Wetlands Ecol Manage (2026) 34:49
https://doi.org/10.1007/s11273-026-10156-6

ORIGINAL PAPER

Microplastics in wetlands: contrasting fish contamination between mangroves and temporary ponds in southeastern Brazil

Gustavo Henrique Soares Guedes · Laryssa Cordeiro · Luís Felipe da Silva Pinto Azeredo · Francisco Gerson Araújo

Received: 14 October 2025 / Accepted: 9 May 2026

Abstract Microplastic (MP) pollution is ubiquitous in aquatic ecosystems, but comparative analyses across wetland types and fish life histories are still rare. This study compares microplastic contamination in killifishes (Cyprinodontiformes: Rivulidae) with contrasting life histories: annual (*Notholebias minimus*, *Leptopanchax opalescens*) *vs*. perennial (*Kryptolebias ocellatus*; *Kryptolebias hermaphroditus*), across two wetland types (temporary ponds *vs*. mangroves) on the coastal plain of Rio de Janeiro (Brazil). The tested hypothesis is that small annual fishes in temporary wetlands exhibit lower microplastic contamination than perennial mangrove species, due to lower hydrological connectivity and shorter exposure time. Fishes were digested (KOH solution), vacuum filtered, and analysed using microscopy and μ-FTIR. Microplastics were detected in all species and 60.5% of individuals (1.58 ± 1.84 items fish^{-1}). Most particles were small (< 1,000 μm), blue/black fragments or microfibers, with polymers dominated by polypropylene and poly(4-methyl-1-pentene). Contrary to H1, MP loads did not differ between mangroves and temporary ponds (GLMM: $\chi^2 = 0.18$, $p = 0.671$), nor with body size ($\chi^2 = 0.44$, $p = 0.507$). Convergent functional traits of rivulids: small gape, generalist foraging, and routine use of shallow microhabitats where fibers and fragments accumulate, likely equalize ingestion probabilities across life histories. Collectively, these findings show that temporary wetlands are not refuges from plastic contamination and should be explicitly included in monitoring and mitigation strategies that target diffuse, landscape-scale MP inputs.

Keywords Killifish · Pollution · Rivulidae · Rio de Janeiro · Bioaccumulation · Micro-FTIR · Plastic debris

Introduction

Microplastics are particles of synthetic polymers smaller than five millimeters that have become a ubiquitous contaminant on a planetary scale (Karak

---

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11273-026-10156-6.

G. H. S. Guedes · L. Cordeiro · F. G. Araújo (✉)
Laboratório de Ecologia de Peixes, Departamento de Biologia Animal, Universidade Federal Rural Do Rio de Janeiro, Seropédica, RJ 23897-000, Brazil
e-mail: gerson@ufrrj.br

G. H. S. Guedes
e-mail: gustavohsg@outlook.com

L. Cordeiro
e-mail: laryssac18@gmail.com

L. F. da Silva Pinto Azeredo
Laboratório de Caracterização Instrumental, Instituto de Química, Universidade Do Estado Do Rio de Janeiro, Rio de Janeiro, RJ 20550-900, Brazil
e-mail: luis.azeredo@uerj.br

et al. 2025). They originate either from the degradation of larger plastic debris ("secondary sources") or are intentionally manufactured at small sizes for use in products such as cosmetics and textiles ("primary sources"), and constitute a significant environmental threat (Hartz et al. 2025). Their persistence, coupled with efficient transport by oceanic circulation and aeolian processes, has led to their detection in the most remote ecosystems, from the deepest ocean trenches (Peng et al. 2020) to the summit of Mount Everest (Napper et al. 2020). This widespread dispersal underscores the transboundary nature of the problem, highlighting failures in global plastic-waste management and the consequent contamination of soils, water bodies, and the atmosphere (Geyer et al. 2017). The massive presence of microplastics across ecosystems entails toxicological risks arising both from their intrinsic chemical composition, which induces inducing oxidative stress, inflammation, and mitochondrial dysfunction, and from their capacity to adsorb and transport other hazardous pollutants (Wang et al. 2020; Leslie et al. 2022), consolidating them as a worldwide environmental and public-health challenge.

There has been a marked global expansion of research on microplastics across environmental compartments, driven by heightened public, regulatory, and academic attention to plastic pollution and its ecological and human-health impacts. Nevertheless, important biases persist in the literature: a geographic concentration of studies in high-income regions (e.g., China, United States), a taxonomic focus biased toward charismatic or economically important fish groups (e.g., *Danio rerio* (Hamilton 1822)*, Cyprinus carpio* Linnaeus 1758), and a disproportionate emphasis on marine–coastal environments (Amparo et al. 2023; Sacco et al. 2024; Hartz et al. 2025; Jolaosho et al. 2025). Within the marine literature, over 80% focuses on sandy beaches (Browne et al. 2015), whereas brackish habitats such as mangroves remain understudied (Deakin et al. 2025). In freshwater systems, this bias is even more pronounced, with most studies targeting lotic environments, particularly large rivers (Moreira et al. 2025; Semensatto et al. 2025), while freshwater wetlands and their biota have received limited attention (Qian et al. 2021; Dalvand and Hamidian 2023; Li et al. 2024). Consequently, a critical knowledge gap persists regarding the magnitude, exposure pathways, and ecological effects of plastic contamination in wetlands, constraining cross-ecosystem comparisons and the design of effective mitigation strategies.

Wetlands, as broadly defined by the Ramsar Convention (1971), encompassing areas of marsh, fen, peatland, or water, whether natural or artificial, permanent or temporary, with water that is static or flowing; fresh, brackish, or salt; and including areas of marine water whose depth at low tide does not exceed six meters. These environments function as hydrological and biogeochemical interfaces where multiple microplastic (MP) input pathways converge (rivers, tides, urban/agricultural runoff, rainfall, winds), and are therefore particularly susceptible to the contamination and retention of these emerging pollutants (Dalvand and Hamidian 2023; Elnahas et al. 2024; Qiao and Wang 2024). The low flow velocity, high lateral connectivity, and long residence times, favor the deposition and accumulation of plastic particles (Li et al. 2024). Dense vegetation (e.g., aerial roots and canopies in mangroves) acts as a physical "sieve" that retains MPs, although high-energy events (storm surges, floods) can remobilize them, characterizing these environments not only as sinks but also, at times, as secondary sources through in situ fragmentation and the export of MPs to adjacent aquatic systems (Paduani 2020; Qiao and Wang 2024; Boyer et al. 2024; Deakin et al. 2025). This export is mediated not only by hydrodynamic processes but also by biological pathways, as aquatic organisms can ingest and transfer microplastics across trophic levels and ecosystem boundaries (Zhao et al. 2026).

Neotropical inland wetlands provide habitat for a diverse fish family (Rivulidae), comprising approximately 490 valid species (Fricke et al. 2025). Rivulid fishes are commonly subdivided into two main life-history groups: annual and perennial (Furness et al. 2018; Guedes et al. 2025). This dichotomy reflects striking evolutionary adaptations to extreme environmental pressures, including high temperatures, low oxygen concentrations, acidic waters, and extreme hydrological fluctuations that approach the limits of vertebrate tolerance (Polačik and Podrabsky 2015; Podrabsky et al. 2016). Annual species are specialized colonizers of temporary wetlands, which are ephemeral, often isolated systems with low hydrological connectivity and predominantly rain-fed hydrology (Loureiro et al. 2018; Lanés et al. 2021; Guedes and Araújo 2026). To survive periodic desiccation, these fishes produce eggs that enter a dormant state known as embryonic diapause (Furness 2016). This trait enables embryos to persist for months within dry soil, awaiting the return of rains for hatching (Abrantes et al. 2020; Guedes et al. 2023a; Costa et al. 2024; Hinncands et al. 2025). Synchrony between the life cycle and the hydrological regime yields one of the shortest lifespans among vertebrates, with individuals living only a few months, which in turn has selected for extremely rapid growth and sexual maturation (Hu et al. 2020; Žák et al. 2021).

By contrast, perennial rivulid species inhabit more stable aquatic environments such as streams, permanent wetlands, and mangroves. Their development follows the typical teleost pattern, without the three obligatory phases of embryonic diapause (Furness et al. 2018). Within the perennial group, a notable case is the genus *Kryptolebias* Costa, 2004, three species of which are known to occur strictly in mangroves: *K. ocellatus* (Hensel, 1868), *K. marmoratus* (Poey, 1880), and *K. hermaphroditus* Costa, 2011. Living in the dynamic and challenging mangrove environment, these species have evolved a suite of extraordinary traits. They are capable of cutaneous respiration, which enables direct oxygen uptake from air, and they can remain out of water for extended periods, sheltering in fallen logs and crab burrows during low tide (Wright 2012; Turko and Wright 2015). In addition, the genus *Kryptolebias* includes the only vertebrates known to exhibit simultaneous hermaphroditism with natural self-fertilization (*K. marmoratus* and *K. hermaphroditus*), allowing a single individual to found new clonal populations (Avise and Tatarenkov 2015; Rhee et al. 2017; Berbel-Filho et al. 2022).

Rivulids exhibit an opportunistic diet, shaped by prey availability and capture ability, exploiting both autochthonous resources (e.g., polychaetes, microcrustaceans, and copepods) and allochthonous inputs (such as dipterans, terrestrial insects). They forage across different strata of the water column, from the bottom to the surface, reflecting a flexible feeding behavior (Taylor 2012; Contente and Stefanoni 2010). In annual fishes inhabiting ephemeral environments, as well as in non-annual species from mangroves, a generalist feeding strategy tends to be more advantageous than specialization, which may impose high costs under spatiotemporal variability in prey availability (Gonçalves et al. 2011; Taylor 2012).

Given the diversity of species' life histories and the heterogeneous distribution of microplastics (MPs) across wetlands, vulnerability to MP contamination among rivulid fishes is unlikely to be uniform. Therefore, the main objective of this study is to compare microplastic (MP) contamination between fish with contrasting life-history (annual *vs*. perennial) across two wetland types (temporary ponds *vs*. mangroves) on the coastal plain of Rio de Janeiro State, southeastern Brazil. We test the hypothesis that annual species inhabiting temporary wetlands exhibit lower MP contamination than perennial species inhabiting mangrove systems with higher hydrological connectivity. This hypothesis is supported by evidence that mangroves act as filters and sinks for MPs due to continuous inputs from rivers and wastewater and to tidal resuspension, which together increase environmental MP availability (Deakin et al. 2025). In addition, field data, reviews, and modeling indicate that age and body size, which serve as proxies for lifespan and exposure time, are positively associated with MP occurrence and loads in fishes (Roch et al. 2020; Yagi et al. 2022; Ding et al. 2023).

Material and methods

Study area

The study area encompasses temporary wetlands in the municipalities of Seropédica (Code T1 in Fig. 1, 22°42′19.5"S – 43°41′36.1"W) and Rio de Janeiro (T2, 22°59′23.8"S – 43°25′03.0"W), as well as mangrove forests in Magé (M1, 22°42′36.9"S – 43°13′05.9"W; M2, 22°39′44.5"S – 43°05′09.7"W), which drain into the Jacarepaguá Lagoon System, and into Sepetiba and Guanabara bays, in the state of Rio de Janeiro, southeastern Brazil (Fig. 1). The sampled wetlands were shallow, with temporary ponds reaching maximum depths of 35 cm at T1 and 50 cm at T2, and located in open vegetation areas with the presence of aquatic macrophytes. In contrast, mangrove sites exhibited even shallower depths (25 cm at M1 and 15 cm at M2) and were associated with dense arboreal vegetation dominated by *Rhizophora mangle* and *Acrostichum aureum*. The distance to the nearest perennial water body varied among sites, being 1000 m at T1 and 83 m at T2, whereas in mangroves it was 270 m at M2 and only 15 m at M1. Rivers and

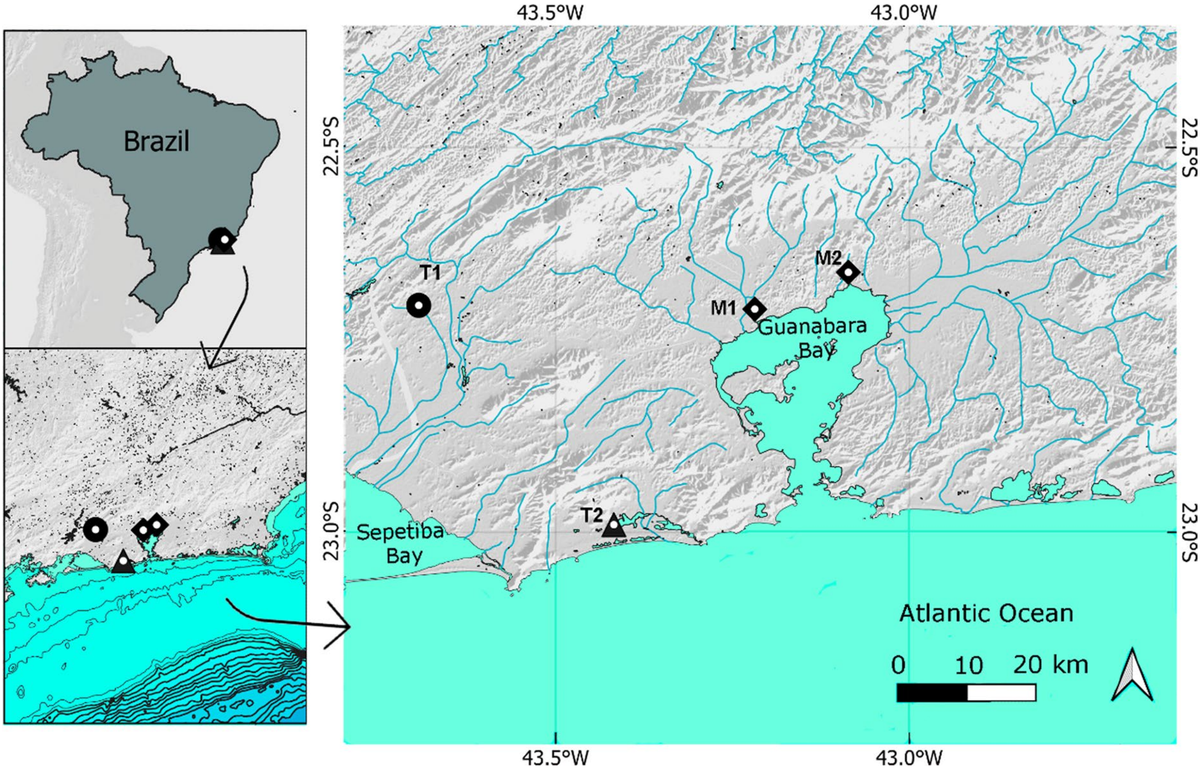

Fig. 1 Map showing the sampling sites of rivulid fishes on the coastal plain of the state of Rio de Janeiro, Brazil. Black circle: *Leptopanchax opalescens* – temporary wetland (T1); triangle: *Notholebias minimus* – temporary wetland (T2); squares*: Kryptolebias ocellatus and Kryptolebias hermaphroditus* – mangroves (M1 and M2)

the biota comprising these drainage systems exhibit high levels of microplastic contamination (Alves and Figueiredo 2023; Drabinski et al. 2023; Cordeiro et al. 2026). The climate in the region ranges from tropical monsoon (Am) in Magé and Rio de Janeiro, and tropical savanna (Aw) in Seropédica, according to the Köppen classification. Mean annual temperatures vary from 21.7 °C to 22.6 °C, and total annual rainfall ranges from 1,332 to 1,806 mm. All localities are situated within the Atlantic Forest biome, a region recognized as a global biodiversity hotspot due to its exceptional species richness and high levels of endemism (Myers et al. 2000).

Fish collection

Fish were collected in June 2025 using immersion nets (oval-shaped hand nets, 50 × 40 cm, 1 mm mesh size). Sampling was conducted by actively sweeping the nets through the water column and along the substrate, covering both marginal and central areas of each site. After capture, specimens were anesthetized with benzocaine hydrochloride (50 mg/L), euthanized, and fixed in 10% formalin in situ. In the laboratory, fish were measured to the nearest 0.01 cm, weighed to the nearest 0.001 g, and, after 48 h, preserved in 70% ethanol. A total of 200 specimens belonging to four rivulid species from four localities (Fig. 1) were analyzed: 100 individuals from temporary wetlands (*Notholebias minimus*-annual specie, n = 50, from the municipality of Rio de Janeiro; *Leptopanchax opalescens*—annual specie, n = 50, from Seropédica) and 100 individuals of the perennial species *Kryptolebias ocellatus* and *K. hermaphroditus* from two mangrove sites in Magé (M1 = 50 and M2 = 50; Table 1). Fish were collected under permits issued by the Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio permits #10,707 and #87,082) and the Ethics Council for Animal Use (CEUA/ICBS/UFRRJ; authorization #12.28.01.00.00.00.45, February 2023).

Table 1 Summary of fish morphometrics (TL = total length—cm, Weight = wet mass—g) and microplastic load by wetland type, site, and specie on the coastal plain of the state of Rio de Janeiro, Brazil. Values are mean ± SD; sample size per species in parentheses

Wetland	Site	Specie (N)	TL (cm)	Weight (g)	MP per ind
Mangrove	M1	*K. ocellatus* (37)	1.99 ± 0.51	0.08 ± 0.05	1.84 ± 1.92
		K. hermaphroditus (13)	2.22 ± 0.51	0.11 ± 0.06	1.46 ± 1.81
	M2	*K. ocellatus* (39)	2.69 ± 0.71	0.24 ± 0.14	1.28 ± 1.61
		K. hermaphroditus (11)	2.82 ± 0.66	0.25 ± 0.16	1.18 ± 1.47
Temporary pond	T1	*Leptopanchax opalescens* (50)	1.44 ± 0.2	0.03 ± 0.02	1.7 ± 1.93
	T2	*Notholebias minimus* (50)	1.77 ± 0.35	0.06 ± 0.04	1.64 ± 1.98

Laboratory analysis

Microplastic extraction

Due to the small body size of the analyzed species (mean ± SD = 1.99 ± 0.6 cm TL; range: 1.1–4.0 cm), whole fish were submerged in a 10% KOH solution (10 mL per gram of tissue) to digest organic matter. Therefore, the microplastic load reported in this study corresponds to the total present in all tissues and organs of each individual. Samples were then heated on a TEC NAL hot plate at 40 °C for four hours, following the protocol adapted from NOAA (Herring et al., 2015). Subsequently, each digest was vacuum-filtered through glass-fiber membrane filters. Filters were examined under a LEICA M205 C stereomicroscope, and all visible microplastics were counted, measured (µm), and classified into four categories: microfibers, fragments, spheres (beads), or pellets according to Dekiff et al. (2014) and Hidalgo-Ruz et al. (2012).

Microplastics characterization

After visual inspection, a subsample corresponding to 10% of the total microplastics observed was randomly selected following Hanke et al. (2013) and subjected to infrared microspectroscopy using a µ-FTIR Spectrum 3 equipped with a Spotlight 200 module (PerkinElmer) for polymer chemical characterization. The material retained during filtration was transferred, under an Olympus SZX10 stereomicroscope, to a polished KBr disk cell (13 × 2 mm) for µ-FTIR analysis in transmission mode. Particle screening was performed using halogen illumination (Olympus LG-PS2-5); for occasional visual enhancement of selected particles, a UV flashlight (A.F-535A) was used. The µ-FTIR was operated in transmittance mode with a spectral resolution of 1 cm^{-1} over a range of 4000–600 cm^{-1}. Aperture size and shape were adjusted for each particle, with dimensions varying between 25 and 150 µm. The 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 75%.

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). Procedural blanks consisted of Petri dishes containing filtered distilled water, which were placed alongside the samples throughout processing to monitor potential airborne contamination; any microplastics detected in these blanks were subsequently quantified. To minimize external contamination, all equipment (Petri dishes, scissors, tweezers) was thoroughly cleaned with distilled water followed by 70% ethanol, and laboratory personnel wore latex gloves and lab coats at all times.

Data analysis

Microplastics were quantified and categorized by manually counting each particle in the samples, recording both their morphotype, color and size. We then calculated the relative frequency of each morphology type (microfibers, fragments, spheres, pellets) and each color category separately for each environment (mangrove and temporary ponds), expressing all values as percentages to provide a comprehensive, comparative overview of microplastic distribution across the analyzed fish.

To test the hypothesis (H1) that annual fish species inhabiting temporary wetlands exhibit lower microplastic contamination than perennial species inhabiting mangroves, a Generalized Linear Mixed Model (GLMM) framework was employed. The response variable, microplastic abundance per fish (MP), showed clear overdispersion (variance/mean = 2.14), moderate positive skewness (1.30), and high kurtosis (7.39), consistent with a long-tailed, sharply peaked distribution. Zeros accounted for 39.5% of observations (79/200), nearly double the proportion expected under a Poisson process with the same mean (20.5%), indicating substantial zero inflation, a common pattern in microplastic contamination datasets (e.g., Hou et al. 2021; Cordeiro et al. 2026).

Given the data structure, we fitted zero-inflated negative binomial GLMMs (ZINB) with a log link using the *glmmTMB* package (Brooks et al., 2017). Fixed effects included wetland type (mangrove vs. temporary ponds), fish body total length (proxies for lifespan and exposure time), and their interaction (wetland type × total body length), with sampling localities specified as random factors. These predictors were included in both the conditional and zero-inflation components of the models. Model significance for main effects and interactions was assessed using Type II Wald χ^2 ANOVA via the *car* package, with $\alpha = 0.05$. Model assumptions and adequacy were checked using the *simulateResiduals* function from the *DHARMa* package (Hartig 2024). Diagnostic plots were used to verify distributional assumptions, check for overdispersion, and identify potential outliers. No significant violations were detected (Fig. S1—Supplemental Material 1). All statistical analyses were performed in R version 4.3.1 (R Core Team, 2024). Data used in the analyses are available in Supplemental Material 2.

Results

Microplastic profiles: morphotype, color, length, polymer composition

Microplastic contamination was detected in all four rivulid fish species, occurring in 121(60.5%) of the 200 specimens analyzed (mean ± SD = 1.58 ± 1.84 MP particles per individual; Table 1, Figure 2). Rates were similar across habitats: 62% in mangroves (1.50 ± 1.84 MP) and 59% in temporary wetlands (1.67 ± 1.97 MP; Table 1). Particle composition was dominated by fragments (Overall: N = 188; 59.3%; mangroves: N = 98; 65.3%; temporary ponds: N = 90; 50.3%) and microfibers (Overall: N = 122; 38.4%; mangroves: N = 48; 32%; temporary ponds: N = 74; 44.3%) in both environments; spheres and pellets were rare (N = 7; < 2%; Figure 2 and 3; Table S1 - Supplemental Material 1). In terms of color, blue (65.3%) and black (23.3%) particles predominated, together accounting for 88.6% of all items recovered (Figure 3; Table S2 - Supplemental Material 1). Regarding size, particle lengths spanned 22–4,192 µm. Smaller particles (<1,000 µm) were the most prevalent across samples from both mangroves and temporary ponds (Figure 3). No microplastics were detected in the Petri dish blanks, indicating the absence of procedural contamination during laboratory analyses.

µ-FTIR analysis showed that the identified particles were mainly polypropylene (PP, 39.5%) and poly (4-methyl-1-pentene) (PMP/TPX, 23.3%), followed by α-cellulose (16.3%), poly(ethylene terephthalate) (PET, 14.0%), cellulose (2.3%), and other polymers (4.7%) (Figure 3). By environment, mangrove was dominated by PP (43.8%), with contributions from PMP (18.8%), α-cellulose (18.8%), PET (12.5%), and cellulose (6.3%). In temporary ponds, PP (37.0%) and PMP (25.9%) predominated, with PET (14.8%) and α-cellulose (14.8%) at intermediate frequencies, plus other polymers (7.4%).

Effects of wetland type and body length on microplastic contamination

Microplastic abundance per fish were modeled with a zero-inflated negative binomial GLMM (AIC = 697.1). The zero-inflation component indicated a significant excess of structural zeros (logit intercept = -1.09 ± 0.36, $p = 0.0026$), corresponding to an average structural-zero probability of ~ 0.25. In the count component, neither wetland type ($\chi^2 = 0.18$, $p = 0.671$) nor fish total length ($\chi^2 = 0.44$, $p = 0.507$), nor their interaction ($\chi^2 = 0.18$, $p = 0.669$) was associated with MP abundance; therefore rejecting H1.

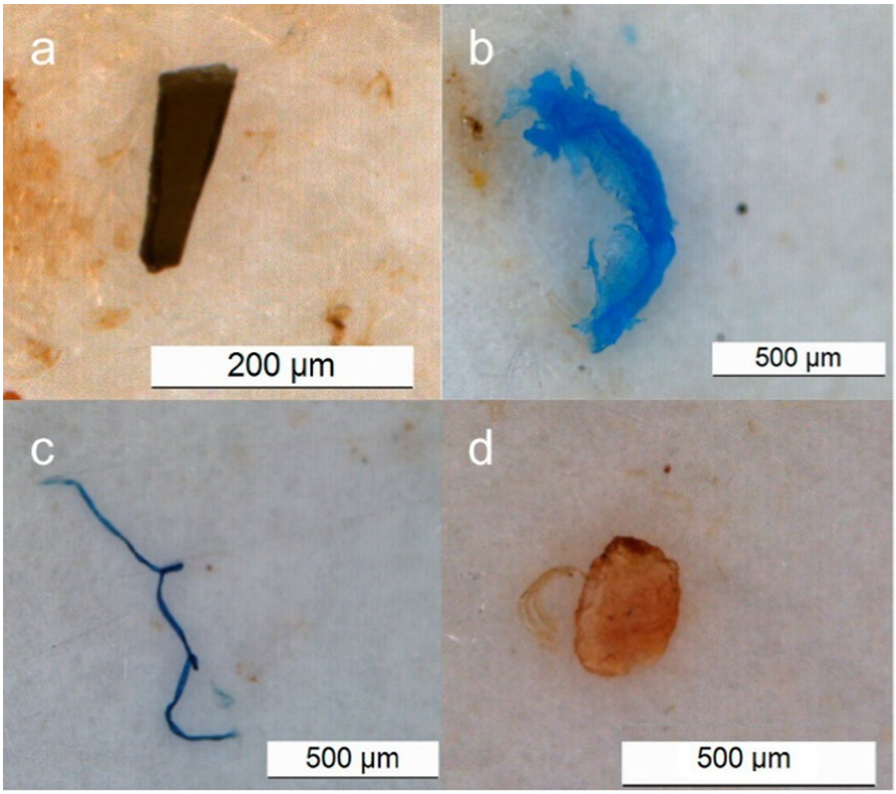

Fig. 2 Photographs of microplastics detected in rivulid fishes from the coastal plain of Rio de Janeiro State (Brazil). Fragments **(a–b)**, microfibers **(c)**, and spheres **(d)**

Discussion

Effects of wetland type and body length on microplastic contamination

Contrary to H1, microplastic (MP) burdens were similar in annual fishes from temporary wetlands and perennial fishes from mangroves, despite the expectation of higher contamination in mangroves owing to stronger hydrological connectivity and longer life spans (and thus greater cumulative exposure). Reviews show that mangrove root structure and tidal regimes promote the retention and enrichment of microplastics in mangroves (e.g., Qiao and Wang 2024; Deakin et al. 2025), and that body size, used as a proxy for lifespan and exposure time, is positively associated with MP occurrence and loads in fishes (Roch et al. 2020; Yagi et al. 2022; Ding et al. 2023), which would, a priori, justify the expectation of higher loads in mangrove fishes. This finding suggests that efficient pathways of MP input and ingestion also operate in fishes from temporary wetlands, offsetting the effects of lower connectivity and shorter life cycles.

A key mechanism underlying MP contamination of fish in the temporary wetlands examined here may be atmospheric, pluvial, and overland runoff inputs. Owing to their small size and low density, MPs become airborne and can be transported over long distances by wind before being redeposited on terrestrial and aquatic surfaces (Allen et al. 2019; Elnahas et al. 2024). Precipitation also plays a crucial role by scavenging suspended MPs from the atmosphere and depositing them in concentrated fluxes, effectively acting as a “concentration funnel” (Brahney et al. 2020; Dong et al. 2024). In addition, overland runoff from roads transports urban waste into temporary wetlands, while traffic-derived dust, particularly tire- and brake-wear particles, constitutes an important MP source (e.g., Jaiswal et al. 2026). This is consistent with the study’s sampling sites: the temporary pond of *Leptopanchax opalescens* is located in an industrial/agricultural zone near a state highway (Guedes et al. 2020), whereas the *Notholebias*

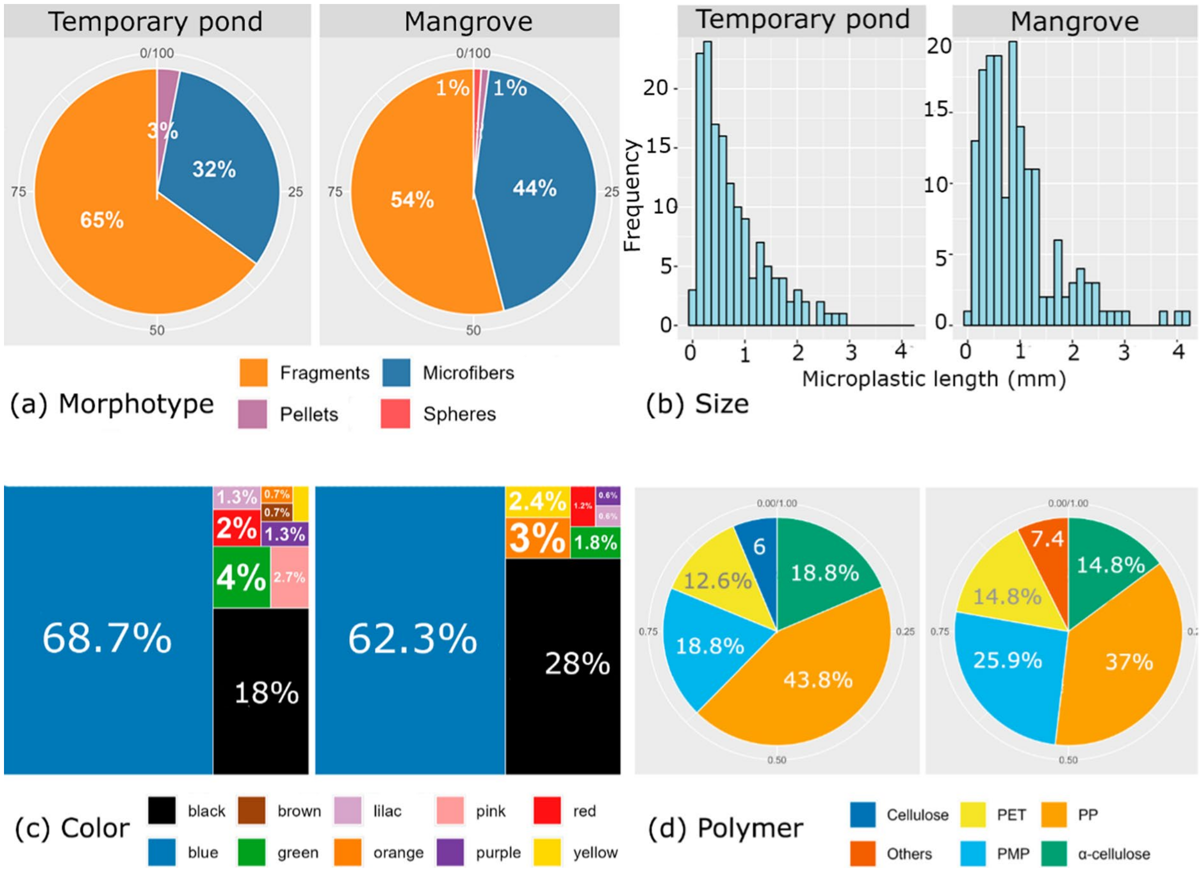

Fig. 3 Comparison of microplastic contamination in rivulid fishes between two wetland types (mangroves and temporary ponds) in southeastern Brazil by: morphology **(a)**, size **(b)**, color **(c)**, and polymer chemical composition **(d)**

minimus site lies within an urban area of the city of Rio de Janeiro (Guedes et al. 2023b), one of the most densely populated regions of Brazil. The central issue in Rio de Janeiro, as well as in much of Brazil, remains the inadequate disposal and management of solid waste and low wastewater treatment rates (Alves and Figueiredo 2023; Drabinski et al. 2023; Andrade and Araujo 2025), factors that contribute to the accumulation of pollutants in temporary wetlands where rivulid fishes occur. The hydrological "isolation" of a temporary wetland from perennial waters is therefore illusory from the standpoint of plastic pollution.

The observed similarity in ingestion among species may stem from functional traits shared by rivulids. Small body size and reduced gape impose size-selective filtering, favoring ingestion of fine particles (<1 mm), the fraction that tends to predominate in MP records (Siddique et al. 2024; Lim et al. 2022). In addition, a generalist trophic habit and recurrent use of shallow benthos, periphyton/detritus, and the air–water interface (Contente and Stefanoni 2010; Gonçalves et al. 2011; Taylor 2012) where fibers and fragments accumulate via flotation, settling, and resuspension, may create similar opportunities for incidental ingestion in both annual and perennial species. Microplastic ingestion by fish occurs predominantly in a passive or incidental manner, reflecting their availability in the aquatic environment, since particles can be mistaken for food or ingested during feeding (Hartz et al. 2025; Jolaosho et al. 2025). Despite shorter lifespans, annual species exhibit high growth and foraging rates to complete a rapid life cycle (Furness 2016; Žák et al. 2021), which may compensate for reduced exposure time and bring MP loads closer to those of perennial species. Taken together, (i) shared morphological traits (small body/

reduced gape), (ii) convergent use of microhabitats with potential high MP availability, and (iii) elevated foraging rates tend to homogenize the spectrum of particle sizes ingested and, consequently, the individual MP burdens observed in this study.

Microplastic profiles: morphotype, color, length, polymer composition

Fragments (60%) and microfibers (38%) dominated the particles recovered from fish in both mangroves and temporary ponds, whereas spheres and pellets contributed only marginally. This profile contrasts with the meta-analysis (Lim et al. 2022; Dalvand and Hamidian 2023), which reported fibers as the dominant morphotype (70–98%) and fragments as secondary (8–19%) in fish globally. The observed inversion for species in the present study may be linked to the absence of temporary wetlands in the studies reviewed and may also reflect a combination of non-exclusive mechanisms: (i) habitat-specific sources and transformations—in mangroves, tidal energy, vessel traffic, and wear of fishing gear favor the secondary fragmentation of macroplastics, while root architecture and fine sediments act as sinks that modulate the relative availability of fibers in the water column (Paduani 2020; Qiao and Wang 2024); and (ii) in temporary ponds, UV radiation, elevated temperatures, and wet–dry cycles accelerate photo-oxidation and abrasion, increasing the proportion of fragments (Qian et al. 2021; Li et al. 2024), while low hydrological connectivity reduces exposure to continuous inputs of textile microfibers from domestic/industrial effluents.

In addition, the present study has methodological particularities that distinguish it from the majority of studies on microplastics in fish. Here, total microplastic burden was assessed at the organism-level exposure, considering the whole fish. This approach is particularly appropriate due to the small body size of the species analyzed, which, like most Neotropical rivulids, exhibit reduced size (Guedes et al. 2023b), with total body mass below 0.5 g. In contrast, most studies on microplastics in fish focus on specific compartments, with a strong predominance of gastrointestinal tract analyses (65%) and a low representation of integrated approaches, with only about 5.3% of studies assessing the organism more comprehensively (Sequeira et al. 2020). This methodological limitation may lead to an underestimation of organism-level exposure, as it does not account for other pathways and compartments of contamination, such as retention and filtering by the gills, as well as possible redistribution to muscle and neural tissues (Lim et al. 2022). Studies exclusively focused on the intestine tend to reflect ingestion patterns associated with feeding behavior, whereas gill-based analyses may capture a more direct and continuous exposure to the aquatic environment, often more heterogeneous in terms of particle availability (Yin et al. 2022). Thus, ecological, hydrological, and methodological particularities may have influenced the predominance of fragments over microfibers observed in the present study.

Blue and black microplastic particles predominated in fish from both wetland types, together accounting for 88.6% of all items recovered. This pattern aligns with scientometric and global meta-analyses in fishes showing that blue and black particles are most frequently reported in field investigations (Lim et al. 2022; Sacco et al. 2024). Ecological and methodological processes likely act in concert across brackish and freshwater habitats: (i) shared inputs from urban effluents, surface run-off, and atmospheric deposition deliver a similar “color mix,” with blue plastics incidentally ingested due to high environmental availability (Lim et al. 2022); (ii) visual selection by fish may favor blue particles that resemble zooplankton prey, while black particles commonly reflect tire-wear debris and ropes/fishing gear (Ory et al. 2017); and (iii) visual sorting can overestimate vivid/dark colors and undercount transparent particles (Lusher et al. 2020).

Particles $< 1{,}000$ µm were the most prevalent in this study, consistent with syntheses in fishes indicating that the 0–1 mm class is the most common among ingested items (Oza et al. 2024). Biologically, the small body size of rivulids imposes gape limitations and favors selection of proportionally small natural prey; such morphological constraints likely render smaller microplastics more susceptible to incidental ingestion during foraging (e.g., Siddique et al. 2024). The high frequency of polypropylene observed in this study is consistent with syntheses and meta-analyses reporting polyolefins (PE/PP) as the most common polymers in fishes, owing to their widespread use in packaging materials, plastic bags, containers, and synthetic fibers (Lim et al. 2022). This pattern reflects their high production, low density, and persistence, which favor surface transport and stranding in physical retention zones such as mangrove roots and emergent macrophytes (Amparo et al. 2023; Oza et al. 2024).

Implications, limitations, and future directions

Among the four rivulid species analyzed in this study, two are globally threatened with extinction (*N. minimus* and *L. opalescens*; IUCN 2025), and one is locally threatened (*Kryptolebias ocellatus*; SMAC Resolution No. 073–2022). The detection of microplastics in all evaluated species represents a relevant warning signal for conservation, not only for these taxa, but also for the more than 130 rivulid species threatened with extinction in Brazil (ICMBio 2026). Furthermore, runoff from agricultural areas can transport mixtures of pesticides into water bodies inhabited by rivulids (Zebral et al. 2018; Godoy et al. 2025), together with microplastics (MPs), creating co-exposure scenarios. Exposure to microplastics in fish has been associated with sublethal effects such as oxidative stress, tissue inflammation, reduced physiological performance, and behavioral alterations (Wang et al. 2024; Jo et al. 2025). In addition, there is potential for bioaccumulation and trophic transfer of microplastics to higher levels of the food chain, especially to piscivorous birds and other predators that use these environments as foraging areas (e.g., Carrillo et al. 2025), which broadens the ecological implications of these findings to the entire local food web.

In Brazil, the main challenge related to plastic pollution remains the inadequate management of solid waste and the low coverage of sewage treatment, factors that favor the continuous entry of contaminants into aquatic environments (Andrade and Araujo 2025). Therefore, conservation strategies should include specific environmental management measures aimed at reducing local sources of microplastics, such as controlling waste disposal, mitigating surface runoff from roads and urban areas, and improving basic sanitation infrastructure.

Despite its contributions, this study has inherent limitations. First, the absence of microplastic data from environmental matrices (soil and water) in both mangroves and temporary wetlands prevents a direct assessment of the relationship between the contamination observed in rivulid fishes and the environmental availability of particles in these habitats. Second, the analysis includes only four species and four localities, which limits the extrapolation of the results to other systems and regions. Third, the sampling design has limited temporal resolution, as microplastic contamination can vary significantly across seasons (e.g., Cordeiro et al. 2026). Future studies encompassing a broader environmental, spatial, temporal, and taxonomic scope, including multiple environmental matrices, are needed to better contextualize the patterns observed in wetland fishes.

Conclusions

This first quantification of microplastics in Rivulidae fishes reveals widespread contamination—particles occurred in all four species and in 60.5% of individuals (1.58 ± 1.84 items fish^{-1})—with profiles dominated by $<1{,}000$ µm blue/black fragments and microfibers, chiefly polypropylene, poly(4-methyl-1-pentene) and PET. Contrary to H1, MP loads did not differ between mangroves and temporary ponds, nor with body size. Convergent functional traits of rivulids—small body and gape, generalist foraging, and routine use of shallow microhabitats where fibers and fragments accumulate—likely equalize ingestion probabilities across life histories. Collectively, these findings show that temporary wetlands are not refuges from plastic contamination, and should be explicitly included in monitoring and mitigation strategies that target diffuse, landscape-scale MP inputs.

Acknowledgements Special thanks to rivulid specialists Dr. Waldir Miron Berbel-Filho and Dr. Luis Esteban Krause Lanés, and the anonymous reviewers for their comments and suggestions to improve the manuscript. We also thank Dr. Igor Cavalcanti de Araújo Souto-Santos for assistance with fish sampling and identification. This study was funded by Fundo Brasileiro para a Biodiversidade – FUNBIO Conservando o Futuro, and Instituto HUMANIZE (Proc. # 028/2023), Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro (E-26/200.897/2021, E-26/210.103/2023), and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq 140.512/2022-5).

Author contributions G.H.S.G. conceived the study, conducted field sampling, curated and analyzed the data, wrote the original draft, and revised and edited the manuscript. L.C. and L.F.S.P.A. performed laboratory work, curated and analyzed data, contributed to the review of the literature and methods, and revised and edited the manuscript. F.G.A. supervised the research process, contributed to the theoretical framework, and revised and edited the manuscript. All authors read and approved the final manuscript.

Funding The Article Processing Charge (APC) for the publication of this research was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) (ROR identifier: 00x0ma614). Brazilian Biodivesity Fund

Data availability The datasets generated during the current study are available in Supplementary material 2.

Declarations

Competing interests The authors declare no competing interests.

References

Abrantes YG, Medeiros LS, Bennemann ABA, Bento DM, Teixeira FK, Rezende CF et al (2020) Geographic distribution and conservation of seasonal killifishes (Cyprinodontiformes, Rivulidae) from the Mid-Northeastern Caatinga ecoregion, northeastern Brazil. Neotrop Biol Conserv 15:301–315. https://doi.org/10.3897/neotropical.15.e51738

Allen S, Allen D, Phoenix VR et al (2019) Atmospheric transport and deposition of microplastics in a remote mountain catchment. Nat Geosci 12:339–344. https://doi.org/10.1038/s41561-019-0335-5

Alves VEN, Figueiredo GM (2023) Assessment of microplastic impacts on whitemouth croaker (*Micropogonias furnieri*) and ecosystem services in Guanabara Bay, Brazil. Environ Biol Fishes 106:2177–2192. https://doi.org/10.1007/s10641-023-01497-9

Amparo SZS, Carvalho LO, Silva GG et al (2023) Microplastics as contaminants in the Brazilian environment: an updated review. Environ Monit Assess 195:1414. https://doi.org/10.1007/s10661-023-12011-0

Andrade FN, Araujo FV (2025) An analysis of the legal and management aspects of plastic waste in Brazil. Sustain Futures 10:101120. https://doi.org/10.1016/j.sftr.2025.101120

Avise JC, Tatarenkov A (2015) Population genetics and evolution of the mangrove rivulus *Kryptolebias marmoratus*, the world's only self-fertilizing hermaphroditic vertebrate. J Fish Biol 87:519–538. https://doi.org/10.1111/jfb.12741

Berbel-Filho WM, Pacheco G, Tatarenkov A, Lira MG, Garcia de Leaniz C, Rodríguez López CM, Lima SMQ, Consuegra S (2022) Phylogenomics reveals extensive introgression and a case of mito-nuclear discordance in the killifish genus *Kryptolebias*. Mol Phylogenet Evol 177:107617. https://doi.org/10.1016/j.ympev.2022.107617

Boyer JJ, Brooks JM, Arias ME (2024) Microplastics in a large constructed wetland: retention, transport, and characteristics. Environ Eng Sci 41:1091–1102. https://doi.org/10.1089/ees.2024.0083

Brahney J, Hallerud M, Heim E, Hahnenberger M, Sukumaran S (2020) Plastic rain in protected areas of the United States. Science 368:1257–1260. https://doi.org/10.1126/science.aaz5819

Browne MA, Chapman MG, Thompson RC, Amaral Zettler LA, Jambeck J, Mallos NJ (2015) Spatial and temporal patterns of stranded intertidal marine debris: is there a picture of global change? Environ Sci Technol 49:7082–7094. https://doi.org/10.1021/es5060572

Carrillo MS, Archuby DI, Lunardelli M, Castresana G, Montalti D, Ibañez AE (2025) Dynamics of microplastic transfer through the food web in a migratory seabird. Environ Pollut 383:126784. https://doi.org/10.1016/j.envpol.2025.126784

Contente R, Stefanoni M (2010) Diet of the Atlantic rainforest killifish *Rivulus santensis* (Rivulidae, Cyprinodontiformes) in Southeastern Brazil. J Appl Ichthyol 26:930–932. https://doi.org/10.1111/j.1439-0426.2010.01465.x

Cordeiro L, Sorrentino R, Guedes GHS, Azeredo LFSP, Araújo FG (2026) Influence of biological, ecological, and anthropogenic factors on microplastic contamination in coastal fishes from Southeastern Brazil. Environ Biol Fish 109:82. https://doi.org/10.1007/s10641-026-01845-5

Costa JHA, Souza UP, Selinger A, Vidal TA, Langeani F, Duarte RM (2024) Rediscovery of the critically endangered annual killifish *Leptopanchax itanhaensis* (Costa, 2008) in a temporary pool and roadside ditch from the Atlantic Forest of Southeast Brazil. Biota Neotrop 24:e20241637. https://doi.org/10.1590/1676-0611-BN-2024-1637

Dalvand M, Hamidian AH (2023) Occurrence and distribution of microplastics in wetlands. Sci Total Environ 862:160740. https://doi.org/10.1016/j.scitotenv.2022.160740

Deakin K, Porter A, Osorio Baquero A, Lewis C (2025) Plastic pollution in mangrove ecosystems: a global meta-analysis. Mar Pollut Bull 218:118165. https://doi.org/10.1016/j.marpolbul.2025.118165

Dekiff JH, Remy D, Klasmeier J, Fries E (2014) Occurrence and spatial distribution of microplastics in sediments from Norderney. Environ Pollut 186:248–256. https://doi.org/10.1016/j.envpol.2013.11.019

Ding J et al (2023) Elder fish means more microplastics? Alaska pollock microplastic story in the Bering Sea. Sci Adv 9:eadf5897. https://doi.org/10.1126/sciadv.adf5897

Dong J, Zhao T, Wang Y, Zhao S, Zhu L, Li H, Wang M, An L (2024) Microplastic characteristics in rain/snow sampled from two northern Chinese cities. Sci Total Environ 956:177352. https://doi.org/10.1016/j.scitotenv.2024.177352

Drabinski TL, de Carvalho DG, Gaylarde CC, Lourenço MFP, Machado WTV, da Fonseca EM, da Silva ALC, Baptista Neto JA (2023) Microplastics in freshwater river in Rio de Janeiro and its role as a source of microplastic pollution in Guanabara Bay, SE Brazil. Micro 3:208–223. https://doi.org/10.3390/micro3010015

Elnahas A, Gray A, Lee J, AlAmiri N, Pokhrel N, Allen S, Foroutan H (2024) Atmospheric deposition of microplastics in South Central Appalachia in the United States. ACS ES&T Air 2:64–72. https://doi.org/10.1021/acsestair.4c00189

Fricke R, Eschmeyer WN, Van der Laan R (2025) Eschmeyer's catalog of fishes. California Academy of Science. https://www.calacademy.org/scientists/projects/eschmeyers-catalog-of-fishes. Accessed 7 Ago 2025

Furness AI (2016) The evolution of an annual life cycle in killifish: adaptation to ephemeral aquatic environments through embryonic diapause. Biol Rev 91:796–812. https://doi.org/10.1111/brv.12194

Furness AI, Reznick DN, Tatarenkov A, Avise J (2018) The evolution of diapause in *Rivulus* (*Laimosemion*). Zool J Linn Soc 184(3):773–790. https://doi.org/10.1093/zoolinnean/zly021

Geyer R et al (2017) Production, use, and fate of all plastics ever made. Sci Adv 3:e1700782. https://doi.org/10.1126/sciadv.1700782

Godoy RS, Weber V, Lanés LEK, Castro BD, Oliveira GT, Arenzon A et al (2025) Early post-hatching sensitivity of a Neotropical annual killifish to glyphosate-based-herbicide. Toxicol Environ Chem 107(7):1322–1338. https://doi.org/10.1080/02772248.2025.2527648

Gonçalves CS, Souza UP, Volcan MV (2011) The opportunistic feeding and reproduction strategies of the annual fish *Cynopoecilus melanotaenia* (Cyprinodontiformes: Rivulidae) inhabiting ephemeral habitats in southern Brazil. Neotrop Ichthyol 9:191–200. https://doi.org/10.1590/S1679-62252011000100019

Guedes GHS, Araújo FG (2026) Water and fire: wildfires threaten fish habitats across Brazilian biomes, and protected areas offer insufficient safeguards. Biol Conserv 315:111692. https://doi.org/10.1016/j.biocon.2025.111692

Guedes GHS, Salgado FLK, Uehara W, Ferreira DLP, Araújo FG (2020) The recapture of *Leptopanchax opalescens* (Aplocheiloidei: Rivulidae), a critically endangered seasonal killifish: habitat and aspects of population structure. Zoologia 37:e54982. https://doi.org/10.3897/zoologia.37.e54982

Guedes GHS, Gomes ID, do Nascimento AA, Azevedo MCC, Souto-Santos ICA, Buckup BA, Araújo FG (2023a) Reproductive strategy of the annual fish *Leptopanchax opalescens* (Rivulidae) and trade-off between egg size and maximum body length in temporary wetlands. Wetlands 43:29. https://doi.org/10.1007/s13157-023-01680-9

Guedes GHS, Luz CHP, Mazzoni R, Lira FO, Araújo FG (2023b) New occurrences of the endangered *Nothobranchius minimus*...

Guedes GHS, Luz CHP, Mazzoni R, Lira FO, Araújo FG (2023b) New occurrences of the endangered *Notholebias minimus* (Cyprinodontiformes: Rivulidae) in coastal plains of the State of Rio de Janeiro, Brazil: populations features and conservation. Neotrop Ichthyol 21:e230013. https://doi.org/10.1590/1982-0224-2023-0013

Guedes GHS, Santangelo JM, Pires APF, Araújo FG (2025) β-diversity scaling patterns across different bioregionalisations for a megadiverse Neotropical fish family. J Biogeogr 52:e15088. https://doi.org/10.1111/jbi.15088

Hartz L, Grabinski L, Salameh S (2025) Microplastic pollution in aquatic environments: a meta-analysis of influencing factors and methodological recommendations. Front Environ Sci 13:1600570. https://doi.org/10.3389/fenvs.2025.1600570

Hidalgo-Ruz V, Gutow L, Thompson RC, Thiel M (2012) Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ Sci Technol 46(6):3060–3075. https://doi.org/10.1021/es2031505

Hinncands D, Lara NFR, Garcia ICB, Polaz CNM (2025) Ecologia reprodutiva de *Hypsolebias auratus*, um peixe-anual do Cerrado: subsídios para o manejo conservacionista. Biodivers Bras 15(1):54–70. https://doi.org/10.37002/biodiversidadebrasileira.v15i1.2366

Hou L, McMahan CD, McNeish RE, Munno K, Rochman CM, Hoellein TJ (2021) A fish tale: a century of museum specimens reveal increasing microplastic concentrations in freshwater fish. Ecol Appl 31:e02320. https://doi.org/10.1002/eap.2320

Hu CK, Wang W, Brind'Amour J, Singh PP, Reeves GA, Lorincz MC et al (2020) Vertebrate diapause preserves organisms long term through Polycomb complex members. Science 367:870–874. https://doi.org/10.1126/science.aaw2601 IUCN (2026) The IUCN Red List of Threatened Species. Version 2025–2. https://www.iucnredlist.org

ICMBio (2026) Sistema de Avaliação do Risco de Extinção da Biodiversidade – SALVE. https://salve.icmbio.gov.br

Jaiswal PK, Singh R, Kumar S et al (2026) Assessment of microplastic pollution load in road dust and associated health risk in a semi-arid region of Rajasthan, India. Environ Sustain 9:131–152. https://doi.org/10.1007/s42398-025-00370-y

Jo AH, Yu YB, Choi JH, Lee JH, Choi CY, Kang JC, Kim JH (2025) Microplastics induce toxic effects in fish: bioaccumulation, hematological parameters and antioxidant responses. Chemosphere 375:144253. https://doi.org/10.1016/j.chemosphere.2025.144253

Jolaosho TL, Rasaq MF, Omotoye EV, Araomo OV, Adekoya OS, Abolaji OY, Hungbo JJ (2025) Microplastics in freshwater and marine ecosystems: occurrence, characterization, sources, distribution dynamics, fate, transport processes, potential mitigation strategies, and policy interventions. Ecotoxicol Environ Saf 294:118036. https://doi.org/10.1016/j.ecoenv.2025.118036

Karak P, Parveen A, Modak A, Adhikari A, Chakrabortty S (2025) Microplastic pollution: a global environmental crisis impacting marine life, human health, and potential innovative sustainable solutions. Int J Environ Res Public Health 22:889. https://doi.org/10.3390/ijerph22060889

Lanés LEK, Volcan MV, Maltchik L (2021) Two new annual fishes (Cyprinodontiformes: Rivulidae) unexpectedly discovered in the highlands of southern Brazil. Zootaxa 4949:499–520. https://doi.org/10.11646/zootaxa.4949.3.4

Leslie HA, Van Velzen MJ, Brandsma SH, Vethaak AD, Garcia-Vallejo JJ, Lamoree MH (2022) Discovery and quantification of plastic particle pollution in human blood. Environ Int 163:107199. https://doi.org/10.1016/j.envint.2022.107199

Li NY, Zhong B, Guo Y, Li XX, Yang Z, He YX (2024) Non-negligible impact of microplastics on wetland ecosystems. Sci Total Environ 924:171252. https://doi.org/10.1016/j.scitotenv.2024.171252

Lim KP, Lim PE, Yusoff S, Sun C, Ding J, Loh KH (2022) A meta-analysis of the characterisations of plastic ingested by fish globally. Toxics 10:186. https://doi.org/10.3390/toxics10040186

Loureiro M, Sá RO, Serra SW, Alonso F, Lanés LEK, Volcan MV, Calviño PA, Nielsen D, Duarte A, García G (2018) Review of the family Rivulidae (Cyprinodontiformes, Aplocheiloidei) and a molecular and morphological phylogeny of the annual fish genus *Austrolebias* Costa 1998. Neotrop Ichthyol 16:1–20. https://doi.org/10.1590/1982-0224-20180007

Lusher AL, Brate ILN, Welden NA (2020) Is or isn't it: the importance of visual classification in microplastic characterization. Appl Spectrosc 74:1139–1153. https://doi.org/10.1177/0003702820930733

Moreira MF, Leal CG, Pompeu PS (2025) Trends and gaps in microplastics research in tropical freshwater ecosystems. An Acad Bras Cienc 97:e20241229. https://doi.org/10.1590/0001-3765202520241229

Myers N, Mittermeier RA, Mittermeier CG, Da Fonseca GA, Kent J (2000) Biodiversity hotspots for conservation priorities. Nature 403:853–858. https://doi.org/10.1038/35002501

Napper IE, Davies BFR, Clifford H, Elvin S, Koldewey HJ, Clark PF, Waluda CM, Thompson RC, Maddaloni M (2020) Reaching new heights in plastic pollution—preliminary findings of microplastics on Mount Everest. One Earth 3:621–630. https://doi.org/10.1016/j.oneear.2020.10.020

Ory NC, Sobral P, Ferreira JL, Thiel M (2017) Amberstripe scad *Decapterus muroadsi* (Carangidae) fish ingest blue microplastics resembling their copepod prey along the coast of Rapa Nui (Easter Island) in the South Pacific subtropical gyre. Sci Total Environ 586:430–437. https://doi.org/10.1016/j.scitotenv.2017.01.175

Oza J, Rabari V, Yadav VK, Sahoo DK, Patel A, Trivedi J (2024) A systematic review on microplastic contamination in fishes of Asia: polymeric risk assessment and future prospectives. Environ Toxicol Chem 43:671–685. https://doi.org/10.1002/etc.5821

Paduani M (2020) Microplastics as novel sedimentary particles in coastal wetlands: a review. Mar Pollut Bull 161:111739. https://doi.org/10.1016/j.marpolbul.2020.111739

Peng G, Bellerby R, Zhang F, Sun X, Li D (2020) The ocean's ultimate trashcan: hadal trenches as major depositories for plastic pollution. Water Res 168:115121. https://doi.org/10.1016/j.watres.2019.115121

Podrabsky JE, Riggs CL, Wagner JT (2016) Tolerance of environmental stress. In: Berois N, García G, de Sá RO (eds) Annual fishes: life history strategy, diversity, and evolution. CRC Press, Boca Ratón, pp 160–180. https://doi.org/10.1201/b19016

Polačik M, Podrabsky JE (2015) Temporary environments. In: Riesch R, Tobler M, Plath M (eds) Extremophile fishes. Springer, Cham, pp 271–305. https://doi.org/10.1007/978-3-319-13362-1_10

Qian J, Tang S, Wang P, Lu B, Li K, Jin W, He X (2021) From source to sink: review and prospects of microplastics in wetland ecosystems. Sci Total Environ 758:143633. https://doi.org/10.1016/j.scitotenv.2020.143633

Qiao K, Wang WX (2024) The dual role of coastal mangroves: sinks and sources of microplastics in rapidly urbanizing areas. J Hazard Mater 480:136408. https://doi.org/10.1016/j.jhazmat.2024.136408

Rhee JS, Choi BS, Kim J, Kim BM, Lee YM, Kim IC et al (2017) Diversity, distribution, and significance of transposable elements in the genome of the only selfing hermaphroditic vertebrate *Kryptolebias marmoratus*. Sci Rep 7:40121. https://doi.org/10.1038/srep40121

Roch S, Friedrich C, Brinker A (2020) Uptake routes of microplastics in fishes: practical and theoretical approaches to test existing theories. Sci Rep 10:3896. https://doi.org/10.1038/s41598-020-60630-1

Sacco VA, Zuanazzi NR, Selinger A, da Costa JHA, Lemunie ÉS, Comelli CL et al (2024) What are the global patterns of microplastic ingestion by fish? A scientometric review. Environ Pollut 350:123972. https://doi.org/10.1016/j.envpol.2024.123972

Semensatto D, Passos CC, Bicalho CS, Mendes-Silva LP, Labuto G (2025) Methodological similarities and discrepancies among studies on microplastics in South American continental aquatic environments. An Acad Bras Cienc 97:e20241459. https://doi.org/10.1590/0001-3765202520241459

Sequeira IF, Prata JC, da Costa JP, Duarte AC, Rocha-Santos T (2020) Worldwide contamination of fish with microplastics: a brief global overview. Mar Pollut Bull 160:111681. https://doi.org/10.1016/j.marpolbul.2020.111681

Siddique MAM, Shazada NE, Ritu JA, Turjo KEZ, Das K (2024) Does the mouth size influence microplastic ingestion in fishes? Mar Pollut Bull 198:115861. https://doi.org/10.1016/j.marpolbul.2023.115861

Taylor DS (2012) Twenty-four years in the mud: what have we learned about the natural history and ecology of the mangrove rivulus, *Kryptolebias marmoratus*? Integr Comp Biol 52:724–736. https://doi.org/10.1093/icb/ics062

Turko AJ, Wright PA (2015) Evolution, ecology and physiology of amphibious killifishes (Cyprinodontiformes). J Fish Biol 87:815–835. https://doi.org/10.1111/jfb.12758

Wang T, Wang L, Chen Q, Kalogerakis N, Ji R, Ma Y (2020) Interactions between microplastics and organic pollutants: effects on toxicity, bioaccumulation, degradation, and transport. Sci Total Environ 748:142427. https://doi.org/10.1016/j.scitotenv.2020.142427

Wang J, Wu F, Dong S, Wang X, Ai S, Liu Z, Wang X (2024) Meta-analysis of the effects of microplastic on fish: insights into growth, survival, reproduction, oxidative stress, and gut microbiota diversity. Water Res 267:122493. https://doi.org/10.1016/j.watres.2024.122493

Wright AP (2012) Environmental physiology of the Mangrove Rivulus, *Kryptolebias marmoratus*, a cutaneously breathing fish that survives for weeks out of water. Integr Comp Biol 52:792–800. https://doi.org/10.1093/icb/ics091

Yagi M, Ono Y, Kawaguchi T (2022) Microplastic pollution in aquatic environments may facilitate misfeeding by fish. Environ Pollut 315:120457. https://doi.org/10.1016/j.envpol.2022.120457

Žák J, Vrtílek M, Polačik M, Blažek R, Reichard M (2021) Short-lived fishes: annual and multivoltine strategies. Fish Fish 22:546–561. https://doi.org/10.1111/faf.12535

Zebral YD, Lansini LR, Costa PG, Roza M, Bianchini A, Robaldo RB (2018) A glyphosate-based herbicide reduces fertility, embryonic upper thermal tolerance and alters embryonic diapause of the threatened annual fish *Austrolebias nigrofasciatus*. Chemosphere 196:260–269. https://doi.org/10.1016/j.chemosphere.2017.12.196

Zhao YX, Song KW, Li WJ et al (2026) Migration, transformation, and ecological effects of microplastics in aquatic ecosystems. Ecol Process 15:28. https://doi.org/10.1186/s13717-026-00681-w