



Influence of biological, ecological, and anthropogenic factors on microplastic contamination in coastal fishes from Southeastern Brazil

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Abstract Microplastics (MPs) are a pervasive environmental threat due to their persistence, bioavailability, and toxicity. In marine environments, MPs are widely distributed and ingested by fish, posing risks to human consumers. This study examined how ecological and anthropogenic factors—body size, water column position, seasonality, and human impact—influence MP concentrations in the muscle and digestive

tissues of coastal fish from southeastern Brazil. We hypothesized that fish from more impacted environments would contain higher MP levels; that pelagic species would ingest more MPs due to particle buoyancy; and that ingestion would be higher in summer and in larger fish due to seasonal and size-related factors. Additionally, we hypothesized that MP loads would be higher in digestive tissues than in muscle, given limited translocation capacity. Four commercially important species (*Caranx crysos*, *Sardinella aurita*, *Menticirrhus americanus*, and *Micropogonias furnieri*) were collected from two bays with contrasting anthropogenic influences—Sepetiba (more impacted) and Ilha Grande (less impacted)—during summer and winter. Digestive tracts and muscle tissues were digested, vacuum-filtered, and analyzed using microscopy and micro-FTIR. MPs were detected in all species and in 83.1% of individuals, with blue microfibers predominating. Generalized linear mixed models revealed positive associations between MP ingestion and anthropogenic impact and season (summer), and a negative association with body size. No significant differences were observed between pelagic and demersal species or between tissues. Thus, MP contamination in coastal fishes from southeastern Brazil appears to be driven primarily by gradients of human impact and seasonality (with a peak in summer), rather than by habitat or tissue differences, indicating that MP monitoring and control programs should prioritize urbanized areas and periods of higher input/resuspension.

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Introduction

Marine environments are facing unprecedented and escalating pressure from plastic pollution, driven by the exponential increase in global plastic production which surpassed 400 million tonnes per year recycling rates of less than 10%, leading to the accumulation of an estimated 8.3 billion tonnes of plastic waste in terrestrial and aquatic ecosystems (Geyer et al. 2017; Hossain et al. 2024; OECD 2022). This pressure is further amplified by improper disposal, lost fishing gear, and illegal dumping, which exacerbate plastic contamination in marine habitats (Lusher et al. 2017; Pal et al. 2025). Plastics are transported by rivers, ocean currents, and wind, reaching previously unaffected areas (Browne et al. 2015; Galgani et al. 2020). Small particles (<5 mm), known as microplastics (MPs), originate from the fragmentation of larger plastics or are produced directly by industry (Arthur et al. 2009). MPs have been detected in aquatic organisms, including fish and invertebrates (e.g., Jamal et al. 2025; Thrift et al. 2025). Once ingested, MPs can cause gastrointestinal blockage and tissue damage (Cannon et al. 2016; Nadal et al. 2016), malnutrition (Gregory et al. 2009), and toxic effects such as oxidative stress, behavioral alterations, impaired reproduction, and mortality (Hanachi et al. 2019; Barboza et al. 2020; Zakeri et al. 2020).

Various factors can influence microplastic contamination in fish, revealing complex, interactive, and sometimes conflicting dynamics. Microplastic contamination in fish is influenced by anthropogenic pressure, seasonality, ecological traits, and body size. Fish from areas with higher human impact exhibit elevated MP concentrations, and ingestion may vary with trophic position, seasonal conditions, and exposure time (Nadal et al. 2016; Guven et al. 2017; Sun et al. 2018). MPs are primarily retained in the gastrointestinal tract, with limited evidence of translocation to edible tissues such as muscle. Therefore, potential human exposure may occur mainly through the consumption of small fish eaten whole and the transfer of plastic-associated chemicals (additives and sorbed

contaminants) along the food web (Karami 2017; Daniel et al. 2020; Bi et al. 2024).

The presence of MPs in edible seafood tissues may threaten consumer health due to their toxic effects on organisms (Karami 2017). Plastics are produced from monomers derived mainly from petroleum and natural gas (Guyen et al. 2017) and often contain chemical additives such as phthalates (Galloway et al. 2017), which are considered carcinogenic. Moreover, plastic particles can adsorb heavy metals from aquatic environments, enhancing their role as vectors of multiple contaminants and amplifying their potential harmful effects on human health (Bi et al. 2024), including cognitive alterations and renal dysfunction (Jomova et al. 2025). The implications of human MPs ingestion are under active investigation, as these particles are increasingly detected along the human food chain (Cole et al. 2011; Kolandhasamy et al. 2018; Wang et al. 2019). Studies have demonstrated the bioavailability of microplastics for absorption into the bloodstream (Leslie et al. 2022), their potential to modulate immune system responses (Yang et al. 2022), and their occurrence in both the male (Zhang et al. 2024) and female reproductive systems (Montano et al. 2025). These evidences suggest a potential risk to human fertility, mainly regarding the number, motility, and viability of reproductive cells (Zhang et al. 2024).

The average annual per-capita fish consumption in Brazil was 5.66 kg (IBGE 2019), and the Southeast region leads in industrial fishing landings—particularly sardine (*Sardinella aurita* Valenciennes, 1847) in the State of Rio de Janeiro—while artisanal fisheries predominantly contribute to croaker (*Micropogonias furnieri* (Desmarest, 1823)) landings (Freire et al. 2021). Sepetiba Bay and Ilha Grande Bay, located on the southern coast of the State of Rio de Janeiro, supply a large portion of the state's fishery products. Moreover, both bays harbor a diverse fauna with high abundances of organisms that rely on these regions for growth, reproduction, and feeding (Araújo et al. 2002, 2016; Azevedo et al. 2017). Despite their significance, these areas are impacted by industrial and urban activities. Nevertheless, substantial knowledge gaps persist concerning microplastic contamination in fish from the South Atlantic Ocean (Markic et al. 2019). In the state of Rio de Janeiro, research remains notably limited, with existing studies restricted to a single

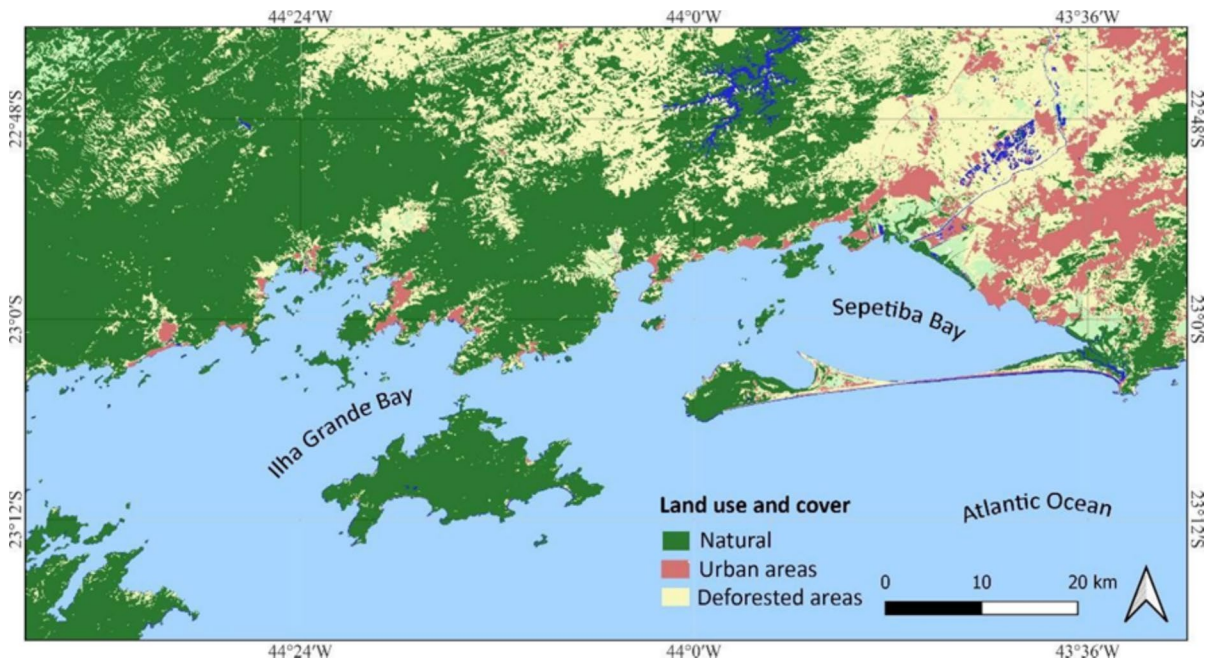


Fig. 1 Map of the southern coast of the Rio de Janeiro State highlighting two coastal bays (Sepetiba and Ilha Grande) with differing urban densities (in pink) and deforested areas (in beige) resulting from anthropogenic activities

species from Guanabara Bay (Alves and Figueiredo 2023); therefore, it is necessary to broaden the scope to other bays and species. Given the conflicting uses of Sepetiba and Ilha Grande bays, along with the threats to biodiversity and risks to human health, further studies are needed to assess MP contamination in coastal fish.

This study aimed to investigate how various ecological and environmental factors influence MP concentrations in four commercially important fish species from southeastern Brazil—*Caranx crysos* (Mitchill, 1815), *Sardinella aurita* Valenciennes, 1847, *Menticirrhus americanus* (Linnaeus, 1758), and *Micropogonias furnieri* (Desmarest, 1823). Specifically, the study sought to (1) compare MP concentrations between bays with contrasting levels of anthropogenic impact (Sepetiba Bay—higher impact—vs. Ilha Grande Bay—lower impact); (2) assess the influence of fish position in the water column (pelagic vs. demersal) on MP concentrations; (3) examine the effect of seasonality (summer vs. winter) on MP concentrations; (4) evaluate differences between tissue types (gastrointestinal tract vs. muscle) in MP concentrations; and (5) investigate

the relationship between fish body size and MP concentrations.

Two hypotheses were tested: (H1) we hypothesized that greater anthropogenic pressure in Sepetiba Bay would result in higher MP contamination than in Ilha Grande Bay and that (H2) pelagic species would accumulate more particles due to buoyancy. We also expected MP ingestion to vary with season, fish size, and tissue type, being higher in summer, in larger individuals, and in digestive tracts, reflecting influences of seasonality (temperature, precipitation, and tourism), longer exposure time, and accumulation from food and water before translocation. The findings are intended to support coastal monitoring and management strategies aimed at reducing MP transfer through the food web and mitigating environmental and public health risks.

Material and methods

Study area

The study area encompasses two coastal bays, Sepetiba Bay and Ilha Grande Bay, located along

Table 1 Summary of demographic data, land use and cover, and pollution levels in Sepetiba and Ilha Grande bays, located along the southern coast of Rio de Janeiro State (Brazil)

Variables	Sepetiba	Ilha Grande	Source
Area and demographic			
Drainage area (km ²)	3816	1843	SigaWeb (2023)
Population (millions of ind.)	1937	0.47	SigaWeb (2023)
Population density (ind/km ²)	765.8	206.7	SigaWeb (2023)
Land use and land cover (%)			
Florest	43	87	Mapbiomas (2023)
Non-forest natural formation	1	1	Mapbiomas (2023)
Urban area	9	1	Mapbiomas (2023)
Agriculture and deforested areas	45	10	Mapbiomas (2023)
Heavy metals			
Copper (Cu)	17.5	2.6	Fiori et al. (2013)
Chrome (Cr)	35.9	24.8	Fiori et al. (2013)
Mercury (Hg)	0.16	0.05	Fiori et al. (2013)
Zinc (Zn)	540.5	63.6	Fiori et al. (2013)

the southern coast of Rio de Janeiro State (Brazil) (Fig. 1; Table 1). Sepetiba Bay—SB (22° 54′–23° 40′ S, 43° 34′–44° 10′ W) covers a drainage basin of approximately 3816 km² and holds about 1,937,000 inhabitants (IBGE, 2018), corresponding to ≈ 765 inhabitants/km². It is a highly anthropized ecosystem, surrounded by a large industrial complex—including the Port of Sepetiba, a shipyard and several petrochemical plants—which contributes to elevated pollution levels (Molisani et al. 2004; Araújo et al. 2016). Elevated concentrations of heavy metals such as zinc and copper have been reported in its waters and sediments (Fiori et al. 2013) (Table 1). Ilha Grande Bay—IGB (23° 04′ 36″ S, 44° 01′ 18″ W) has a smaller drainage basin of 1843 km² and about 470,000 inhabitants (IBGE 2018), i.e., ≈ 206 inhabitants/km². This region comprises roughly 350 islands surrounded by shallow coastal waters (Ignacio et al. 2010; Teixeira-Neves et al. 2016;) and is subject to lower pollution levels (Table 1). Although economic activities such as tourism, nuclear power generation (Angra dos Reis plants), shipbuilding, oil terminals, fishing, and a commercial port occur here, their combined environmental impact is notably less than that observed in Sepetiba Bay (Neves 2016).

Fish collection

Four commercially relevant fish species occupying distinct positions in the water column were selected: two pelagic species, *C. crysos* and *S. aurita*, and

two demersal species, *M. americanus* and *M. furnieri*. The selection of species was based on their significant representativeness in regional consumption, particularly in the southeastern region of the State of Rio de Janeiro, where they are widely marketed and consumed. In addition to occupying distinct habitats, the studied species exhibit divergent feeding strategies. *M. furnieri*, *M. americanus*, and *C. crysos* are classified as carnivorous fish. *M. furnieri* and *M. americanus* display a varied diet primarily composed of crustaceans, bivalves, and polychaetes (Fernandez et al. 2009; Turra et al. 2012), whereas *C. crysos* predominantly preys on benthic organisms, including crustaceans and fish (Sley et al. 2009). In contrast, *S. aurita* is a planktivorous species, feeding on filtered planktonic organisms, mainly crustaceans, polychaetes, and mollusks (Bayhan et al. 2015; Borme et al. 2022). Fish were captured with artisanal trawl nets and immediately stored on ice. Sampling took place at two locations: BSP (Municipality of Rio de Janeiro) and IGB (Municipality of Angra dos Reis). A total of 289 specimens were obtained from bays (SB and IGB) during two sampling periods—summer (December 2022) and winter (July 2023) (Table 2). For most species, approximately 20 individuals were collected in each season and bay, except for *Menticirrhus americanus*, for which only 13 individuals per bay were collected in summer due to limited availability. In winter, the full sample size of 20 individuals per species per bay was achieved. Information on the total number of individuals collected per species,

Table 2 Results of the Type II Wald χ^2 Analysis of Deviance for the ZINB model fitted to investigate the factors influencing microplastic load (MP/g \times 1000) in coastal fish from South-eastern Brazil

Factors	χ^2	df	p-value
Tissue	0.0567	1	0.8118
Bay	6.5171	1	0.01068*
Season	36.514	1	<0.001***
Total length	18.166	1	<0.001***
Water column position	0.2199	1	0.6391
Interactions			
Tissue \times bay	0.0277	1	0.8678
Tissue \times season	7.9603	1	0.00478**
Tissue \times total length	7.5583	1	0.00597**
Tissue \times water column position	5.4367	1	0.01972*
Bay \times season	11.912	1	0.000558***
Bay \times total length	4.9742	1	0.02573*
Bay \times water column position	2.4907	1	0.1145
Season \times total length	3.0903	1	0.07876
Season \times water column position	4.237	1	0.03955*
Total length \times water column position	0.4762	1	0.4902

across bays, seasons, and tissues, is provided in the Supplementary Material (Table S1). From each individual, two tissue types were collected (muscle and gastrointestinal tract). A total of 289 gastrointestinal tract samples and 283 muscle samples (fillet region) were obtained. The lower number of muscle samples reflects the exclusion of six muscle samples that became unsuitable for reliable MP quantification during laboratory processing (e.g., digestion and/or filtration), due to suspected contamination and compromised tissue integrity.

Laboratory analysis

Microplastic extraction

After collection, fish were transported to the laboratory, where they were sexed (male or female), measured (total length, in cm), weighed (total wet weight, in g), and dissected. For microplastic analysis, muscle tissue (approximately 5 g) was excised from the fillet region, which corresponds to the portion most commonly consumed by humans. Prior to excision, skin and scales were carefully removed, and the exposed surface was rinsed with filtered distilled water to

minimize the risk of external fiber contamination. Gastrointestinal tract samples (stomach and intestine) were also collected. For microplastic extraction, each tissue (stomach, intestine, and 5 g of muscle) was submerged in a 10% KOH solution (10 mL per gram of tissue) to digest organic matter. Samples were then heated on a TEC NAL hot plate at 40 °C for 4 h. This procedure was adapted from NOAA (Masura et al. 2015), with modifications including a lower digestion temperature and time, and a standardized tissue-to-solution ratio, to optimize microplastic recovery while preventing polymer degradation.

Subsequently, each digest was vacuum-filtered through glass-fiber membrane filters (0.7- μ m pore size, 47 mm diameter), which defined the minimum size threshold of microplastics considered in this study. Filtered distilled water was used to rinse the glass containers in order to recover particles adhered to their inner surfaces (Barboza et al. 2020; Khan et al. 2022).

Physical and chemical characterization of microplastics

Filters were examined under a LEICA M205 C stereomicroscope, and all visible microplastics were counted, measured (mm), and classified. Particle sizes were recorded in millimeters (mm), and the size range analyzed extended from 0.011 to 19.349 mm. Microplastics were further categorized by colors and shape into four classes—microfibers, fragments, spheres (beads), or pellets—according to Dekiff et al. (2014).

After visual inspection, a subsample corresponding to 12.7% of the total observed microplastics ($n = 140$ particles) was selected for polymer characterization. The proportion followed the recommendation of Hanke et al. (2013), who suggested spectroscopic characterization of at least 10% of the observed particles. The selection was designed to represent both bays, both tissues (digestive tract and muscle), and all target species. Polymer characterization was conducted on a pooled set of particles, and therefore polymer composition is reported in an aggregated form. Samples were analyzed by Fourier-transform infrared microspectroscopy (μ -FTIR) using a Spectrum 3 instrument coupled with a Spotlight 200 module (PerkinElmer) to determine the chemical composition of the polymers. The filtered material was transferred

onto a KBr slide under an Olympus SZX10 stereomicroscope. The μ -FTIR was operated in transmittance mode with a spectral resolution of 1 cm^{-1} over a range of $4000\text{--}600\text{ cm}^{-1}$. Aperture size and shape were adjusted for each particle, with dimensions varying between 25 and 150 μm . Obtained spectra were compared against the PerkinElmer “Polymers” reference library using Spectrum IR software (v. 10.7.2), and particles were classified as microplastics when their spectral match exceeded 70%.

Quality assurance and control

Recovery tests were performed to assess the efficiency of the extraction procedures. Samples were spiked with two microfibers of each polymer type: PET (polyethylene terephthalate), PVC (polyvinyl chloride), PS (polystyrene), and PA (polyamide). The overall recovery efficiency of the procedure was 95%, indicating high effectiveness of the digestion and extraction protocol. Procedural air contamination control of Petri dishes containing filtered distilled water was placed alongside the samples processing. Blank contamination was evaluated based on particle attributes (morphology, size, color, and polymer type), following Munno et al. (2023). As blank particles did not match those observed in samples, no blank correction was applied. To minimize external contamination, all equipment (Petri dishes, scissors, tweezers) was thoroughly cleaned with distilled water followed by 70% ethanol. In addition, all solutions used during sample processing (including distilled water and KOH solution) were pre-filtered to reduce the risk of contamination. Laboratory personnel wore latex gloves and lab coats at all times. Although strict laboratory protocols and airborne controls were implemented to minimize contamination, a residual risk of fiber contamination from reagents or the laboratory environment cannot be completely excluded.

Data analysis

Microplastics were quantified and categorized by manually counting each particle in the samples, recording both their color and size. Particle lengths were measured and grouped into five size classes ($<100\text{ }\mu\text{m}$, $100\text{--}250\text{ }\mu\text{m}$, $250\text{--}500\text{ }\mu\text{m}$, $500\text{--}1000\text{ }\mu\text{m}$, and $>1000\text{ }\mu\text{m}$) (Parvin et al. 2021). We then calculated the relative frequency of each morphology type

(microfibers, fragments, spheres, pellets), each color category (Free et al. 2014), and each size class, expressing all values as percentages to provide a comprehensive, comparative overview of microplastic distribution across the analyzed fish tissues.

We applied an information-theoretic approach to assess whether microplastic abundance per gram of wet weight (MP/g; dependent variable) is influenced by anthropogenic impact (polluted SPB vs. less-polluted IGB), fish position in the water column (pelagic vs. demersal), season (summer vs. winter), tissue type (gastrointestinal tract vs. muscle), and body size—all treated as fixed effects. Expressing microplastic abundance per gram of tissue (MP/g), rather than as total counts, standardizes sampling effort and allows more accurate comparisons among individuals or study groups of varying body sizes and masses (Frias et al. 2018). Microplastic data often exhibit zero inflation, characterized by many zero-count observations (Hou et al. 2021), which can distort model assumptions. Therefore, we fitted Generalized Linear Mixed Models (GLMMs) with a zero-inflated negative binomial (ZINB) error distribution and a log link.

Candidate distributions (Poisson, Gaussian, negative binomial, zero-inflated Poisson, and zero-inflated negative binomial) were compared using the Akaike Information Criterion corrected for small sample sizes (AICc), with the ZINB model showing the best fit. To account for taxonomic effects and interspecific variability, “Species” was included as a random effect. Prior to modeling, the dependent variable (MP/g) was multiplied by 1000 to convert it to integer counts compatible with count-based distributions (Zuur et al. 2009). The significance of main effects and two-way interactions were tested via Type II Wald χ^2 ANOVA at $\alpha=0.05$. Residual diagnoses, assumptions and model adequacy (Figures S1 and S2) were investigated using the “*simulateResiduals*” function in the DHARMA package (Hartig 2022). All models were fitted using the `glmmTMB()` function from the `glmmTMB` package (Brooks et al. 2017) in the R environment (R Core Team 2024).

Results

General patterns of microplastic contamination

The results indicated widespread contamination, with 83.1% of individuals containing microplastics;

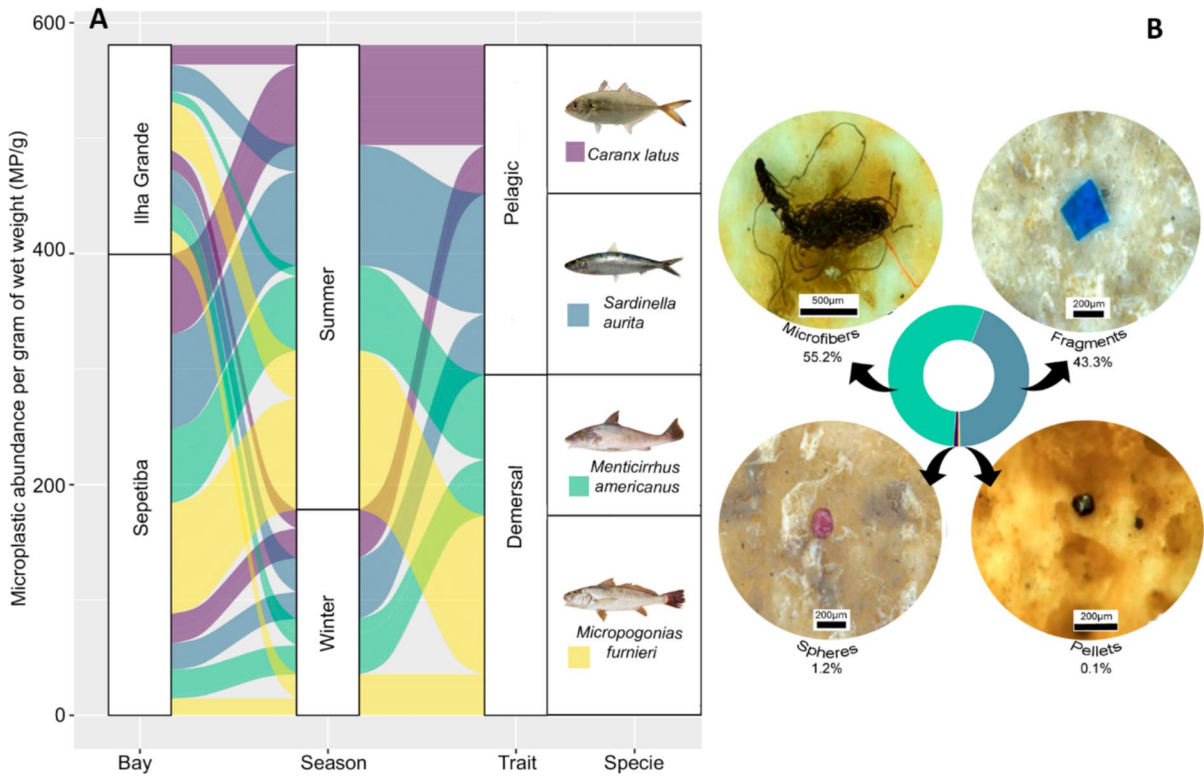


Fig. 2 a Variation in microplastic prevalence (MP/g) ingested by coastal fishes of Southeastern Brazil, grouped by bay (Sepetiba vs. Ilha Grande), season (summer vs. winter), functional trait (pelagic vs. demersal), and species of Southeastern

Brazil. **b** Representative images and relative contributions (%) of the four microplastic types: microfibers, fragments, spheres, and pellets

of these, 34.2% had MPs in both tissues and 48.9% had MPs in only one tissue. Among species, *M. furnieri* exhibited the highest microplastic load (1.23 ± 3.16 MP/g), followed by *S. aurita* (0.98 ± 1.59 MP/g), *M. americanus* (0.95 ± 2.46 MP/g), and *C. caryos* (0.89 ± 1.57 MP/g), yielding an overall mean of 1.01 ± 2.26 MP/g per individual (Table S1—Supplementary material; Fig. 2a). The majority of particles were microfibers (55.2%) and fragments (43.3%), whereas spheres (1.2%) and pellets (0.1%) were far less abundant (Fig. 2b; Table S2—Supplementary material). In terms of color, blue particles predominated (61%), followed by black (22.7%), red (7.0%), and yellow (3.8%) (Table S3—Supplementary material). Regarding size, the largest particles ($> 1000 \mu\text{m}$) were the most prevalent in the samples (32.5%; Fig. S3—Supplementary material). Size-dependent distribution patterns differed between tissues: particles $> 1000 \mu\text{m}$

predominated in the digestive tract, while those $< 100 \mu\text{m}$ were concentrated primarily in muscle tissue (Fig. S3).

Chemical composition of microplastics

μ -FTIR analysis of a subsample representing 12.7% of the total total observed microplastics selected for analysis revealed that the microplastics were predominantly composed of α -cellulose (23.2%), cellulose (18.6%), polypropylene (18.6%), polyethylene terephthalate (9.3%), and polyethylene (6.9%) (Fig. 3). Ten additional polymers—ethylene–vinyl acetate (EVA), ethylene–acrylic acid copolymer, magnesium silicate, nylon, pentaerythritol, phenyl salicylate, polyacrylamide, polystyrene, polyvinyl alcohol, and sodium dehydroacetate—each accounted for 2.3% of the identified particles.

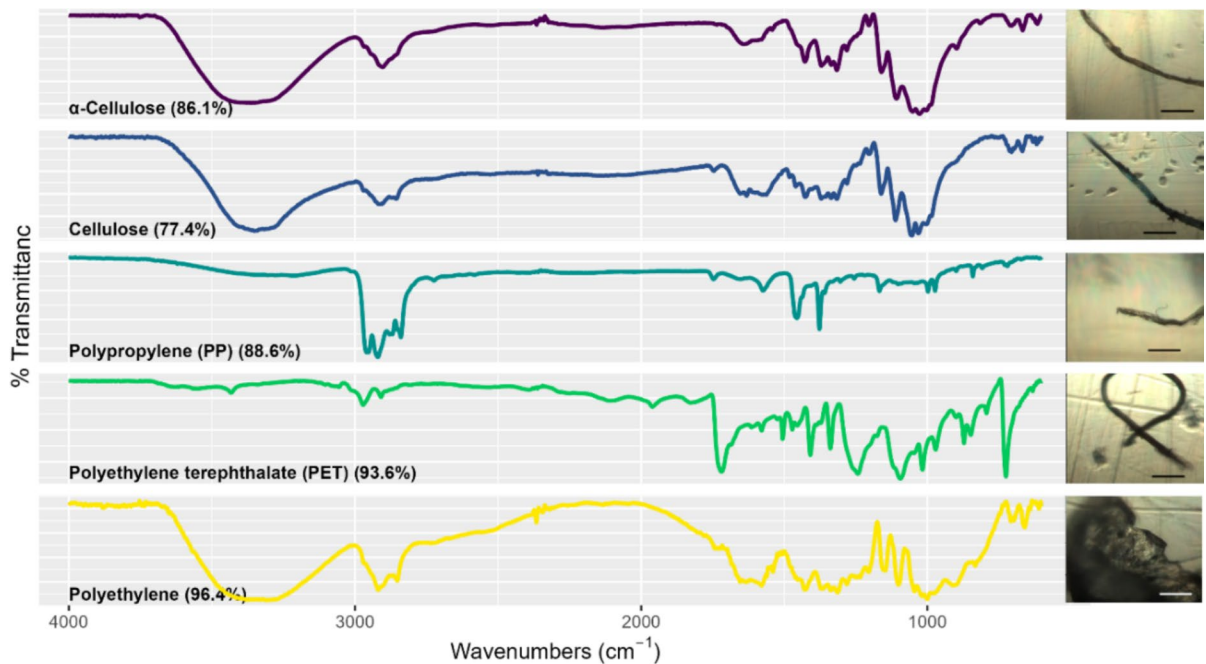


Fig. 3 μ -FTIR spectra (4000–600 cm^{-1}) and corresponding transmitted-light micrographs of the five most frequently identified polymers in coastal fish samples from Southeastern Brazil. Colored continuous lines represent percent transmittance

(%) as a function of wavenumber (cm^{-1}). Transmitted-light micrographs on the right illustrate the morphology of the identified particles (scale bar = 100 μm)

Table 3 Coefficient estimates from the zero-inflated negative binomial (ZINB) regression model fitted to investigate the factors influencing microplastic load ($\text{MP/g} \times 1000$) in coastal fish from Southeastern Brazil. The table displays the main effects and two-way interactions from the conditional component (count model), as well as the intercept from the zero-inflation component. Reported values include coefficient estimates (Estimate), standard errors (Std. Error), z statistics (z value), 95% confidence intervals (95% CI), and p -values ($\text{Pr}(>|z|)$). *Position*, water column position

Term	Estimate	Std. Error	z value	IC 95%	$\text{Pr}(> z)$
Conditional model					
(Intercept)	9.99	0.88	11.302	[8.26; 11.7]	<0.001 ***
Tissue _{Muscle}	-0.78	0.58	-1.358	[-1.91; 0.34]	0.1745
Bay _{Sepetiba}	1.54	0.60	2.569	[0.36; 2.72]	0.0102 *
Season _{Winter}	-1.19	0.66	-1.817	[-2.47; 0.09]	0.0693
Total length	-0.11	0.03	-3.495	[-0.17; -0.04]	0.0005 **
Position _{Pelagic}	-0.87	0.88	-0.993	[-2.6; 0.85]	0.3207
Interaction					
Tissue \times bay	0.03	0.20	0.166	[-0.35; 0.42]	0.8678
Tissue \times season	-0.59	0.21	-2.821	[-0.99; -0.17]	0.0048 **
Tissue \times total length	0.05	0.02	2.749	[0.01; 0.09]	0.0060 **
Tissue \times position	-0.50	0.21	-2.332	[-0.92; -0.07]	0.0197 *
Bay \times season	-0.69	0.20	-3.451	[-1.09; -0.3]	0.0006 ***
Bay \times total length	-0.05	0.02	-2.23	[-0.08; -0.005]	0.0257 *
Bay \times position	0.36	0.23	1.578	[-0.08; 0.79]	0.1145
Season \times total length	0.04	0.02	1.758	[-0.004; 0.08]	0.0788
Season \times position	0.49	0.24	2.058	[0.02; 0.95]	0.0396 *
Total length \times position	0.02	0.03	0.69	[-0.04; 0.08]	0.4902
Zero-inflation model					
(Intercept)	-0.40	0.085	-4.654	[-0.56; -0.23]	<0.001 ***

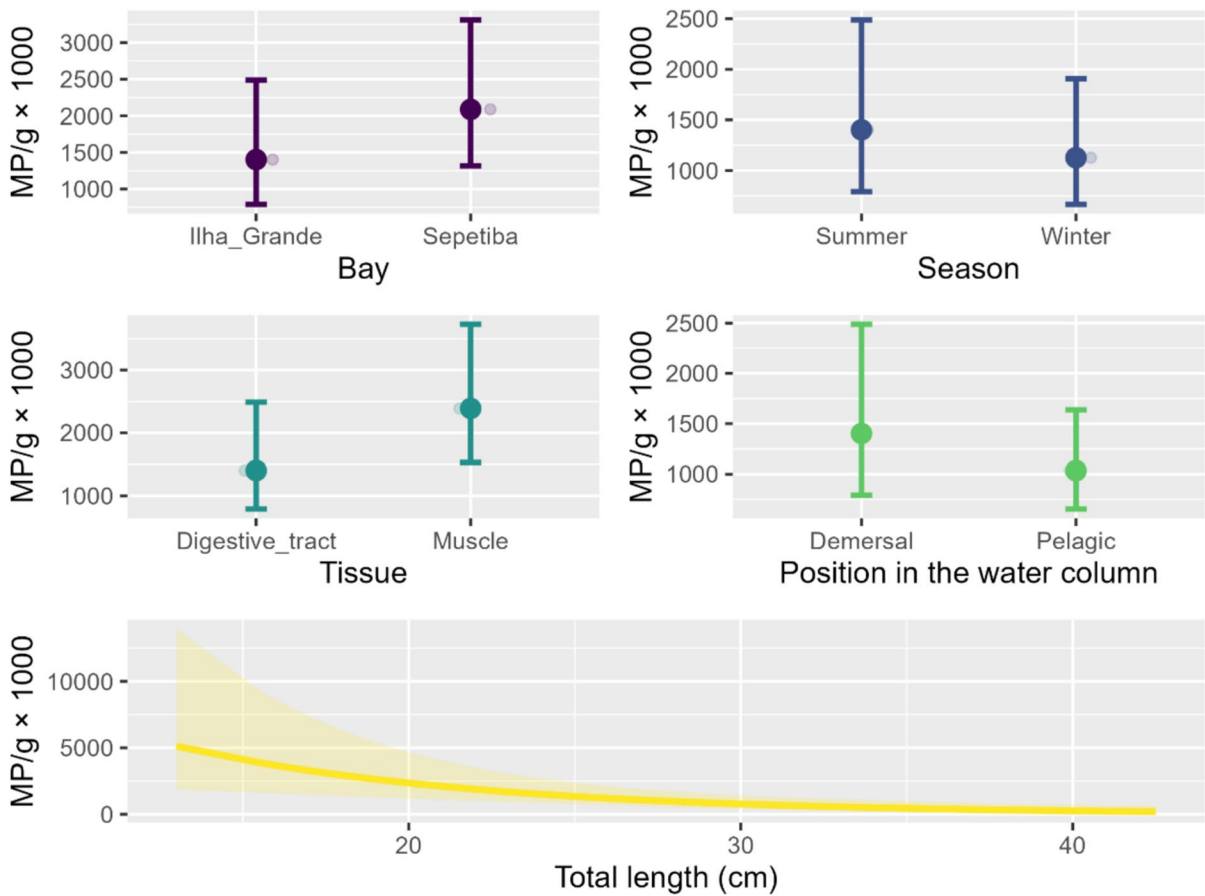


Fig. 4 Marginal effects of each predictor (fixed factor) on predicted microplastic load (MP/g×1000) in coastal fish from Southeastern Brazil. Colored circles mark the model-predicted mean for each category (or length value), with vertical bars (or

shaded ribbons) showing the 95% confidence intervals. For the significant two-way interaction plots, see Figure S4 in the Supplementary material

Factors influencing microplastic contamination

The zero-inflated negative binomial (ZINB) model reveals distinct influences on microplastic ingestion patterns in coastal fish (Tables 2 and 3, Fig. 4). In the count component, the intercept was highly significant ($\beta=9.99 \pm 0.88$; $z=11.30$; $p<0.001$), indicating a high predicted mean microplastic burden under reference conditions (Table 3, Fig. 4). Among the main effects, tissue type (muscle vs. gastrointestinal tract; $\chi^2=0.22$; $p=0.639$) and water-column position (demersal vs. pelagic; $\chi^2=0.22$; $p=0.639$) were not statistically significant (Tables 1 and 2). In contrast, fish captured in the more polluted bay (Sepetiba) exhibited 1.54 more MP units than those from the less impacted bay (Ilha Grande) ($\chi^2=6.52$; $p=0.0107$;

Table 3, Fig. 4). Season was also influential: winter burdens were marginally lower than summer burdens ($\chi^2=36.51$; $p<0.001$). Total length showed a robust negative effect, with a reduction of 0.11 MP/g per extra centimeter of length ($\beta=-0.111 \pm 0.032$; $p<0.001$; $\chi^2=18.17$; $p<0.001$) (Table 3, Fig. 4).

Several second-order interactions are also significant (Tables 2 and 3; Fig. S4—Supplementary material). The tissue×season interaction indicated lower muscle contamination in winter ($\chi^2=7.96$; $p=0.0048$). The tissue×pelagic position interaction further reduced muscle MP burden ($\chi^2=5.44$; $p=0.0197$). The bay×season interaction showed that, in Sepetiba Bay, the summer increase in MP ingestion was more pronounced ($\chi^2=11.91$; $p=0.0006$), while the bay×total length interaction indicated a

stronger negative length effect in Sepetiba ($\chi^2=4.97$; $p=0.0257$). Finally, in the zero-inflation component the intercept is highly significant ($\beta=-0.397\pm 0.085$; $z=-4.65$; $p<0.001$; 95% CI $[-0.564, -0.230]$), confirming the need to account for structural zeros in addition to the negative binomial distribution (Table 3).

Discussion

General patterns of microplastic contamination

A clear predominance of microfibers (MFs) and fragments was observed, whereas spherical particles and pellets were almost negligible. The elongated shape of MFs grants them low sedimentation velocities, which favors their vertical transport and continuous dispersion throughout the water column (Tseng et al. 2024). At a global scale, studies consistently demonstrate that fibers are the most abundant type of microplastic found in the digestive contents of fish (Lim et al. 2022). Numerous studies report microfibers as the most abundant synthetic polymers in aquatic organisms, particularly in fish prey items such as crustaceans and mollusks (Catarino et al. 2018; De-La-Torre et al. 2019; Amin et al. 2020; Fagiano et al. 2023; Sacco et al. 2024). This high environmental occurrence is directly linked to the extensive use of textile fibers and the wear of fishing materials—nets, ropes, and lines. The use of washing machines also contributes substantially to the increased release of microfibers into the environment. Studies show that a single domestic laundry cycle can release thousands of microfibers into the generated effluent, which can reach freshwater systems and marine environments through surface runoff and wastewater treatment plants, which are often inefficient at retaining these particles (De Falco et al. 2019). Moreover, anthropogenic activities such as intensive fishing, maritime traffic, and the discharge of urban and industrial effluents constitute significant sources that reinforce the dispersion of microfibers in coastal zones.

The color blue was the most prevalent among the microplastics identified in this study, corroborating findings from previous research on fish (Neves et al. 2015; Bessa et al. 2018; Barboza et al. 2020; Lopes et al. 2023). Records in surface waters of the Atlantic also indicate blue fragments as dominant (Lusher

et al. 2014), as well as in deep sediments of the Atlantic, Mediterranean, and Indian Oceans (Woodall et al. 2014). The widespread use of blue pigments in fishing gear—nets, ropes, and other nautical implements—partly explains this predominance. Additionally, visual analysis favors the detection of high-contrast particles, such as blue ones, to the detriment of less conspicuous colors, which may overestimate their actual frequency in the environment (Lavers et al. 2016; Lusher et al. 2020). Consequently, blue microplastics tend to be reported with greater abundance in marine contamination studies.

A differential distribution of MP size among the analyzed tissues was observed: larger particles predominated in the digestive tract, while smaller ones were more frequent in muscle. This distinction can be attributed to the higher probability of small particles translocating from the digestive system to other organs via the bloodstream (Browne et al. 2008; Lu et al. 2016). Indeed, Zitouni et al. (2020), examining *Serranus scriba* (Linnaeus, 1758) found that smaller MPs (0.45–1.2 μm) concentrated in muscle, whereas larger particles (> 3 μm and 1.2–3 μm) accumulated in the gastrointestinal tract. In contrast, Makhdoumi et al. (2021) identified an inverse pattern across seven species, reporting a higher incidence of 25–1000 μm MPs in muscle tissue and 1–25 μm MPs in the intestine. Additionally, particle size influences their uptake by visual predators: MPs with dimensions similar to natural prey have a greater chance of active ingestion (De Sá et al. 2015; Galloway et al. 2017). Thus, it is plausible that larger particles were mistaken for dietary items, explaining their higher representation among the larger size classes in the digestive tract compared to muscle in the present study.

Chemical composition of microplastics

The μ -FTIR results revealed a differentiated polymer distribution between tissues: alpha-cellulose and cellulose (of cotton origin) predominated in muscle, whereas in the digestive tract, synthetic polymers such as polyethylene and polypropylene were mainly observed. This polymeric diversity reflects multiple anthropogenic sources, including effluents from sewage treatment plants (Browne et al. 2011) and fishing and recreational activities in the study area. The translocation of plastic particles following ingestion is presumably mediated by mechanisms such as

cellular internalization through intestinal epithelial cells into the circulatory system (Merril et al. 2023) or by phagocytosis (Ikuta et al. 2022). Considering that many of the particles detected in muscle tissue in this study were predominantly fibers, shape may play an important role in their translocation capacity, allowing them to reach the circulatory system more easily (Merril et al. 2023).

The high occurrence of alpha-cellulose and cellulose can be attributed to the widespread use of these materials in textile fibers, cosmetics, cleaning products, and paper artifacts, followed by disposal via wastewater (Rochman et al. 2015). Pre-existing studies (Lusher et al. 2013; Remy et al. 2015; Frias et al. 2016; Dris et al. 2017) have also recorded a high prevalence of semi-synthetic cellulose in marine environments, and Lopes et al. (2023) described cellulose-based polymers as the most common group in tissues of three pelagic species, relating them to fibers. However, the chemical similarity between natural and synthetic fibers hinders the precise distinction of these particles during spectral analysis (Peeken et al. 2018), and limitations in reference libraries of identification software may underestimate the actual abundance of semi-synthetic cellulosic materials (Cai et al. 2019).

Polypropylene (PP) was the most abundant synthetic polymer in the evaluated species. In the marine environment, PP predominates at the surface of the water column, as reported by Gago et al. (2018) and corroborated by earlier studies from Doyle et al. (2011) and Eriksen et al. (2013). This prevalence is due to PP's resistance to high temperatures, its widespread application, and low cost (Lefteri 2003). Additionally, biofilm formation by algae and bacteria on PP particles increases their palatability, making them resemble natural prey for aquatic organisms (Michels et al. 2018). Furthermore, the presence of plastic additives such as oleamide can trigger attractive responses similar to hormones involved in crustacean feeding and mating (Greenshields et al. 2021). Thus, although each polymer alone may exhibit low toxicity, its association with other contaminants enhances its pollutant impact in the marine environment.

Factors influencing microplastic contamination

Microplastic ingestion in the present study was strongly modulated by the interaction of spatial,

seasonal, biological, and ecological factors, emphasizing the complexity of bioaccumulation processes in marine environments. The observation of a positive correlation between microplastic ingestion and the degree of anthropogenic influence supports the initial hypothesis that environments under greater anthropogenic pressure exhibit higher microplastic abundances in fish. Coastal urbanization and anthropogenic activities intensify pollution sources, increasing the availability of plastic particles to aquatic biota (Rezania et al. 2025), which translates into higher MP ingestion by fish in these regions (Silva-Cavalcanti et al. 2017). Our findings align with previous studies that reported the influences of human activities in the introduction and dispersion of microplastics in marine environments (Browne et al. 2011; Collignon et al. 2012; Sun et al. 2018), reinforcing these findings.

Seasonality also emerged as a significant variable, with higher MP ingestion occurring during summer, especially in the more polluted bay (Sepetiba), thus corroborating our first hypothesis (H1). This interaction may reflect the combination of climatic, hydrological, and anthropogenic factors. In the southeastern Brazilian summer, intense rainfall increases fluvial input and urban surface runoff, elevating the load of plastic debris transported to coastal zones (Molisani et al. 2004; Soares et al. 2014). The more polluted bay (Sepetiba) currently receives an average water discharge of 129 m³/s from its main tributary, while the more preserved bay (Ilha Grande) rarely exceeds 50 m³/s even during flood events (Molisani et al. 2006). This exceptionally higher freshwater volume in Sepetiba amplifies the transport of terrestrial-origin microplastics to the estuary, increasing the particle load in the water column and, consequently, fish exposure and ingestion in this region during summer. The reduced flow in Ilha Grande limits the input of plastic debris, resulting in more stable MP concentrations across seasons. Previous seasonal analyses have also identified higher MP concentrations during periods of heavy precipitation, corroborating the results of this study (Garcés-Ordóñez et al. 2023; Saarni et al. 2023). Moreover, during the summer, increased tourism and recreational activities in coastal regions lead to the additional introduction of plastic waste into these environments. The effect of sunlight incidence during summer should also be considered, given that solar radiation can accelerate the fragmentation of

larger plastics (Cózar et al. 2014). Therefore, factors such as precipitation, temperature, and hydrodynamic characteristics play a fundamental role in MP distribution and abundance in marine environments.

Contrary to our expectation, MP ingestion was higher in smaller fish than in larger individuals. This negative correlation between fish body size and MP abundance was previously reported by Hosseinpour et al. (2021), who attributed this trend to factors influencing higher MP ingestion, such as fish swimming behavior, where more active small fish ingest more MPs (Li et al. 2024), when they are filter-feeding or have less selective feeding habits (Hurt et al. 2020). Higher MP concentrations in smaller fish are associated with biological traits such as more generalist feeding behavior (Hurt et al. 2020), suggesting ecological implications, including the transfer of MPs along the food chain. In addition to these behavioral and ecological mechanisms, this pattern may also be explained by the biological dilution (or growth-dilution) effect, whereby, as fish grow and increase in body mass, MP intake does not increase proportionally, resulting in a lower concentration of MPs per unit of tissue in larger individuals (Collins et al. 2025). It is important to observe that the mass of the analyzed tissue may also influence the estimation of MP load, potentially leading to overestimation and affecting the interpretation of accumulation patterns, as discussed by Jin et al. (2025). In this context, it is relevant to consider standardized protocols for the analysis of microplastics in fish, particularly with regard to tissue mass determination, fish morphometric measurements, and microplastic extraction procedures. Considering that body size is a key biological trait, understanding how MP load correlates with fish size can enhance ecological knowledge and inform management strategies. Therefore, this relationship should be further investigated, with careful control of confounding factors, given its relevance to human health.

In the present study, microplastic concentrations in fish muscle and digestive tissues were of similar magnitude, confirming previous findings of comparable abundances in intestine and muscle (Lusher et al. 2013; Dekiff et al. 2014; Neves et al. 2015; Selvam et al. 2021), which does not support our expectation of higher concentrations in the digestive tract. This similarity between tissues can be explained by the translocation of smaller particles from the intestinal

cavity to the systemic circulation, facilitated by digestive processes and fluid transport, allowing their accumulation in peripheral tissues such as muscle (Browne et al. 2008; Hossain et al. 2024). Additionally, bioaccumulation along the trophic chain enhances this distribution: larger individuals and higher trophic levels tend to ingest already contaminated prey, progressively increasing the microplastic load in muscle (Lusher et al. 2017; Selvam et al. 2021). In contrast, smaller fish with faster metabolisms may excrete particles shortly after direct environmental ingestion (Jovanovic 2017). These findings highlight the complexity of microplastic distribution within fish tissues and underscore the need for further research on translocation mechanisms and trophic transfer.

The results of this study did not reveal significant differences in microplastic concentrations between pelagic and demersal habitats, which also did not meet our expectation of higher concentrations in pelagic fish due to the buoyant nature of many MPs (H2). This similarity can be explained by the wide variability in polymer densities, which determine whether particles float or sink, leading to their distribution throughout the water column and sediments (Phaksopa et al. 2021). Consequently, fish from both habitats are exposed to comparable levels of MPs. Although previous investigations have reported higher concentrations in pelagic species, mainly attributed to the predominance of lightweight fibers in the water column (Lima et al. 2014; Katsnelson 2015; Bellas et al. 2016), this pattern has been further supported by recent studies (Giani et al. 2023; Polt et al. 2023). Our findings, however, suggest that habitat alone may not be a reliable predictor of MP exposure, emphasizing the omnipresence of MPs in the ocean layers and the need to consider additional ecological and environmental factors.

Analysis of feeding habits showed that the carnivorous species *C. crysos* and *M. furnieri* exhibited higher MP abundances. Previous studies have demonstrated that crustaceans, an important dietary item for *M. furnieri*, *M. americanus*, and *C. crysos*, can bioaccumulate contaminants at concentrations exceeding ambient levels (Ricciardi et al. 2010; Batvari et al. 2013; Liao et al. 2015). An experimental study employing a prey–predator model, consisting of the mysid crustacean (*Neomysis* spp.) and the benthic fish *Myoxocephalus brandti* (Steindachner, 1867),

demonstrated that trophic transfer constitutes the primary pathway for MP ingestion in fish, as the quantity of MPs ingested via bioaccumulation exceeded 3 times more than that from direct exposure in the water column (Hasegawa and Nakaoka 2021). Furthermore, it was observed that prey such as mysids are capable of fragmenting MPs, thereby facilitating the transfer of these particles to higher trophic levels. These results suggest that elevated MP burdens in carnivorous fishes are likely driven, at least in part, by indirect exposure through consumption of contaminated prey.

Conclusions

In summary, 83.1% of the analyzed individuals contained microplastics, indicating widespread contamination in coastal fish of southeastern Brazil. The MP load was strongly influenced by the anthropogenic impact gradient—with the highest concentrations in Sepetiba Bay—and by seasonal variations, peaking in summer, when freshwater input intensifies particle transport. The similar abundances between muscle and digestive tract, as well as the lack of differences between pelagic and demersal habitats, highlight the capacity for translocation and wide dispersion of polymers in the water column. The predominance of microfibers, fragments, and polymers such as PP, PE, and cellulose suggests multiple emission sources, from urban effluents to textile and fishing debris. This study advances understanding of MP contamination in commercial species and understudied environments, providing an essential basis for future monitoring programs, source identification, and integrated coastal management strategies aimed at mitigating ecological impacts and human health risks.

Author contribution Laryssa Cordeiro: writing—original draft, visualization, methodology, investigation, formal analysis, and conceptualization. Rayane Sorrentino: writing—review and editing and resources. Gustavo Henrique Soares Guedes: writing—original draft, editing, and formal analysis. Luiz F.S.P. Azeredo: methodology and formal analysis. Francisco G. Araújo: writing—review, supervision, resources, methodology, investigation, funding acquisition, and conceptualization.

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Data availability Data will be made available on request.

Declarations

Competing interests The authors declare no competing interests.

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