Correia, and Araioses being the closest and having a greater influence on the delta, totalling more than 241,000 inhabitants (IBGE, 2022). Five channels connect the Parnaíba Delta estuary to the ocean, which is 1450 km from the river's mouth (Machado-Júnior & Macedo, 2016). Limited primary productivity is observed in this area with warm water, low precipitation, and high salinity ranges from 1.1 to 33.3 psu (Matsuura, 1996; IBAMA, 1998; Chielle, 2019). Potential plastic pollution sources in this delta include tourism, port operations, fishing gear losses, and solid waste disposal from nearby urban centers (Paula Filho et al., 2015; Luz-Santos et al., 2025).

Sample collection

Pará River estuary and the Caeté River estuary were sampled in January 2018 (rainy season) and July 2018 (dry season) in order to capture seasonal variability in ichthyofaunal composition and microparticle ingestion patterns. In contrast, the Parnaíba Delta was sampled exclusively during the rainy season (April 2015) due to logistical constraints and the availability of previously scheduled scientific expeditions during that period. Nevertheless, this region was included in the study due to its ecological importance and because it represents an estuarine area with distinct characteristics, thus expanding the spatial coverage of the research. Moreover, the rainy season coincides with the period of highest primary productivity and trophic availability in estuaries of the North and Northeast regions of Brazil, which favors the analysis of fish diet and microparticle ingestion. To allow interspecific comparisons, we collected up to 13 individuals of each species in each estuary and hydrological period. Although the number of species within each trophic guild varied (8 omnivores, 7 carnivores, 5 planktivores), the sample size per species was sufficient for statistical comparisons.

Fish specimens were collected in intertidal zones using hand-drag nets ("picaré": 3×1.3 m, with a 3 m bag and 10 mm mesh size). In tidal channels, blocking nets were used (10×3 m, 12 mm mesh). In aquatic habitats with difficult access—such as mangrove roots and saltmarsh areas—sampling was conducted using hand nets (50 cm diameter, 2 mm mesh). All captured individuals were counted, euthanized using the ice-slurry method following ethical guidelines to minimize stress and pain in fish, and immediately stored on ice until laboratory processing. Species identification was performed using regional taxonomic keys, and guild classification followed FishBase (Froese & Pauly, 2025). All procedures involving fish collection and euthanasia complied with Brazilian legislation and were approved by the Institutional Animal Care and Use Committee (SISBIO 46679-1).

Juveniles were distinguished from adults based on the total length (TL) at first maturity reported in the literature, following Giarrizzo & Krumme (2007). When this information was not available, the length at maturity (L50) was estimated using the empirical equation of Froese & Binohlan (2020) through the life-history tool provided by FishBase (Froese & Pauly, 2025). Only juvenile individuals were used in the analyses to avoid potential biases associated with ontogenetic differences in morphology, physiology, behavior, and feeding ecology among the collected species. After species identification and the collection of biometric data (standard length—SL and weight—W), the specimens were transported to the laboratory, where all subsequent procedures were conducted under controlled conditions.

In the laboratory, the entire gastrointestinal tract was removed and preserved in filtered 70% ethanol (5 µm mesh) until content analysis. The stomachs were opened, and the stomach contents were transferred to a Petri dish for sorting. Then, the food items present in each fish were classified and identified under a binocular stereomicroscope to the lowest possible taxonomic level, using the *Illustrated Guide: Biodiversity of the Coast of Piauí* (Mai & Loebmann, 2010) as an additional reference. Each food item was carefully separated and weighed (± 0.01 g).

Anthropogenic microparticles found in the stomach contents of each individual were separated from the other particles and subsequently quantified and classified. They were classified by size (micro, meso, and macro), by shape (fragment, foam, film, fiber, and pellet), and by color, always following the criteria established by GESAMP (2019). Empty gastrointestinal tract was counted but excluded from the analyses.

Contamination control

All materials and equipment used in the laboratory procedures underwent regular cleaning after each analysis and were protected against potential external contamination by microplastics. Consequently, the processing of fish samples (extraction and analysis of gastrointestinal tract contents) took place inside a laboratory fume hood, conducted by a single person wearing cotton clothing, with doors and windows closed. To ensure the precision of the readings, a clean Petri dish was positioned next to the stereomicroscope at the beginning of the gastrointestinal tract content analysis. After processing the day's samples, they were subsequently inspected to detect any potential external contamination by anthropogenic microparticles present in the laboratory environment, thereby ensuring the accuracy of the results (Prata et al., 2021). All particles found in the gastrointestinal tract that matched with the fibers found in the Petri dish were excluded from the statistical analyses.

Data analysis

The plastics samples were identified through 2D FTIR imaging using a Cary 620–670 FTIR microscope equipped with a focal plane array detector (FPA, Agilent Technologies), which features an array of 128 × 128 photosensitive elements (pixels). The spectra were acquired on the surface of the samples (or of the Au background) with no additional sample preparation, in reflectance mode. The experimental conditions were as follows: open aperture, 8 cm^{-1} spectral resolution, and 128 scans for each pixel. A "single-tile" analysis with this setup produces a false-color IR map of ca. 700 × 700 μm^2; each pixel corresponds to an independent spectrum related to an area of 5.5 × 5.5 μm^2 on the sample surface, i.e., each tile yields more than 16,000 independent spectra, and already ca. 400 independent spectra on a fragment/fiber that is 200 µm long and 10 µm thick. Synthetic or natural polymers (artificial cellulose) were identified using standards reported in the literature (Garside & Wyeth, 2003; Jung et al., 2018), carefully checking all the main absorptions and the full spectral profile, including minor absorptions as well as alterations of spectral features, or absorptions by adsorbed matter or degradation products, in comparison with published spectra of the standards. Automatic identification was not adopted for two main reasons: (1) the lack of current extended libraries of Reflectance spectra; current libraries are mostly ATR or Transmission and do not account for the presence of deformations of absorption bands in the Reflectance spectra compared to ATR or Transmission standards; (2) the presence of different bands or band alteration in the experimental spectra owing to the degradation of the natural or synthetic polymeric fibers/fragments, which are typically not well considered in libraries. The major diagnostic bands were imaged in false-color IR maps. Spectra with less than, at least, 5 diagnostic peaks, as compared to the standards, were discarded. The absorbance intensity of each diagnostic band in the false-color IR maps followed the order RED > YELLOW > GREEN > BLUE. This experimental setup was selected since it has been shown to enable the non-invasive collection of many independent spectra (~ 10 or more) from microfibres and micro fragments (Pegado et al., 2018).

The frequency of occurrence of anthropogenic microparticles in the digestive tract was calculated as $Fi\% = (Ni/N) \times 100$, where Ni is the number of gastrointestinal tracts containing anthropogenic microparticles and N is the total number of gastrointestinal tracts examined. The importance of the food items consumed was estimated from the alimentary index according to Kawakami & Vazzoler (1980): $Ai = Fi \times Wi / \sum ni = 1\ (Fi \times Wi)$, where Fi is the frequency of occurrence of item *i* and Wi is the relative weight of item *i* and visualized through heatmaps to compare food categories among trophic guilds, estuaries, and hydrological periods (Clarke et al., 2013). The proposed hypotheses were tested using a combination of univariate and multivariate analyses. Differences in microparticle ingestion frequency and composition among fish species, trophic guilds, estuaries, and seasons, as well as variations in particle shape, color, and size, were assessed using permutational multivariate analysis of variance (PERMANOVA) with 9999 permutations based on Bray–Curtis dissimilarity matrices, implemented in the 'vegan' package (Oksanen et al., 2017) in R (R Development Core

Team, 2021). The null hypothesis of equal occurrence across all groups was evaluated by the absence of statistically significant differences.

Results

Diet composition

Twenty target species were chosen at their juvenile stages because of their co-occurrence, high abundance, and biomass in captures in the three estuaries, as well as their ecological and commercial value. The 20 species collected belong to 10 orders and 15 families and correspond to 3 trophic guilds (8 omnivorous species, 7 carnivorous, and 5 planktivorous species) (Table 1).

Up to 13 individuals of each species were collected in each estuary and in each hydrological period, with a total of 736 gastrointestinal tracts analyzed between the three estuaries, 1516 food items were found, 128 of which were anthropogenic microparticles in 91 individuals (12%) (Table 1). Anthropogenic microparticles were present in the gastrointestinal tract contents of all examined species. When the guilds were compared across seasons and estuaries, no differences in the amount of food consumed were detected. Algae, crustaceans, and plants were largely ingested by the omnivorous guild (Table S1). The planktivorous guild mostly ingested aquatic invertebrates, whereas the carnivorous guild mostly consumed mollusks and limited amounts of fish and crabs (Fig. 2).

Anthropogenic particles

The Caeté River estuary contained most fish that ingested anthropogenic microparticles during both the rainy and dry seasons, with 13% (21 individuals) in each period. Among the species that ingested the most anthropogenic microparticles in the rainy season were *D. auratus*, where five of the eight fish collected had anthropogenic microparticles in their gastrointestinal tract contents in Pará River estuary; *C. spixii,* with five of the eight fish collected in the Caeté estuary; and *B. surinamensis,* with three of the five fish collected in the estuary of the Parnaíba Delta. In the dry period, the species that ingested the most anthropogenic microparticles were *S. psittacus,* with four of the eight fish collected in Pará River estuary and in the Caeté estuary being *C. acoupa* and *C. spixii*, both with three of the eight fish collected with anthropogenic microparticles in their gastrointestinal tract contents (Table 1).

Regarding size classification, 109 microparticles, 18 mesoparticles, and only one macroparticle were found in this study; the latter was found in *S. psittacus* sampled in Pará River estuary. More than 60% of the anthropogenic microparticles analyzed were cellulose fibers (Figs. 3 and 4), followed by polyamide (20%), polypropylene (7%), polyacrylonitrile (5%), and polyurethane (6%) (Figs. S2–S5).

The frequency of anthropogenic microparticles occurrence varied according to the estuary and sampling season for the fish that presented anthropogenic microparticles, ranging from 12.5 to 50% for Pará River estuary in the dry season and from 7.69 to 62.5% during the rainy season; from 12.5 to 37.5% for the Caeté estuary in the dry season and from 12.5 to 62.5% in the rainy season; and from 12.5 to 60% for the estuary of the Parnaíba Delta in the rainy season (Fig. 5). Despite these variations in FO%, there were no significant differences in anthropogenic particle ingestion among estuaries (PERMANOVA, pseudo-F = 0.266, p = 0.774), seasons (PERMANOVA, pseudo-F = 0.352, p = 0.556), or their interactions (PERMANOVA, pseudo-F = 0.551, p = 0.454).

Regarding the color and type of anthropogenic microparticles, only two forms were identified: fibers (95%) and fragments (5%). Blue particles were the most abundant, representing 57.81% across all three estuaries and both hydrological periods, predominantly composed of cellulose fibers. Black particles followed with 30.47%, comprising materials such as cellulose, polyacrylonitrile, polyamide, and polypropylene. Green particles accounted for 4.69% and were exclusively classified as polyurethane. Brown particles represented 3.13%, identified as polyamide, while transparent ones totalled 2.34%, consisting solely of cellulose. Red particles were the least frequent (1.56%) and were identified as polyamide. Blue and black plastics were dominant in all three estuaries during both periods. On the other hand, red plastics were the least frequent and were identified exclusively in the Caeté estuary during the dry season (Table S2).

Table 1 Number of fish that were analyzed, separated by species, trophic guild, estuary and season

Order, Family, *Species*, Common name	Trophic Guild	Rainy						Dry			
		Pará River		Caeté River		Parnaíba Delta		Pará River		Caeté River	
		N (Np)	FO%	N (Np)	FO%	N (Np)	FO%	N (Np)	FO%	N (Np)	FO%
Atheriniformes											
Atherinopsidae											
Atherinella brasiliensis (Quoy & Gaimard 1825)—Brazilian silversides	Planktivorous	6 (0)	0	7 (0)	0	7 (1)	14.3	7 (0)	0	8 (2)	25
Batrachoidiformes											
Batrachoididae											
Batrachoides surinamensis (Bloch & Schneider 1801)—Pacuma toadfish	Omnivorous	8 (1)	12.5	8 (1)	12.5	5 (3)	60	8 (2)	25	8 (1)	12.5
Beloniformes											
Belonidae											
Strongylura timucu (Walbaum 1792)—Timucu	Carnivorous	7 (0)	0	8 (0)	0	8 (0)	0	8 (0)	0	8 (2)	25
Clupeiformes											
Clupeidae											
Rhinosardinia amazonica (Steindachner 1879)—Amazon spinejaw sprat	Planktivorous	4 (0)	0	7 (3)	42.9	6 (0)	0	8 (0)	0	7 (0)	0
Engraulidae											
Anchovia clupeoides (Swainson 1839)—Zabaleta anchovy	Planktivorous	13 (1)	7.7	8 (0)	0	6 (0)	0	8 (0)	0	8 (0)	0
Lycengraulis grossidens (Spix & Agassiz 1829)—Atlantic sabretooth anchovy	Omnivorous	8 (1)	12.5	7 (0)	0	6 (2)	33.4	8 (0)	0	8 (1)	12.5
Pterengraulis atherinoides (Linnaeus 1766)—Wingfin anchovy	Carnivorous	5 (1)	20	7 (1)	14.3	8 (1)	12.5	8 (0)	0	8 (1)	12.5
Cyprinodontiformes											
Anablepidae											
Anableps anableps (Linnaeus 1758)—Largescale foureyes	Omnivorous	7 (0)	0	8 (0)	0	8 (1)	12.5	8 (1)	12.5	8 (0)	0
Mugiliformes											
Mugilidae											
Mugil sp.	Planktivorous	7 (0)	0	7 (1)	14.3	7 (1)	14.3	8 (0)	0	8 (0)	0
Perciformes											
Centropomidae											
Centropomus undecimalis (Bloch 1792)—Common snook	Carnivorous	7 (1)	14.3	8 (0)	0	8 (1)	12.5	8 (0)	0	8 (0)	0
Gerreidae											
Diapterus auratus (Ranzani 1842)—Irish mojarra	Planktivorous	8 (5)	62.5	6 (0)	0	7 (2)	28.6	8 (0)	0	8 (1)	12.5
Haemulidae											
Genyatremus luteus (Bloch 1790)—Torroto grunt	Omnivorous	7 (1)	14.3	8 (2)	25	8 (2)	25	7 (0)	0	8 (1)	12.5
Lutjanidae											

Table 1 (continued)

Order, Family, *Species*, Common name	Trophic Guild	Rainy						Dry			
		Pará River		Caeté River		Parnaíba Delta		Pará River		Caeté River	
		N (Np)	FO%	N (Np)	FO%	N (Np)	FO%	N (Np)	FO%	N (Np)	FO%
Lutjanus jocu (Bloch & Schneider 1801)—Dog snapper	Omnivorous	4 (2)	50	8 (2)	25	7 (1)	14.3	5 (1)	20	8 (1)	12.5
Sciaenidae											
Cynoscion acoupa (Lacepède 1801)—Acoupa weakfish	Carnivorous	5 (0)	0	7 (0)	0	3 (0)	0	8 (0)	0	8 (3)	37.5
Macrodon ancylodon (Bloch & Schneider 1801)—King weakfish	Carnivorous	8 (1)	12.5	6 (1)	16.7	1 (0)	0	8 (1)	12.5	8 (2)	25
Stellifer naso (Jordan 1889)—Naso stardrum	Omnivorous	9 (2)	22.3	6 (0)	0	7 (0)	0	8 (0)	0	8 (1)	12.5
Pleuronectiformes											
Achiridae											
Achirus achirus (Linnaeus 1758)—Drab sole	Carnivorous	7 (1)	14.3	8 (0)	0	7 (0)	0	8 (1)	12.5	8 (0)	0
Siluriformes											
Ariidae											
Cathorops spixii (Agassiz 1829)—Madamango sea catfish	Omnivorous	8 (1)	12.5	8 (5)	62.5	8 (0)	0	8 (2)	25	8 (3)	37.5
Sciades herzbergii (Bloch 1794)—Pemecou sea catfish	Omnivorous	6 (0)	0	12 (4)	33.4	8 (0)	0	8 (1)	12.5	8 (2)	25
Tetraodontiformes											
Tetraodontidae											
Sphoeroides psittacus (Bloch & Schneider 1801)—Banded puffer	Carnivorous	5 (0)	0	7 (1)	14.3	7 (3)	42.9	8 (4)	50	8 (0)	0
Total		139 (18)		151 (21)		132 (18)		155 (13)		159 (21)	

N number of fish collected, *Np* number of fish that ingested anthropogenic microparticles, *FO%* frequency of occurrences of anthropogenic microparticles

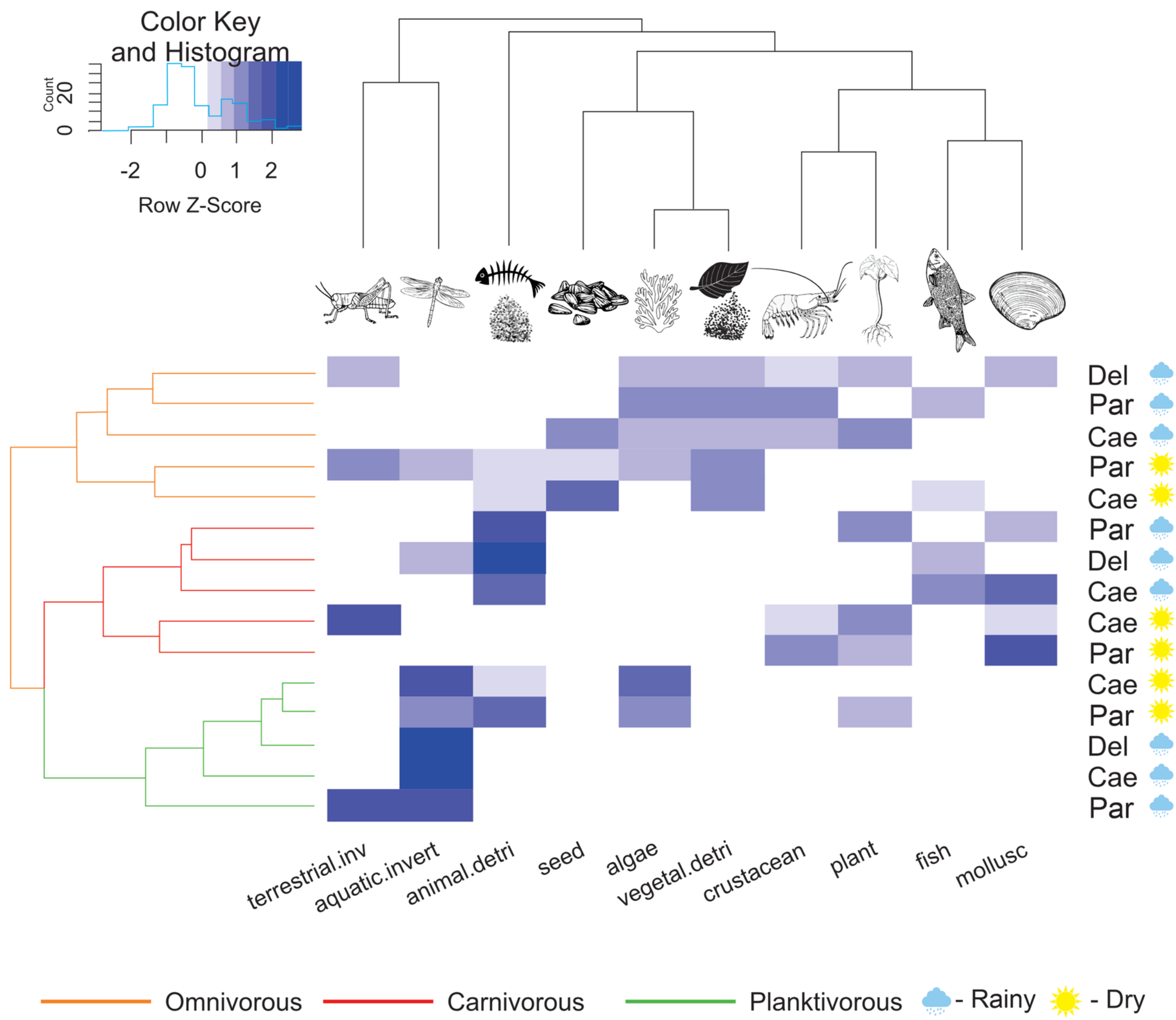

Fig. 2 Shadow graph identifying trophic guilds and similarities in diet composition. *Del* Parnaiba Delta, *Par* Pará River, *Cae* Caeté Estuary

Discussion

Even highly productive and structurally complex mangrove ecosystems are not exempt from pervasive anthropogenic contamination, as evidenced by the widespread occurrence of synthetic and semi-synthetic particles in aquatic food webs. Anthropogenic particles were detected in all 20 fish species analyzed, making this the first study to document plastic consumption by fish in the largest mangrove system in South America. More than 60% of the anthropogenic microparticles identified were cellulose fibers, highlighting the predominance of this type in the study area and reflecting its widespread use by the Brazilian population. This finding is consistent with the high proportions of cellulose fibers reported in surface waters of the Brazilian Amazon Shelf (Queiroz et al., 2022), suggesting similar patterns of fiber occurrence across different environmental compartments in the region, possibly influenced by the overlap in sampling periods between studies.

Building on these regional patterns, Queiroz et al. (2022) reported higher abundances of microparticles in surface waters during the rainy season than during the dry season, with fibers—especially cellulose-based—being the dominant particle type,

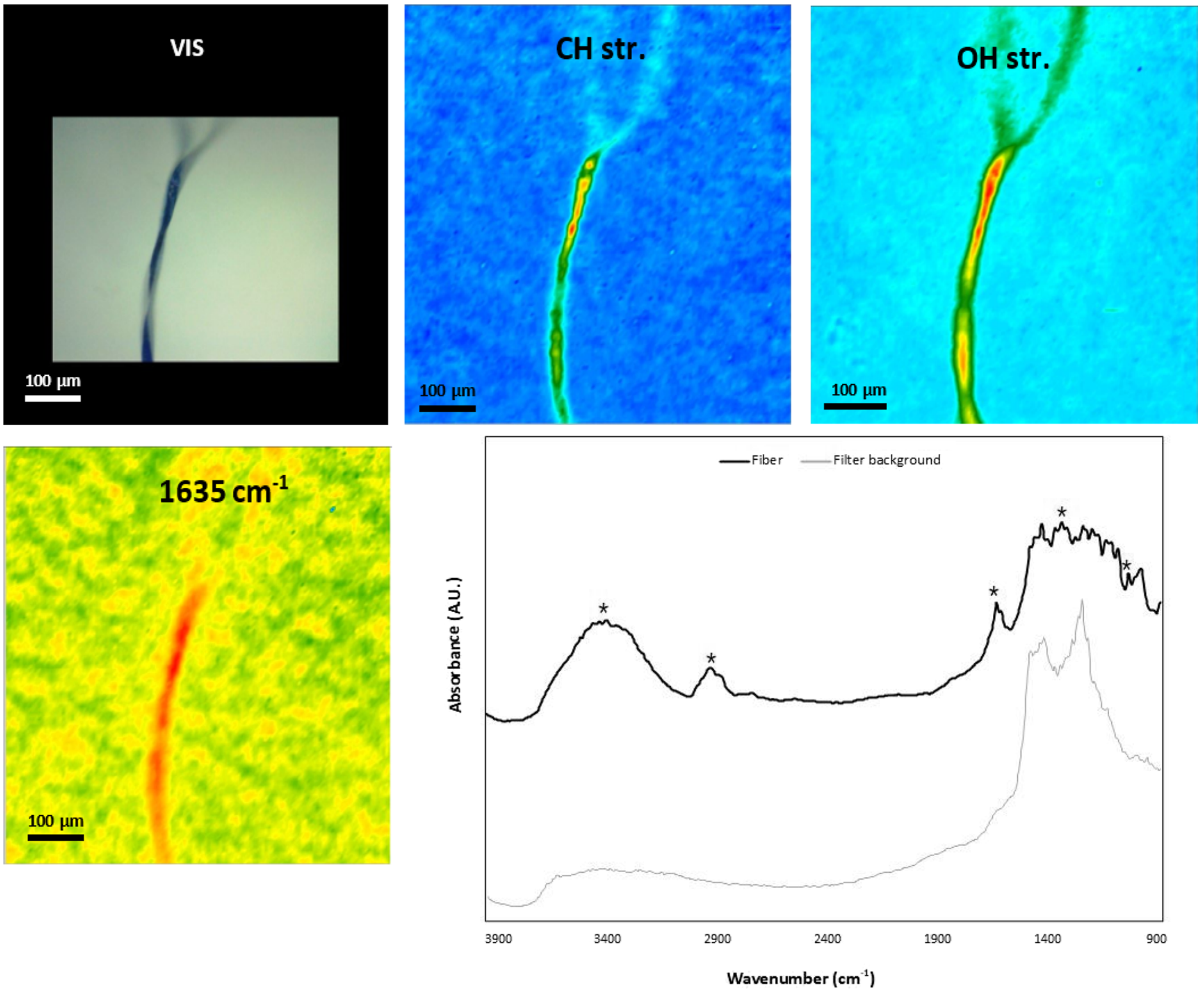

Fig. 3 Visible light map and 2D FTIR imaging maps (top and center panels) and FTIR spectra (bottom panel) of a fiber identified as textile/artificial cellulose showing absorptions at 3500–3000 cm^{-1} (OH stretching), 3000–2800 cm^{-1} (CH stretching), 1635 cm^{-1} (absorbed water), 1335 cm^{-1} (CH stretching), and 1120 cm^{-1} (C–OH stretching). The major absorption bands of the fiber are marked with a "*." Each spectrum relates to a single pixel (5.5×5.5 μm^2) of the 2D imaging maps

a trend consistent with our observations of microparticle ingestion by estuarine fish. Whereas their study focused on environmental concentrations and polymer composition of microparticles in seawater, our findings extend this framework by providing biological evidence of microparticle uptake across multiple fish species and trophic guilds. Together, these complementary lines of evidence underscore the pervasive presence of cellulose fibers and other polymers (e.g., polyamide and polyurethane) throughout the Amazon coastal environments, spanning both abiotic and biotic compartments and highlighting the potential for trophic transfer and bioaccumulation.

Extending this regional comparison, the proportion of cellulose fibers observed in the present study was lower than that reported for Guajará Bay, located in the Pará River estuary (Santos et al., 2023) indicating spatial variability in fiber prevalence along the Amazonian coastal system. Although cellulose itself is generally considered environmentally benign, textile-derived cellulose microfibers are often associated with a wide range of chemical compounds—including dyes, pesticides, monomers, manufacturing

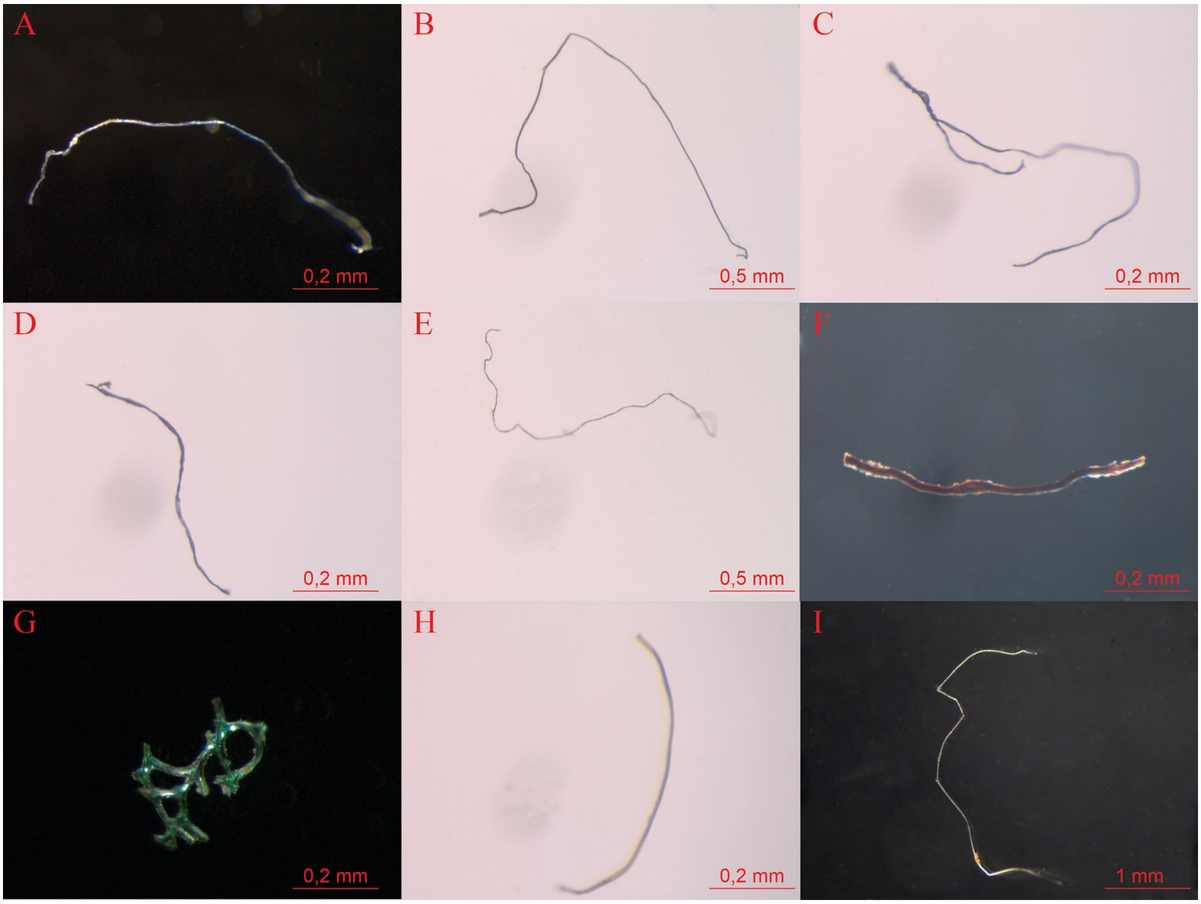

Fig. 4 Polymers found in the stomachs of the fishes sampled in this study: **A** cellulose, **B** polypropylene, **C** cellulose, **D** cellulose, **E** cellulose, **F** polyamide, **G** polyurethane, **H** polyacrylonitrile, **I** polyamide

additives, and solvents—that can pose substantial risks to marine ecosystems (Browne et al., 2011; Remy et al., 2015; Kelly et al., 2019). These microfibers have been repeatedly documented even in marine protected areas, including natural parks, highlighting their high dispersal potential and persistence in the environment (Scopetani et al., 2021). Moreover, Browne et al. (2011) demonstrated that a single garment can release up to 1900 fibers per wash, many of which bypass wastewater treatment systems that remain inefficient at fully retaining such microparticles, thereby facilitating their widespread distribution in both coastal and estuarine environments.

In line with the growing evidence of cellulose fiber prevalence in both abiotic and biotic compartments, Remy et al. (2015), in a study conducted in Calvi Bay (Corsica), reported that approximately 27% of the gastrointestinal tract contents of the analyzed invertebrates consisted of cellulose fibers (viscose), predominantly blue and red in color, results that closely align with our findings. Likewise, Macieira et al. (2021) are among the few studies documenting the ingestion of cellulose fibers by reef fishes, reporting that 77% of the analyzed samples were composed of cellulose fibers, primarily transparent. Despite these observations, the ingestion of cellulose fibers by marine organisms remains underreported in literature. This knowledge gap likely reflects the limited use of advanced chemical characterization techniques, particularly Raman spectroscopy, which are essential for accurate polymer identification. Cellulose-based materials such as viscose can readily misidentified as synthetic plastics due to similarities in color, morphology,

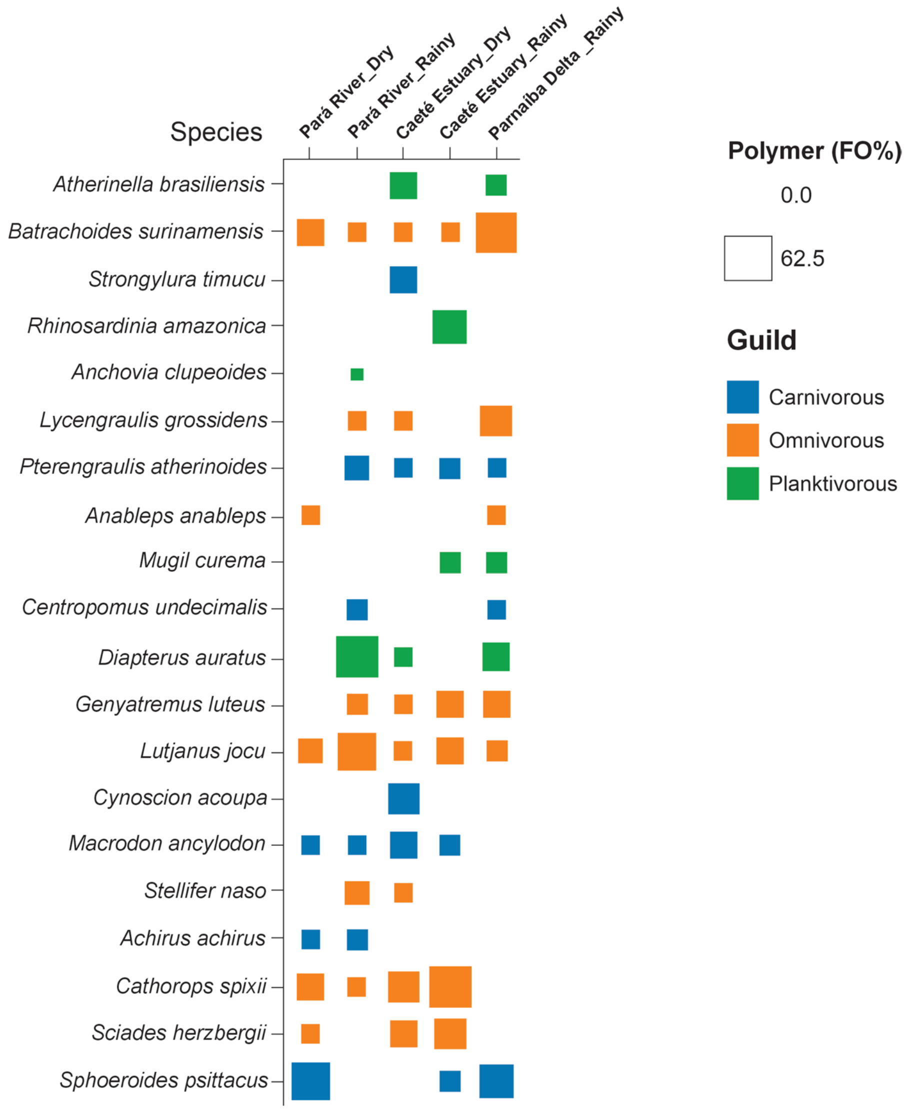

Fig. 5 Matrix plot displaying the frequency of occurrence (%) of anthropogenic microparticles ingestion by fish species, segmented by estuary and season (dry and rainy). The highest frequency observed (62.5%) occurred in the Caeté estuary during the rainy season

and buoyancy, thereby obscuring their true prevalence in marine ecosystems (Remy et al., 2015).

Within this broader context of anthropogenic particle ingestion, studies documenting plastic polymer consumption by fish in Brazil have increased in recent years (e.g., Pegado et al., 2018; Schmid et al., 2018; Trindade et al., 2023), alongside compelling evidence that the volume of plastic waste entering marine environments will continue to rise (Azevedo-Santos et al., 2019; Mendes et al., 2024). Plastics account for more than 80% of debris found on land and aquatic surfaces, reaching even the most remote and diverse ecosystems worldwide (Barnes et al., 2009). Consistent with our findings, Andrade et al. (2019) reported plastic ingestion across all trophic guilds of piranha-related fishes, indicating that plastic pollution permeates entire food webs rather than being restricted to specific feeding strategies. A global review by Azevedo-Santos et al. (2019) further showed that carnivorous and omnivorous fishes are the most frequently reported consumers of plastic polymers, likely reflecting their dietary plasticity and their ability to transfer matter across trophic levels. These guilds exploit a wide range of prey types and occupy multiple depths within the water column, with omnivorous species in particular exhibiting highly diverse diets that include macroinvertebrates, fish, and macrophytes (Carbery et al., 2018; Garcés-Ordóñez et al., 2020), thereby increasing their exposure to plastic debris.

Extending the discussion on trophic guilds and plastic exposure, although no significant differences were detected among estuaries or seasons in therms of particle ingestion frequency, clear interspecific differences were observed. Vendel et al. (2017), for example, identified *D. auratus* as the species with the highest microplastic ingestion in a Paraíba estuary, a pattern consistent with our findings, as this species also exhibited the highest particle ingestion during the rainy season in the Pará River estuary. This trend likely reflects its broad and opportunistic diet, which includes benthic invertebrates, detritus, algae, and cyanobacteria, increasing the likelihood of incidental particle ingestion. These results raise concerns regarding potential ecological consequences, particularly for higher trophic levels. As highlighted by Ferreira et al. (2018), top predators such as *C. acoupa* may accumulate substantial quantities of microplastics, reinforcing the potential for trophic transfer and bioaccumulation of polymer-associated contaminants. This pattern is consistent with the synthesis provided by Azevedo-Santos et al. (2019) and Carbery et al. (2018), who emphasize the key role of omnivorous and carnivorous species in mediating the movement of plastic-derived substances through aquatic food webs. Given the ecological and economic importance of these estuarine species, many of which are widely consumed by local communities, our findings suggest point potential risks not only for biodiversity but also for food safety and human health (Paiva & Silva, 2020).

In line with the species-specific patterns discussed above, no statistically significant differences in microparticle ingestion were detected between dry and rainy seasons. Nevertheless, a consistent qualitative trend was observed, with a higher frequency of particle ingestion during the rainy season. This pattern may be driven by surface runoff associated with intense rainfall, which increases the transport of domestic and industrial wastes into estuarine systems, particularly in more urbanized areas such as the Pará River estuary. In addition, seasonal hydrodynamics processes, characterized by pulses of river discharge and tidal oscillations, may further influence the distribution, availability, and retention of microparticles within estuarine habitats (Ivar do Sul & Costa, 2013; Miranda et al., 2022). Therefore, despite the lack of statistical significance, the environmental dynamics of the rainy season may still play an ecologically meaningful role in shaping observed ingestion patterns.

Consistent with broader patterns reported in the literature, microplastics account for more than 80% of the polymers detected in fish diets (e.g., Ferreira et al., 2018; Garcia et al., 2020; Pegado et al., 2020) reported the presence of more than 1000 microplastic particles in the gastrointestinal tract of *C. acoupa*, a top predator in the food web (Ferreira et al., 2018). In our study, this species was also identified as a major consumer of anthropogenic particles during the dry season, indicating a high susceptibility to particle contamination. Similarly, the omnivorous species *C. spixii* showed higher particle ingestion during the rainy season in the Caeté estuary, a pattern comparable to that reported by Dantas et al. (2020), who identified this species as having the highest frequency of microplastic ingestion (75%) on a beach in Ceará, Brazil. This pattern may be associated with the elevated concentrations of microplastics reported for the Caeté estuary itself (Mendes et al., 2024), suggesting that local contamination levels directly influence ingestion rates by estuarine fish. The omnivorous feeding strategy of *C. spixii*, which involves the consumption of diverse food items within its habitat, may further increase its exposure to anthropogenic particles.

Building on these species-specific patterns, the occurrence of anthropogenic microparticles across all trophic guilds further underscores the pervasive nature of plastic pollution in estuarine environments. Nevertheless, omnivorous and carnivorous species exhibited higher ingestion frequencies, likely reflecting their broader dietary breadth and use of multiple estuarine microhabitats, which increases exposure to contaminants. Omnivorous species such as *C. spixii* and *L. grossidens* forage on both benthic and pelagic food sources (including detritus and macroinvertebrates) that are commonly associated with microplastic accumulation. Likewise, carnivorous species such as *S. psittacus* and *C. acoupa*, which occupy higher trophic positions, may ingest anthropogenic particles indirectly through trophic transfer. In contrast, planktivorous fishes showed lower ingestion rates, potentially due to more selective feeding strategies or reduced spatial overlap with microplastic-enriched habitats. Overall, these patterns indicate that trophic behavior plays a key role in mediating exposure risk, corroborating observations from other tropical estuarine systems (Andrade et al., 2019; Garcés-Ordóñez et al., 2020).

Beyond trophic-related differences in exposure, the sources of anthropogenic microplastics may also vary substantially among estuarine systems. The Pará River estuary, for instance, is strongly influenced by densely populated urban centers and industrial waste, particularly during the rainy season, when increased surface runoff intensifies material transport into the estuary (Martins & Mendes, 2011; Morales et al., 2025). In contrast, although urbanization is less pronounced in the Caeté River estuary, the presence of fishing villages, inadequate solid waste disposal, and low sewage treatment efficiency contribute to the introduction of microparticles into the system (Costa & Soares, 2021). In the Parnaíba Delta, tourism (Junior & Macedo, 2016), artisanal fisheries, and intensive agriculture in surrounding areas generate a multifactorial context of anthropogenic pressure (Mattos & Irving, 2003). Across all three regions, the widespread use of fishing gear, such as nets, ropes, and lines manufactured from polymers including nylon and polyamide, represents a direct and continuous source of plastic filaments. Moreover, estuarine hydrodynamics, driven by tidal regimes and seasonal river discharge, acts as a key mechanism for the transport, redistribution, and persistence of these particles across diverse aquatic microhabitats (Miranda et al., 2022).

Within this context of multiple anthropogenic sources, fishing activities appear to be a major contributor to microparticle contamination in the study area. A high incidence of plastic filaments derived from fishing materials has been consistently reported in the region (Queiroz et al., 2022; Lopes et al., 2024). Owing to their low density and filamentous shape, these particles remain suspended in the water column and are therefore more readily available for accidental ingestion by a wide range of fish species (Lima et al., 2014), potentially leading to high ingestion rates (Vendel et al., 2017). Dantas et al. (2012) demonstrated that fish frequently ingest blue nylon® threads, a polymer commonly used in fishing gear. The recurrent presence of blue nylon residues in fish gastrointestinal tracts strongly indicates fishing nets, lines, and related marine operations as primary sources of contamination (Dantas et al., 2012; Lima et al., 2014; Costa & Barletta, 2015). Consistent with these observations, Pegado et al. (2020) reported that blue (57%) and black (30%) polymers dominated the gastrointestinal contents of *H. guttatus* along the Brazilian coast. This predominance is likely associated with the fishing fleet, as gear is frequently lost or improperly discarded at sea, contributing substantially to plastic inputs in coastal and estuarine environments (Andrady, 2011).

Building on the evidence that fishing-related materials are a major source of microplastic contamination, the polymer composition identified in this study was dominated by cellulose and polyamide fibers. This pattern is consistent with the findings of Sultan et al. (2023), who reported the same polymers in the gastrointestinal contents of fish from a Bangladesh estuary, and with Garcés-Ordóñez et al. (2020), who classified ingested plastics primarily as nylon (polyamide) in a Colombian mangrove system. In addition to these polymers, polyurethane was also detected, raising ecological concerns given its known toxicological effects, including oxidative stress, endocrine disruption, oxidative stress, endocrine disruption, and cytotoxicity (Zimmermann et al., 2019). Experimental exposure of *Danio rerio* to polyurethane for approximately 10 days resulted in morphological and histopathological alterations, such as discoloration of the intestinal mucosa, epithelial damage, gastric wall lesions, and inflammation in the abdominal and hepatic tissues (Dinani et al., 2021). Together with the observations of Hitchcock & Mitrovic (2019), these findings reinforce the view estuaries tend to accumulate higher concentrations of microplastics than the open ocean, reflecting their role as natural retention zones at the interface between freshwater and marine environments.

Taken together, these findings extend beyond the ecological patterns observed and raise broader environmental and socio-ecological concerns. The widespread presence of anthropogenic microparticles across all analyzed estuaries confirms that plastic contamination is pervasive, even in regions distant from major urban centers, suggesting that pollution arises not only from local sources but also from long-distance hydrological connectivity within the Amazon basin that facilitates the transport and redistribution of microparticles. Importantly, many of the fish species examined are of economic and subsistence relevance to local communities, and the detection of potentially toxic polymers such as polyamide and polyurethane underscores potential risks not only to biodiversity but also to food security and human health (Pan et al., 2021; Ye et al., 2023). Estuarine ecosystems are already subjected to cumulative pressures—including overfishing, eutrophication, and habitat degradation—and microplastic contamination represents an additional, largely invisible yet persistent stressor that threatens their ecological integrity (Baechler et al., 2020). In this context, our results provide a critical baseline for future ecotoxicological assessments and highlight the urgency need to incorporate plastic pollution into estuarine management and conservation strategies.

Conclusion

The detection of anthropogenic microparticles across all trophic guilds and estuaries indicates that plastic contamination has become an intrinsic feature of these ecosystems, irrespective of remoteness or conservation status. This widespread exposure suggests that estuarine food webs are chronically interacting with anthropogenic particles, with potential implications for key ecological processes, including nutrient cycling, prey selection, and energy transfer. The predominance of cellulose and synthetic fibers—largely associated with urban effluents and fishing activities—further highlights the vulnerability of estuarine environments to land-based pressures and underscores the need for improved waste management and targeted monitoring strategies, particularly in small coastal communities. Importantly, the ingestion of microparticles by species of both ecological and economic importance raises concerns about trophic transfer and potential bioaccumulation, with cascading effects that may extend beyond ecosystem integrity. Collectively, these patterns demonstrate that plastic pollution in estuaries is not solely a conservation issue but also a broader socio-environmental challenge, with potential consequences for local fisheries, human health, and the long-term sustainability of communities that depend on these resources.

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Data availability Datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that there are no conflicts of interest or personal relationships that could have influenced the work reported in this article.

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