UNIVERSIDADE ESTADUAL DE MARINGÁ
CENTRO DE CIÊNCIAS BIOLÓGICAS
DEPARTAMENTO DE BIOLOGIA
PROGRAMA DE PÓS-GRADUAÇÃO EM ECOLOGIA DE AMBIENTES AQUÁTICOS CONTINENTAIS

KÁTIA YASUKO YOFUKUJI

Foraging in the Anthropocene: exploring the dynamics of reservoir and plastic pollution in freshwater organisms

Maringá
2024

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Tese apresentada ao Programa de Pós-Graduação em Ecologia de Ambientes Aquáticos Continentais do Departamento de Biologia, Centro de Ciências Biológicas da Universidade Estadual de Maringá, como requisito parcial para obtenção do título de Doutora em Ecologia e Limnologia.
Área de concentração: Ecologia e Limnologia

Orientadora: Dr.ª Rosemara Fugi

Maringá
2024

"Dados Internacionais de Catalogação na Publicação (CIP)"
(Biblioteca Setorial - UEM. Nupélia, Maringá, PR, Brasil)

Y54f

Yofukuji, Kátia Yasuko, 1996-
Foraging in the Anthropocene: exploring the dynamics of reservoir and plastic pollution in freshwater organisms / Kátia Yasuko Yofukuji. -- Maringá, 2024.
148 f. : il. (algumas color.).

Tese (doutorado em Ecologia de Ambientes Aquáticos Continentais)--Universidade Estadual de Maringá, Dep. de Biologia, 2024.
Orientadora: Dr.ª Rosemara Fugi.

1. Peixes de água doce - Cadeia trófica - Represamento de rios - Reservatório de Itaipu - Impactos ambientais - Paraná (Estado). 2. Peixes de água doce - Cadeia trófica - Poluição por plásticos - Reservatório de Itaipu - Impactos ambientais - Paraná (Estado). 3. Invertebrados de água doce - Cadeia trófica - Represamento de rios - Reservatório de Itaipu - Impactos ambientais - Paraná (Estado). 4. Ecologia trófica – Microplásticos - Represamento de rios - Impactos ambientais. I. Universidade Estadual de Maringá. Departamento de Biologia. Programa de Pós-Graduação em Ecologia de Ambientes Aquáticos Continentais.

CDD 23. ed. -597.176427098162

Maria Salete Ribelatto Arita CRB 9/858
João Fábio Hildebrandt CRB 9/1140

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BANCA EXAMINADORA

Dr.ª Rosemara Fugi
Nupélia/Universidade Estadual de Maringá (Presidente)

Prof. Dr. David Valença Dantas
Universidade do Estado de Santa Catarina (UDESC)

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Nupélia/Universidade Estadual de Maringá (UEM)

Prof. Dr. Angelo Antônio Agostinho
Nupélia/Universidade Estadual de Maringá (UEM)

Aprovada em: 27 de fevereiro de 2024.
Local de defesa: Anfiteatro Prof. “Yoshiaki Fukushigue”, Bloco E-90, *campus* da Universidade Estadual de Maringá.

AGRADECIMENTOS

Ainda que esta tese tenha sido escrita por um par de mãos, inúmeros pares foram necessários para que eu chegasse até aqui. Todos os trabalhos desenvolvidos que compõe esta tese só foram possíveis graças a uma rede de pessoas, instituições e circunstâncias. Sendo assim, deixo os meus mais sinceros e profundos agradecimentos a todos que permitiram que eu trilhasse e escrevesse mais esse capítulo na minha trajetória.

Agradeço aos meus pais, especialmente à minha mãe, pelo amor e apoio irrestrito em todas as decisões que me levaram até aqui. Nunca imaginei chegar aonde estou, e só cheguei graças a vocês.

Agradeço ao meu companheiro e duplinha, Henrique, por todo apoio, amor, cumplicidade, e por sempre me fazer acreditar que eu seria capaz de finalizar essa tese, mesmo quando não parecia possível. Obrigada por ensolarar os meus dias mais nublados e partilhar as conquistas e derrotas, risos e choros.

Agradeço a minha orientadora, Ro, por ter me orientado durante essa jornada. Obrigada por ter aceitado me orientar ainda no mestrado, quando nem me conhecia. Agradeço todas as oportunidades, incentivo e confiança depositada em mim. Mas para além disso, sou profundamente grata por ter me permitido me reinventar várias vezes ao longo do doutorado. Sou muito feliz de ter crescido tanto, pessoal e profissionalmente, no seu laboratório, que é um exemplo de cooperação.

Aos meus companheiros de laboratório: Ana, Ba, Isa, Karis, Luana, Matheus e Thiago. Obrigada por me ensinarem tanto, pelas risadas, confidências, dias do bolo. Agradeço a parceria nos trabalhos e na vida.

A Ana Lúcia Paz Cardozo, por todo o companheirismo nessa jornada, por sermos Chris & Greg. Sou muito grata pelos nossos caminhos terem se cruzado. Sem dúvidas, essa tese não teria saído sem você minha amiga. Todos os perrengues (inclusive internacional), aventuras, conquistas, choros, surtos, e pão de queijo da vendinha, foram primordiais para tornar o caminho mais leve e passível de ser trilhado. Obrigada por toda contribuição, apoio emocional, críticas construtivas. Muito dessa tese é sua também.

Agradeço ao meu amigo Gabriel Arndt por ter sido apoio fundamental durante uma pandemia global. Sou grata pela nossa amizade, por ter me apresentado o melhor salgadinho frito, pelas confidências, apoio psicológico e muuuitas horas de passeio com os cachorros.

Agradeço aos meus amigos Sabrina, Lari, Japa e Le, por se fazerem presentes na minha vida.

Ao amor mais incondicional que eu pude sentir, meu cachorro Tofu. Embora nunca chegue a ler, obrigada por ter sido o motivo de eu levantar da cama inúmeras vezes, quando achei que não conseguiria.

Aos professores do PEA/Nupélia, que tiveram contribuições diretas ou indiretas na minha formação profissional e científica, pelo exemplo de ética e dedicação a pesquisa e formação de novos pesquisadores.

Ao professor Dr. Roger pelo auxílio e apoio para a mobilidade internacional, que agregou conhecimento pessoal e profissional.

Ao Dr. Martin Blettler, e seu laboratório, que me receberam para o estágio na Argentina e contribuiu com vários “insights” desta tese e em conhecimento prático da área. Muchas gracias!

Agradeço à Bete, por toda dedicação, auxílio e apoio em todas as etapas do doutorado. Muito obrigada por toda ajuda e por ouvir todas (e muitas) dúvidas que foram surgindo nesse período, sua paciência e apoio foram fundamentais para finalizar este doutorado.

Agradeço a toda equipe técnica do PEA/Nupélia, que tornam possível as diferentes atividades pertinentes (ou não) ao doutorado. Em especial a Marlyze e Norton, pela prontidão e suporte; a Salete e ao João pela dedicação a Biblioteca Setorial do Nupélia e ao apoio sempre que solicitado.

A todos os funcionários que participaram das coletas e triagem dos peixes do reservatório de Itaipu, que foram fundamentais para a realização dos manuscritos. Em especial a Cintia e Rosi, pela ajuda na triagem dos peixes e pela disposição em auxiliarem no que fosse preciso. E ao Tato, pelo apoio emocional durante a minha primeira coleta “sozinha”.

A todos os coautores que participaram dos manuscritos da tese, e de outros trabalhos desenvolvidos e publicados durante o doutorado.

Aos membros da banca avaliadora por aceitarem de prontidão o convite e contribuírem com o trabalho.

Ao PEA, ao Nupélia, a UEM por todas as oportunidades, pelo apoio e infraestrutura, que possibilitaram as coletas e as análises laboratoriais.

A CAPES pela bolsa concedida e pelo financiamento do projeto de pesquisa.

À Fundação Araucária pelo apoio financeiro durante minha visita a Argentina.

Forrageando no Antropoceno: explorando as dinâmicas de reservatórios e poluição plástica em organismos de água doce

RESUMO

Os ecossistemas de água doce enfrentam sérias ameaças em um mundo cada vez mais dominado pelo homem, especialmente devido a pressões como o represamento e a poluição plástica. Ambas as perturbações antrópicas têm sido associadas ao declínio global das áreas de água doce e da biodiversidade. Avaliar como esses distúrbios afetam os organismos é de extrema importância para fins de conservação e implementação de políticas públicas e estratégias de gestão eficazes. Avaliou-se os efeitos do represamento de rios e (ii) a poluição plástica através da lente da ecologia trófica dos peixes. Realizou-se uma síntese global para desvendar o conhecimento atual sobre a ocorrência de plástico em peixes e invertebrados de água doce. Investigou-se a ecologia trófica de peixes do reservatório de Itaipu, revelando mudanças na dieta e na estrutura trófica ao longo de gradientes longitudinais induzidos pelo represamento. A transição de recursos predominantemente alóctones para recursos autóctones influenciou significativamente a distribuição espacial das guildas tróficas ao longo do reservatório. Houve mudanças nas guildas dominantes com o envelhecimento do reservatório, particularmente a ascensão e queda de planctívoros e insetívoros aquáticos. Avaliou-se a ocorrência de microplásticos em uma comunidade de peixes neotropicais. O estudo constatou baixa incidência geral de ingestão de plástico, com fibras e fragmentos de plástico identificados como poliamida, poliestireno e polietileno. Peixes da zona lacustre, insetívoros e espécies bentopelágicas apresentaram relação significativa com a ingestão de plástico. Realizou-se uma revisão sistemática que sintetiza a literatura sobre a ocorrência de plástico em peixes e invertebrados de água doce em todo o mundo. Destaca-se que os estudos sobre a ocorrência de plástico se concentraram principalmente nos peixes, com esforços recentes reconhecendo a ameaça aos invertebrados. Explorou-se fatores biológicos e ecológicos que influenciam a prevalência de plástico, revelando um poder preditivo limitado para o aumento da ocorrência de plástico em ambos os grupos, enfatizando a vulnerabilidade de ambos os táxons à poluição plástica. Destaca-se a necessidade crítica de compreender e abordar os impactos do represamento e da poluição plástica nos ecossistemas de água doce para, em última análise, salvaguardar a biodiversidade.

Palavras-chave: represamento de rios; poluição plástica; impacto humano; ecologia trófica; peixe de água doce; invertebrados.

Foraging in the Anthropocene: exploring the dynamics of reservoir and plastic pollution in freshwater organisms

ABSTRACT

Freshwater ecosystems face serious threats in our increasingly human-dominated world, particularly from pressures such as impoundment and plastic pollution due to mismanagement of plastic waste. Both anthropic disturbances have been linked to global declines in freshwater area and biodiversity. Evaluating how these disturbances affect organisms is of extremely importance for conservation purposes and the implementation of effective public policies and management strategies. The effects of river impoundment and plastic pollution through the lens of fish trophic ecology were assessed. A global synthesis was conducted to unravel the current knowledge on plastic occurrence regarding freshwater fish and invertebrates. The trophic ecology of fish from the Itaipu reservoir was assessed, revealing shifts in diet and trophic structure along longitudinal gradients induced by damming. The transition from predominantly allochthonous to autochthonous resources significantly influenced the spatial distribution of trophic guilds across the reservoir. We highlighted changes in dominant guilds with the reservoir's aging, particularly the rise and fall of planktivores and aquatic insectivores. Microplastic occurrence in a Neotropical fish community was evaluated. Low incidence of plastic ingestion was evident, with fibers and fragments of plastics identified as polyamide, polystyrene, and polyethylene. Fish from the lacustrine zone, insectivores, and benthopelagic species showed a significant correlation with plastic ingestion. A systematic review synthesizing literature on plastic occurrence in freshwater fish and invertebrates was conducted globally. It was highlighted that reporting on plastic occurrence has primarily focused on fish, with recent efforts acknowledging the threat to invertebrates. Biological and ecological factors were explored to influence plastic prevalence, revealing limited predictive power for increased plastic occurrence in both groups, emphasizing the vulnerability of both taxa to plastic pollution. We emphasize the critical need to understand and address the impacts of impoundment and plastic pollution on freshwater ecosystems to ultimately safeguard freshwater biodiversity.

Keywords: river impoundment; plastic pollution; human impact; trophic ecology; freshwater fish; invertebrates.

Tese elaborada e formatada conforme as
normas das publicações científicas:

Ecology of Freshwater Fish. Disponível em: <https://onlinelibrary.wiley.com/page/journal/16000633/homepage/forauthors.html>

Water, Air, & Soil Pollution. Aceito em 12/01/2024 (os direitos autorais pertencem a revista). O artigo está disponível em: https://doi.org/10.1007/s11270-024-06911-1

Hydrobiologia. Disponível em: <https://www.springer.com/journal/10750/submissionguidelines#Instructions%20for%20Authors>

SUMÁRIO

1 GENERAL INTRODUCTION

In an increasingly human-dominated planet, many ecosystem level processes are remarkably jeopardized by human activities. At a global scale, freshwater ecosystems are the most threatened, especially when considering that inland waters cover a minor portion of the Earth's surface (Downing et al. 2006). Freshwaters and freshwater biodiversity are valuable to humankind because the goods and services it provides, ultimately assuring for our well-being and survival. The benefits that freshwater provides for humanity, namely ecosystem services, can be many. Some are directly provided within rivers, such as the case of hydroelectricity, supply of drinking water, fisheries; and others such as recreational activities, regulation of ecosystem processes and habitat provision (Hanna et al. 2017; Vári et al. 2021). Despite these crucial contributions, human pressures have led to global declines in freshwater area and unprecedented rates of biodiversity extinction (Vrösömarty et al. 2010; Dudgeon 2019; Reid et al. 2019).

Freshwaters are under multiple stressors across spatial scales and ecosystem types (i.e. lakes, rivers, floodplains, wetlands), which threatens water, food security, and biodiversity. In a recent review by Dudgeon (2019), he identified six threats that imperil freshwater biodiversity, in which flow regulation and pollution were two leading causes of population declines worldwide. For instance, as human population is growing rapidly, two pervasive outcomes are inherent: demand for hydroelectricity and plastic pollution by waste mismanagement (Dudgeon et al. 2019; Ahmed et al. 2022). River impoundment has been widely investigated, and its myriad of impacts are well-established, but plastic pollution, although only recently on the spotlight, have concerned researchers globally regarding the effects it can have on ecosystems and animals (Blettler et al. 2018). To what extent these impacts can be related needs further investigation. So, the idea explored in this thesis was based on assessing the impact of river impoundment and plastic pollution through the lens of trophic ecology.

The construction of dams drastically alters the riverine ecosystem where it is constructed, by severely regulating the river flow, causing the loss and fragmentation of habitats, changes in limnological conditions and spatial heterogeneity (Poff et al. 1997; Poff and Zimmerman 2010). This new ecosystem can transit from a more lotic condition, close to the free-flowing river, to a lacustrine section near the dam, impacting the productivity dynamics, nutrient cycling, and the distribution of biota in space (Thornton et al. 1990; Agostinho et al. 2016; Carneiro and Bini 2020). These changes can affect resource availability, suitability of habitats, and alter trophic dynamics with consequences for the community of fish and other animals.

On the other hand, plastic pollution is ubiquitous in inland waters, and their associated biota is at high risk to interact with this hazardous material (Blettler et al., 2018; Azevedo-Santos et al. 2021). Plastic can be entrapped and persist in the environment for decades, and fragment into multiple sizes and shapes, increasing availability for freshwater animals (Barnes et al. 2009). Because of this inherent feature, its widespread presence across the globe is undeniable, and several factors have been investigated to understand the threat they pose to animals. Fish and invertebrates can uptake plastic, and factors like trophic guilds, use of habitat, and behavior have been suggested to predict the intake of plastics by organisms (Bertoli et al. 2022; Cardozo et al. 2023). Other factors as urbanization (da Costa et al. 2023), seasonality, hydrological dynamics (van Emmerik et al. 2023), and ecosystem type (i.e river, lakes, reservoirs; Guo et al. 2021) has been pointed out to influence the dynamics of plastic distribution and availability to animals.

These two impacts can be assessed through the lens of trophic ecology. Utilizing diet composition, trophic guilds, and trophic structure of the community can serve as proxies of environmental changes (El-Sabaawi, 2018) and aid in detecting plastic pollution (Fossi et al. 2018). For example, the use of fish diet can serve as proxy to detect changes in other communities, like invertebrates that can serve as prey for fish (Wang et al. 2018). This evaluation can be an early alarming to the rise or extinction of some species, whether of fish themselves or other prey animals. The guild-based approach is promising to aggregate taxonomic distinct species that share similar resources, and ultimately allows comparisons across locations and environments. Finally, the trophic structure of the community is helpful to illustrate fluctuations in abundance, biomass, and richness of species affected by river damming and associated reservoirs (Delariva et al. 2013; Dias et al. 2020).

Thus, this thesis compiles three studies that evaluated (i) the impact of reservoir on fish trophic ecology, (ii) the influence of the reservoir on plastic ingestion by fish and (iii) a global synthesis of plastic pollution on fish and invertebrates from freshwater ecosystems. The first and second approaches were conducted in the Itaipu reservoir. In the first study we assessed the diet, trophic guilds, and trophic structure of the fish community across the longitudinal axis of the reservoir. We also compared the current trophic guilds and trophic structure to the fish community described by Hahn et al. (1998) in the first years after the formation of the Itaipu reservoir. The second study investigated whether fish from the Itaipu reservoir were ingesting plastic, exploring the influence of reservoir longitudinal zonation and intrinsic fish characteristics (such as trophic guilds and habitat use) on plastic ingestion. Finally, we conducted a global synthesis concerning the current knowledge on plastic occurrence regarding freshwater fish and invertebrates. We considered various factors that could influence the presence of this pervasive pollutant, including the sampling environment, trophic guild, habitat use, body part assessed, body length, body weight, and plastic size.

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2 DIET AND TROPHIC STRUCTURE OF FISH IN THE ITAIPU RESERVOIR: SHIFTS AFTER 37 YEARS OF IMPOUNDMENT

ABSTRACT

River systems are characterized by the presence of longitudinal processes that shape fish assemblages. However, dam construction is disrupting these processes all over the world. Here, we assessed the trophic ecology of fish surveyed from the Itaipu reservoir, describing the current patterns of fish diet, as well as the trophic guilds and trophic structure of fish assemblages from fluvial to lacustrine zones. We also compared the current trophic guilds and trophic structure to the fish community from early post-impoundment period. We analyzed the stomach contents of fish species and grouped them into 12 trophic guilds, revealing shifts in diets and trophic structure along longitudinal gradients induced by damming. Use of resources transitioned from predominantly allochthonous (fluvial zone) to autochthonous resources (lacustrine zone), which notably influenced the spatial distribution of trophic guilds across the reservoir. Fluvial and intermediate zones shared a similar trophic structure characterized by dominance of herbivore, piscivore and terrestrial insectivore, while the lacustrine zone exhibited dominance by detritivore, piscivore, and omnivore guilds. Furthermore, we showed that as the reservoir aged, there was a shift in dominant guilds in terms of abundance and biomass, particularly the rise (early years) and fall of the planktivore group, and to a lesser extent, the fall of the aquatic insectivores.

***Keywords*:** Freshwater Environment; Aquatic Pollution; Anthropic Impacts; Upper Paraná River; Feeding Ecology; Top Predators.

2.1 Introduction

Studies on fish trophic ecology are essential to understand the relationships among species in ecosystems, particularly of those affected by human-induced alterations, like reservoirs (El-Sabaawi, 2018; Oliveira et al. 2021). The complexities of dietary interactions and trophic structure are critical factors for understanding the underlying mechanisms governing the distribution, abundance, and coexistence of species (Barili et al. 2012; Neves et al., 2021). Examining the changing fish trophic dynamics in response to shifts in resource through spatial and temporal scales provides insights into fish distribution and resources availability (Wang et al., 2018), which contribute to addressing pressing concerns as effective fish management and conservation. The links between fish groups sharing similar feeding habits, and their utilized prey, are crucial in newly disturbed habitats (Wang et al., 2018; Miranda et al., 2019), once fish are subjected to two situations: either they find the resources they are adapted to or may adapt to explore new prey (Albrecht & Pellegrini-Caramaschi, 2003; Dias et al., 2020).

In a rapidly changing world, riverine ecosystems face several challenges, and the construction of reservoirs for hydropower generation and water supply lead to extreme negative threats for freshwater fish biodiversity (Agostinho et al., 2008; 2016; Arantes et al., 2019). Dams have significant environmental consequences, among others, such as habitat fragmentation, declining biodiversity and impeding fish movement along longitudinal scales (Pompeu et al., 2012; Reid et al., 2018). Globally, studies have estimated that 63% of long rivers (>1.000 km) are no longer free flowing over their entire length (Grill et al., 2019), mainly due to river impoundments (Zarfl et al., 2015; Winemiller et al., 2016). Large scale reservoirs can profoundly change riverine ecosystems by controlling the water flow, productive dynamics (matter and energy), nutrient cycling and altering the distribution of biota in space and time (Poff et al., 1997; Poff & Zimmerman, 2010). Often, they can present spatial gradients along its main axis as consequences of hydrological variation, reservoir age, and the presence of a cascade of reservoirs, forming the fluvial, intermediate, and lacustrine zones as proposed by Thornton et al. (1990). This process forms a lentic zone close to the dam (lacustrine zone) with gradual upstream transitions resembling the lotic riverine settings (fluvial zone) (Thornton et al., 1990; Carneiro & Bini, 2020). These dammed environments can present a longitudinal pattern with distinct ecological and functional features, and the characteristics of the habitats (e.g. flow velocity, sedimentation rate, nutrient levels, and water clarity) can differ from one another (Vašek et al. 2004; Carneiro & Bini, 2020). These differing habitats can control distribution of fish because this spatial gradient can limit the establishment of species. For instance, fish species adapted to the running waters of free-flowing rivers are certainly poorly adapted to inhabit the lentic zones of the reservoir (Agostinho et al. 2008). Another difference can be the greater connection of the fluvial zone to the river and riparian forests, contributing to the influx of allochthonous resources into this zone (Agostinho & Zalewski, 1995), vital food resources for rheophilic fish that primarily feed on terrestrial plants and insects. Ultimately this can affect distribution of trophic guilds and shifts fish trophic structure following this spatial pattern (Garcia et al., 2023).

Reservoirs not only affect the spatial dynamics, but over time, this artificial ecosystem undergoes dramatic changes. Initially, after closing the dam, the reservoir is subject to fast and intense modifications, due to the filling phase (Agostinho et al., 2008). The free-flowing river becomes lentic, and these modifications strongly affect several aspects of the communities inhabiting this new ecosystem such as assemblages' composition, availability of resources and the trophic structure (Liermann et al., 2012; Turgeon et al., 2019). This new ecosystem is colonized by species that inhabited the original river; however, the establishment of this community will depend on pre-adaptations of species to successfully inhabit and explore lentic environments with extensive pelagic areas (Gomes & Miranda, 2001; Agostinho et al., 2007). Consequently, it is anticipated that the trophic structure of the fish community will undergo notable and expected changes (Agostinho et al., 2016; Arantes et al., 2019). Nevertheless, the responses of the fish community through time are not so straightforward, as it depends on the successful establishment of species through time, and can be related with size, feeding plasticity and reproductive performance (Agostinho et al., 2016; Muniz et al., 2019).

In the first years after the reservoir formation, there is a period known as the trophic upsurge, marked by the flooding and decomposition of terrestrial vegetation (Agostinho et al., 2008; Turgeon et al., 2016). This process increases aquatic productivity, supporting trophic guilds that can initially take advantage of these resources, particularly the detritivores and omnivores (Luz-Agostinho et al., 2006; Delariva et al., 2007). After the forests are flooded, terrestrial insects become plentiful for small insectivorous fish. This surge in insectivorous species initially benefits the piscivores (Cantanhêde et al., 2008; Arantes et al., 2019). Additionally, as the reservoir ages and as further downstream, the intensity of oligotrophication processes keeps on favoring visually oriented predators, due to higher water transparency (Ortega et al., 2020). Over time, this process, on the other hand, seems to decline detritivore abundance in reservoirs, because of decreased quantity and quality of sediment used by detritivore fishes (Santos et al., 2020). Hence, these spatial and temporal shifts in the trophic ecology of species could reflect the influence of environmental stressors on the food web structure (Wang et al, 2016; Dias et al., 2020).

The Paraná River basin is severely regulated by hundreds of small and large dams, intensively exploited for energy supply (Agostinho et al., 2007). The Itaipu reservoir, on the Brazil-Paraguay border, is one of the largest reservoirs in area in the basin and the second largest in energy production hydroelectric power plants in the world (Dias et al., 2018). The formation and filling of the reservoir, in 1982, submerged an area of 1460 km^2 and its construction not only dramatically altered the landscape, but also caused profound ecological shifts, particularly for the fish community (Hahn et al., 1998; Agostinho et al., 1999). Studies have explored the rise and fall in species abundance, diversity, and fisheries harvest within the Itaipu reservoir (Oliveira et al., 2003; Okada et al., 2005; Makrakis et al., 2011). However, beyond these factors, investigations into the broader ecological interactions, like trophic studies, have been limited. Shortly after the formation of the Itaipu reservoir, fish dietary composition and alterations in the community's trophic structure were documented by Hahn et al. (1998). Despite these initial findings, the trophic ecology of fish community in the Itaipu reservoir remains underexplored as the reservoir ages. In this context, the goal of this study was to describe the current patterns of fish diet along the Itaipu reservoir, as well as the trophic guilds and trophic structure of fish assemblages from fluvial to lacustrine zones across the reservoir. For this, we describe the diet composition of fish within each reservoir zone, determining the trophic guilds and trophic structure. We also compared the current trophic guilds and trophic structure, 37 years later, with the fish community from the first years after the formation of the Itaipu reservoir, described by Hahn et al. (1998).

2.2 Materials and Methods

2.2.1 Study area and sampling

The Itaipu Reservoir is located on the Paraná River, on the border between Brazil and Paraguay (24º15' and 25º33' S; 54º00 and 54º37' W). It has an extension of about 150 km, with an average depth of 22 m and a maximum depth of 170 m close to the dam. According to the sedimentation rate, the limnological characteristics and the composition of the ichthyofauna, it presents three distinct zones: fluvial, intermediate, and lacustrine (Okada et al., 2005). Sampling occurred quarterly (March, June, September, and December) in 2019 at three stations (fluvial: Guaíra, intermediate: Santa Helena, and lacustrine: Foz do Iguaçu – Figure 1), the same stations that were sampled in Hahn et al. (1998). At each station, three sets of gillnets (mesh sizes: 2.4, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15 and 16 cm) were deployed and left for 24 hours, checked at 8:00 am, 4:00 pm, and 10:00 pm. According to the zonation concept by Thornton et al. (1990), nets were positioned across the reservoir zones and further stratified into littoral, pelagic, and benthopelagic layers. Fish captured (ICMBio License Number: 65850-1) were anesthetized using benzocaine and sacrificed in accordance with ethical standards (CEUA number: 9593221218), preserved in 10% formalin, then identified to species level following Ota et al. (2018). They were measured for total and standard length, weighed, eviscerated, and their gastrointestinal tract (stomachs and intestines) preserved in 4% formaldehyde for subsequent analysis.

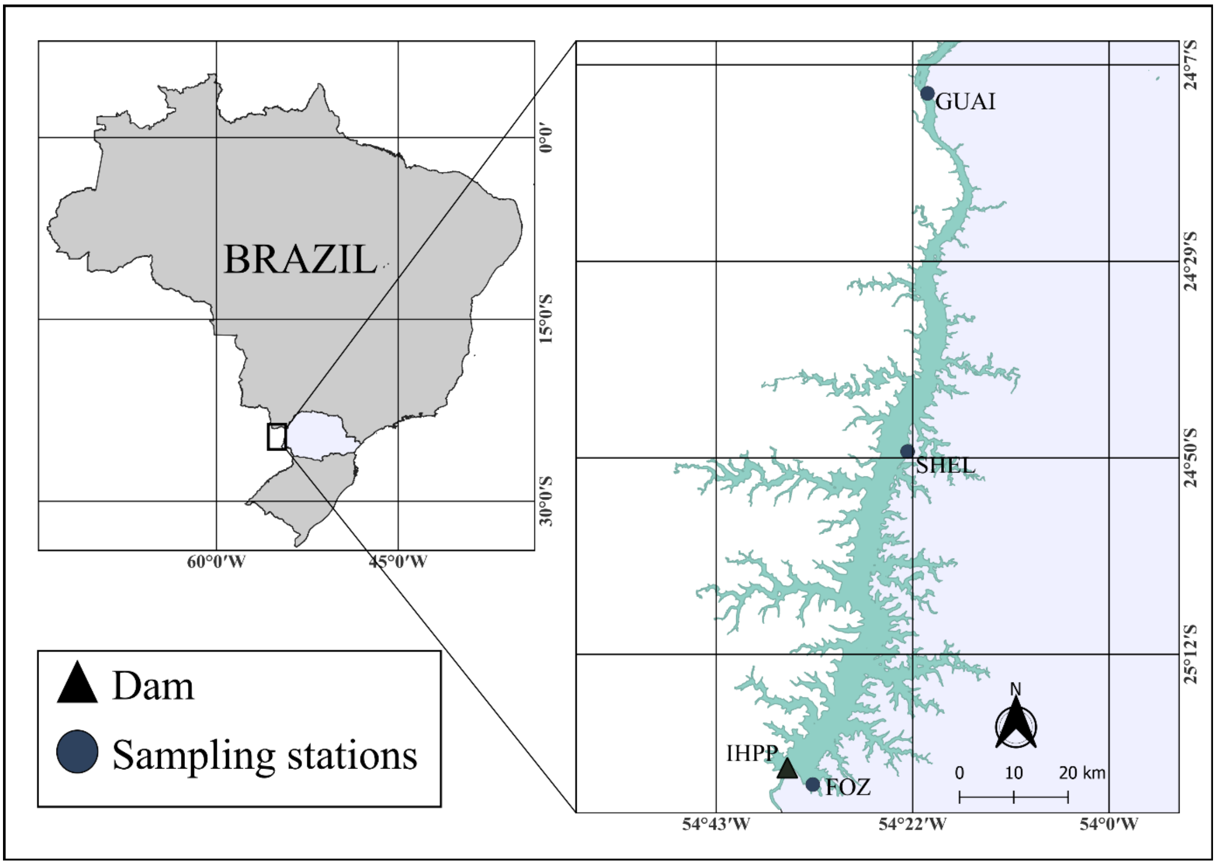

Figure 1. Map showing the location of the sampling zones along Itaipu reservoir. GUAI = Guaíra station, the fluvial zone; SHEL = Santa Helena, intermediate zone; FOZ = Foz do Iguaçu, the lacustrine zone and IHPP = Itaipu Hydropower Power Plant

2.2.2 Stomach content and diet analysis

For diet analysis, all fish with gastric content were analyzed under a stereoscopic and optical microscope, and the prey items were identified to the lowest possible taxonomic level and quantified using the volumetric method (Hyslop, 1980) in two distinct ways: (i) by displacement of the water column with graduated beakers; and (ii) with a grid-like dish, where the volume of the items was measured in 1 mm^3 and later converted to ml. The second technique was used as the items were so small that determining the volume in graduated cylinders was not possible. The prey items were pooled into nine groups as follows: algae, higher plants, detritus, aquatic insects (Chironomidae, Ceratopogonidae, Sarcophagidae, Diptera pupae, Odonata, Ephemeroptera, Hemiptera, Trichoptera and Plecoptera), terrestrial insects (Coleoptera, Lepidoptera, Hymenoptera, Orthoptera, Isoptera, Blattodea), microcrustacean (Cladocera and Ostracoda), mollusks, decapods and fish remains.

To characterize fish species diet, we used the Index of Alimentary Importance (IAi) (Kawakami & Vazzoler, 1980), which combines frequency of occurrence and volumetric approaches to provide an index that confirms the diet's main food resources, calculated as follows:

$$IAi = \frac{Fi \times Vi}{\sum_{i=1}^{n}(Fi \times Vi)}$$

where: Fi is the frequency of occurrence of item i (%); Vi is the relative volume of item i (%); and *n* is the number of items.

Trophic guilds were identified based on an intermediate value (60%) of the main food group of the diet based on the IAi values for each species, at each reservoir zone. Thus, fish were classified in 12 trophic guilds: algivores - species that consume algae; benthophagus - species that feed on the riverbed, consuming benthic invertebrates with sediment; carcinophagus - species that consume great quantities of Decapoda; detritivore - species that feed on the riverbed, consuming large quantity of decomposed organic matter; herbivore - fish that consume higher plants, including seeds and leaves; aquatic insectivore - species that feed on different stages of aquatic insects (adults and immatures); terrestrial insectivore - species that feed on terrestrial insects, adults or immatures; invertivore - species that feed on similar proportions of aquatic and terrestrial invertebrates; molluscivore - fish that consume large quantities of mollusks; omnivore - species that can consume from algae to other fishes, without an obvious predominance of any particular resource; piscivore - species that feed on fish; planktivore - species that consume mainly microcrustaceans. Trophic guilds were determined for each species within each reservoir zone from analyzed gut contents, or from the literature when species were sampled but gut content was empty (this was detailed in Table 1). Lastly, to quantify the use of prey resources by fish longitudinally, the percentage contribution of each food group, calculated using the IAi, was pooled for each zone, by combining all species.

2.2.3 Data analysis

To verify if diet composition of fish species was spatially different across the reservoir zones, a Permutational Multivariate Analysis of Variance (PERMANOVA; Anderson, 2005) for each species that had diet data for at least two zones and three individuals per zone was performed. This analysis was performed using the "adonis" function in the package "vegan" in the R software. To perform the analysis, we used a matrix of food groups per fish species, with the IAi values, and created dissimilarity matrices with the Bray–Curtis distance. We generated 9,999 permutations to assess the significance of the pseudo-F derived from thr PERMANOVA.

To describe potential spatial changes in trophic structure of fish assemblages within the reservoir, we estimated the relative biomass, abundance, and species richness for each trophic guild across sampled months in the fluvial, intermediate, and lacustrine zones. Changes in the relative biomass, abundance, and species richness (response variables) of each trophic guild (detritivore, herbivore, aquatic insectivore, terrestrial insectivore, invertivore, molluscivore, omnivore, piscivore and planktivore) among reservoir zones were tested using a Kruskall Wallis, followed by Dunn's test, using the sampling months as replicates.

To compare temporal changes in species trophic guilds and trophic structure with the earlier study by Hahn et al. (1998), we initially provided a descriptive overview. In the initial years of the Itaipu Reservoir, Hahn et al. (1998) carried out a detailed study on the diet and trophic structure of the fish fauna, and 37 years later, we analyzed the diet and trophic structure of fish from the same sampling sites within the reservoir. Additionally, we conducted a PCoA (Principal Coordinates Analysis), utilizing Bray-Curtis distance. This analysis aimed to visualize the spatial distribution of fish trophic guilds across reservoir zones, using their relative abundance and biomass.

2.3 Results

We sampled 68 fish species across the reservoir, and 46 of them had 552 individuals with gastric content that could be analyzed for diet. We caught 46 species in the intermediate and lacustrine zones, and 47 in the fluvial zone. Between the three locations, 27 species coexisted (Table S1). Nine species were unique to the fluvial zone, nine to the lacustrine zone, and five to the intermediate zone.

2.3.1 Longitudinal shifts of prey consumption by fishes

For the 46 species with diets analyzed in this study, prey consumed by the fish community clearly changed along the longitudinal zonation (Fig. 2; Fig S1). The fluvial zone was distinguished by more balanced resource utilization compared to the other stretches, that is, none of the resource categories was predominant. Decapoda consumed in the fluvial zone, accounted for approximately 23.16% of the diet. Terrestrial insects and fish were also consumed in similar proportions, accounting for 22.59% and 21.30% of total consumption, respectively (Fig. 2). Higher plants (12.68%) and algae (11.47%) were consumed in smaller but comparable amounts (Fig. S1). Further downstream, in the intermediate zone, a shift in resource utilization became evident. The consumption of fish increased, representing 38.81% of the diet. Higher plants were consumed the most in this zone, compared to the fluvial and lacustrine zones, representing 25.43% of the diet. Mollusca also played a more significant role in the intermediate zone, comprising 14.13% of the diet, in contrast to its lesser importance in the fluvial zone (less than 1% of importance) (Fig. 2; Fig S1). However, the most noticeable distinction occurred in the lacustrine zone, where fish was the most consumed resource, having exceeded 64% of the diet. Higher plants were the second most important item, accounting for 14.11% of the diet, while the remaining resources in each category represented less than 10% (Fig. 2; Fig S1).

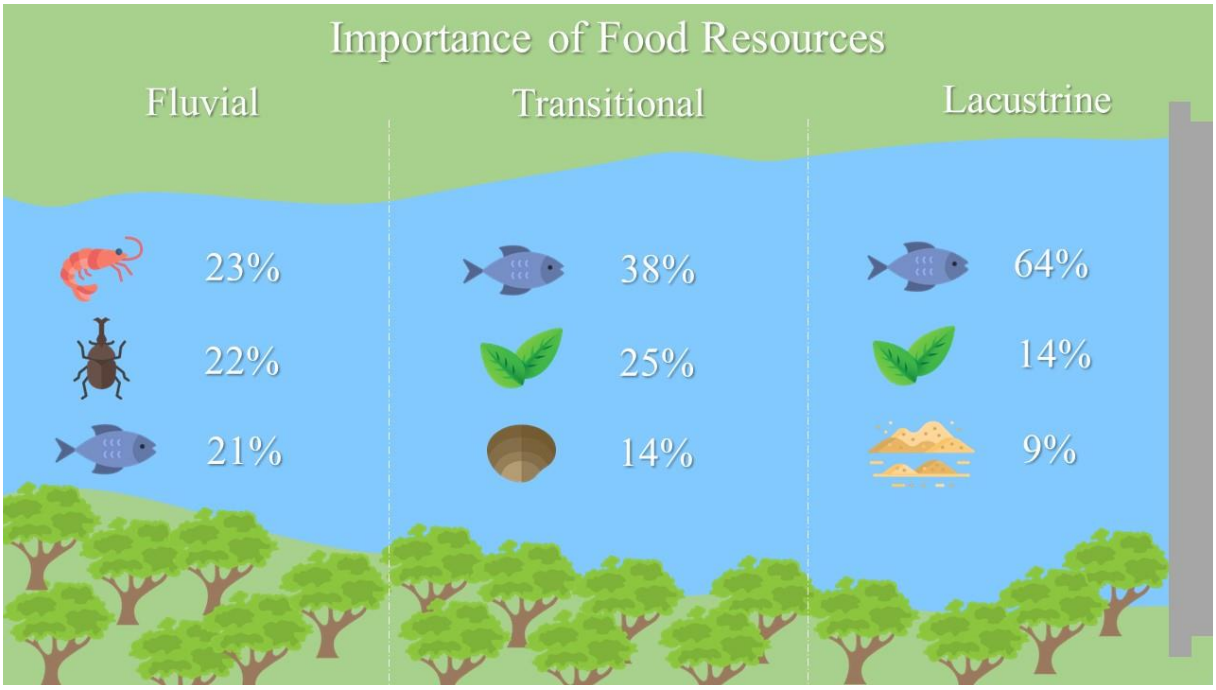

Fig. 2 Schematic drawing of main prey consumed by fish assemblages and their percent contributions at each reservoir zone.

2.3.2. Longitudinal variations on fish species diet

When comparing the diet of each species among the reservoir zones through PERMANOVA, we found that only 3, out of 16 species, showed significant differences in their diets (Table S2). Notably, these differences were found when comparing the diet in the lacustrine zone, the furthest downstream area of the reservoir, with the other stretches. Specifically, *Geophagus sveni* showed different diets when comparing the lacustrine zone with fluvial and intermediate zones. In both fluvial and intermediate zones, *G.sveni* consumed mostly higher plants (63.19% and 60.72%, respectively), whereas in the lacustrine zone, detritus (62.82%) and mollusks (31.56%) were the most consumed resources (Table S3). *Hemiodus orthonops* diet only changed between the lacustrine and intermediate zones, consuming more than 70% of detritus in the lacustrine zone, and more than 60% of higher plants in the intermediate zone (Table S3). *Parauchenipterus galeatus* had different diets only between the lacustrine and fluvial zones. In the fluvial zone, over 90% of the diet consisted of terrestrial insects, while in the lacustrine zone, *P. galeatus* consumed around 50% of its diet in terrestrial insects, as well as Decapoda (25.40%) and higher plants (19%) (Table S3).

2.3.3 Trophic guilds

Based on the IAi analysis, the 68 species sampled were categorized into 12 trophic guilds (algivore, benthophagous, carcinophagous, detritivore, herbivore, aquatic insectivore, terrestrial insectivore, invertivore, molluscivore, omnivore, piscivore and planktivore), each comprising species with similar prey preferences (Table 1). The planktivore guild was exclusively found in the intermediate zone (represented by *Hypophthalmus oremaculatus*). When comparing species guilds across the three zones in our study, we found that eight out of the 68 species exhibited variations in their trophic guild classifications. Specifically, *Auchenipterus osteomystax, Crenicichla britskii, Galeocharax gulo, G. sveni, H. orthonops*, and *P. galeatus* exhibited distinct trophic guilds in the lacustrine zone, while maintaining consistent guild classifications in the other reservoir zones. In the intermediate zone, there were only two species that changed their trophic guilds. *Leporinus friderici* shifted from an omnivore to a molluscivore, while *Serrasalmus marginatus* shifted from piscivore to an omnivore.

Table 1. Trophic guild classification of fish species within the reservoir zones analyzed in our study (based on the Index of Alimentary Importance), juxtaposed with the trophic classification of fish species documented by Hahn et al. (1998) during the early years post-Itaipu formation. *Refers to species that had trophic guilds classification based on diet analysis

Species		**Reservoir zones**		
	Fluvial	**Intermediate**	**Lacustrine**	**Hahn et al. 1998**
Acestrorhynchus lacustris	Piscivore	Piscivore*	Piscivore*	Piscivore
Ageneiosus ucayalensis	Carcinophagus*			Piscivore
Apareiodon affinis	Detritivore	Detritivore	Detritivore*	Iliophagous
Astyanax aff. fasciatus			Insectivore (T)	Insectivore (T)
Astyanax lacustris	Insectivore (T)	Insectivore (T)*	Insectivore (T)*	Insectivore (T)
Auchenipterus osteomystax	Insectivore (T)*	Insectivore (T)*	Invertivore*	Insectivore (A)
Brycon hilarii			Herbivore	
Brycon orbignyanus			Omnivore	Omnivore
Cichla kelberi	Piscivore	Piscivore	Piscivore	
Cichla piquiti	Piscivore	Piscivore*	Piscivore	
Crenicichla britskii	Herbivore*		Omnivore*	Insectivore (A)
Eigenmannia virescens	Insectivore (A)			Insectivore (A)
Galeocharax gulo	Piscivore*	Piscivore*	Carcinophagus*	Piscivore
Geophagus sveni	Herbivore*	Herbivore*	Detritivore*	
Gymnotus inaequilabiatus	Benthophagous	Benthophagous		
Hemiodus orthonops	Herbivore*	Herbivore*	Detritivore*	
Hoplias argentinensis		Piscivore*	Piscivore*	
Hoplias mbigua	Piscivore	Piscivore*	Piscivore*	
Hoplias sp.			Piscivore*	
Hoplias sp. 2		Piscivore*		
Hoplias spp			Piscivore	
Hoplosternum littorale	Benthophagous	Benthophagous		Benthophagous
Hypophthalmus oremaculatus		Planktivore		Planktivore
Hypostomus ancistroides			Detritivore	
Hypostomus cf. strigaticeps		Detritivore	Detritivore*	
Hypostomus cochliodon	Herbivore*			
Hypostomus regani	Detritivore*		Detritivore*	
Iheringichthys labrosus	Benthophagous*	Benthophagous*	Benthophagous*	Benthophagous
Leporinus friderici	Omnivore*	Molluscivore*		Omnivore
Leporinus lacustris	Omnivore	Omnivore	Omnivore*	
Leporinus octofasciatus		Omnivore		Omnivore
Leporinus tigrinus	Omnivore	Omnivore		
Leporinus unitaeniatus	Omnivore	Omnivore		
Loricaria sp.	Molluscivore*	Molluscivore*	Molluscivore	Detritivore
Loricariichthys platymetopon	Detritivore*	Detritivore*	Detritivore*	Detritivore
Loricariichthys rostratus	Detritivore	Detritivore*	Detritivore*	Detritivore
Megalancistrus parananus			Molluscivore*	Detritivore

Megaleporinus macrocephalus	Omnivore			
Megaleporinus obtusidens			Omnivore	Omnivore
Megaleporinus piavussu		Herbivore	Herbivore	
Metynnis lippincottianus		Algivore*	Algivore*	
Parauchenipterus galeatus	Insectivore (T)*	Insectivore (T)*	Invertivore*	Omnivore
Pimelodella gracilis	Insectivore (T)*	Insectivore (T)*	Insectivore (T)	Insectivore (A)
Pimelodus maculatus	Omnivore	Omnivore	Omnivore*	Omnivore
Pimelodus mysteriosus	Piscivore	Piscivore*		
Pimelodus ornatus	Omnivore			Omnivore
Pinirampus pirinampu	Piscivore	Piscivore*	Piscivore	Piscivore
Plagioscion squamosissimus	Piscivore*	Piscivore*	Piscivore*	Piscivore
Potamotrygon amandae		Piscivore	Piscivore*	
Potamotrygon cf. falkneri		Piscivore*		
Prochilodus lineatus	Detritivore*	Detritivore*	Detritivore*	Iliophagous
Pseudoplatystoma corruscans		Piscivore		Piscivore
Pterodoras granulosus		Molluscivore*	Molluscivore*	Omnivore
Pterygoplichthys ambrosettii	Detritivore*	Detritivore		
Rhamphichthys hahni	Insectivore (A)*	Insectivore (A)*		Insectivore (A)
Rhaphiodon vulpinus	Piscivore	Piscivore*	Piscivore*	Piscivore
Roeboides descalvadensis	Insectivore (A)	Insectivore (A)	Insectivore (A)	Insectivore (A)
Salminus brasiliensis			Piscivore*	Piscivore
Satanoperca setepele	Herbivore*	Herbivore*	Herbivore*	Bentophagous
Schizodon borellii	Herbivore*	Herbivore*	Herbivore	Herbivore
Schizodon nasutus	Herbivore			Herbivore
Serrasalmus geryi	Piscivore			
Serrasalmus maculatus		Piscivore	Piscivore*	Piscivore
Serrasalmus marginatus	Piscivore	Omnivore*	Piscivore*	Piscivore
Sorubim lima	Piscivore*			Piscivore
Steindachnerina brevipinna	Detritivore		Detritivore*	Iliophagous
Synbranchus marmoratus	Piscivore			
Trachydoras paraguayensis	Benthophagous*			Benthophagous

2.3.4 Trophic structure

Results revealed a distinctive spatial distribution of dominant trophic guilds (in abundance and biomass) from the lacustrine zone when compared with the fluvial and intermediate zones, which had similar dominant guilds (Fig. 3). In the fluvial zone, we recorded nine trophic guilds. Among them, the herbivores emerged as the dominant trophic guild in abundance, accounting for a substantial proportion of the fish community. Specifically, seven herbivore species constituted nearly 40% of the total fish abundance in this area and contributed to approximately 30% of the total biomass. Among these herbivores, *Hypostomus cochliodon*, a species exclusively captured in the fluvial section, stood out as the most abundant, accounting for 45.40% of all individuals within this guild. The second most dominant guild in terms of numerical abundance were piscivores, comprising 23.19% of the fish community and represented by 13 species, followed by the terrestrial insectivores (four species), representing 17.23%. However, when it comes to biomass, piscivores contributed to nearly 40% of total biomass in the fluvial zone. Within this guild, *Plagioscion squamosissimus* accounted for more than 51% of the catches, both in abundance and biomass.

Similar patterns were found in the intermediate section, with the same dominant trophic guilds in terms of abundance and biomass (Fig. 3). However, ten trophic guilds were sampled in this zone. The trophic structure in the intermediate zone was characterized by the prevalence of herbivores (34.29%), piscivores (26.99%), and terrestrial insectivores (13.77%) as the most abundant guilds. When assessing biomass contributions, it was clear that piscivores remained important, accounting for more than 40% of total biomass in the intermediate zone, like the pattern observed in the fluvial zone. The piscivores were also the richest guild in this zone, comprising 15 species. However, in terms of biomass, Molluscivores were more important (nearly 10%) when compared to terrestrial insectivores (5.9%). A notable difference between the intermediate and fluvial zones was also the presence of two additional trophic guilds, algivores and planktivores, the latter being sampled only in the intermediate zone.

The trophic structure in the lacustrine zone shifted from the other two zones (Fig. 3). We recorded 11 out of 12 guilds in the lacustrine zone and different dominant guilds. The abundance in this area was primarily influenced by three trophic guilds: detritivores, piscivores, and omnivores. Detritivores accounted for the greatest abundance, representing 40.6% of the fish community and represented by 10 species. *Geophagus sveni* represented 38% of all individuals within this guild, but only 10% in total biomass. Piscivores were the second most abundant guild, accounting for 30.38% of the fish community, while omnivores accounted for 11.60%. In this zone, the piscivores were also the richest guild, represented by 14 species. As in the fluvial zone, *Plagioscion squamosissimus* accounted for nearly 50% of all catches within the piscivore guild. When it comes to biomass contributions, piscivores was also the most important guild, accounting for 43.13% of total biomass in the lacustrine zone. Detritivores accounted for 21.43% and omnivores, accounted for 17.47% of total biomass. Additionally, the Molluscivore guild was also important, representing 11.8% of the biomass in the lacustrine zone. In contrast to the other zones, the lacustrine zone exhibited a lower representation of terrestrial insectivores, accounting for less than 1% in both numerical abundance and biomass.

We found a significant difference for the relative abundance of herbivore species ($X^2 = 8.40$; $p = 0.01$), where the fluvial and intermediate zones had on average higher abundance than the lacustrine zone. The abundance ($X^2 = 5.33$; $p= 0.06$) and biomass ($X^2 = 5.79$; $p= 0.05$) of terrestrial insectivores showed a marginal significant result, presenting on the fluvial and intermediate zones, a higher abundance on average. No significant differences in the relative abundance and biomass were found for the remaining trophic guilds among the three zones (Table S4). Regarding the mean richness of trophic guilds, they did not differ among zones ($X^2 = 3.26$; $p = 0.19$).

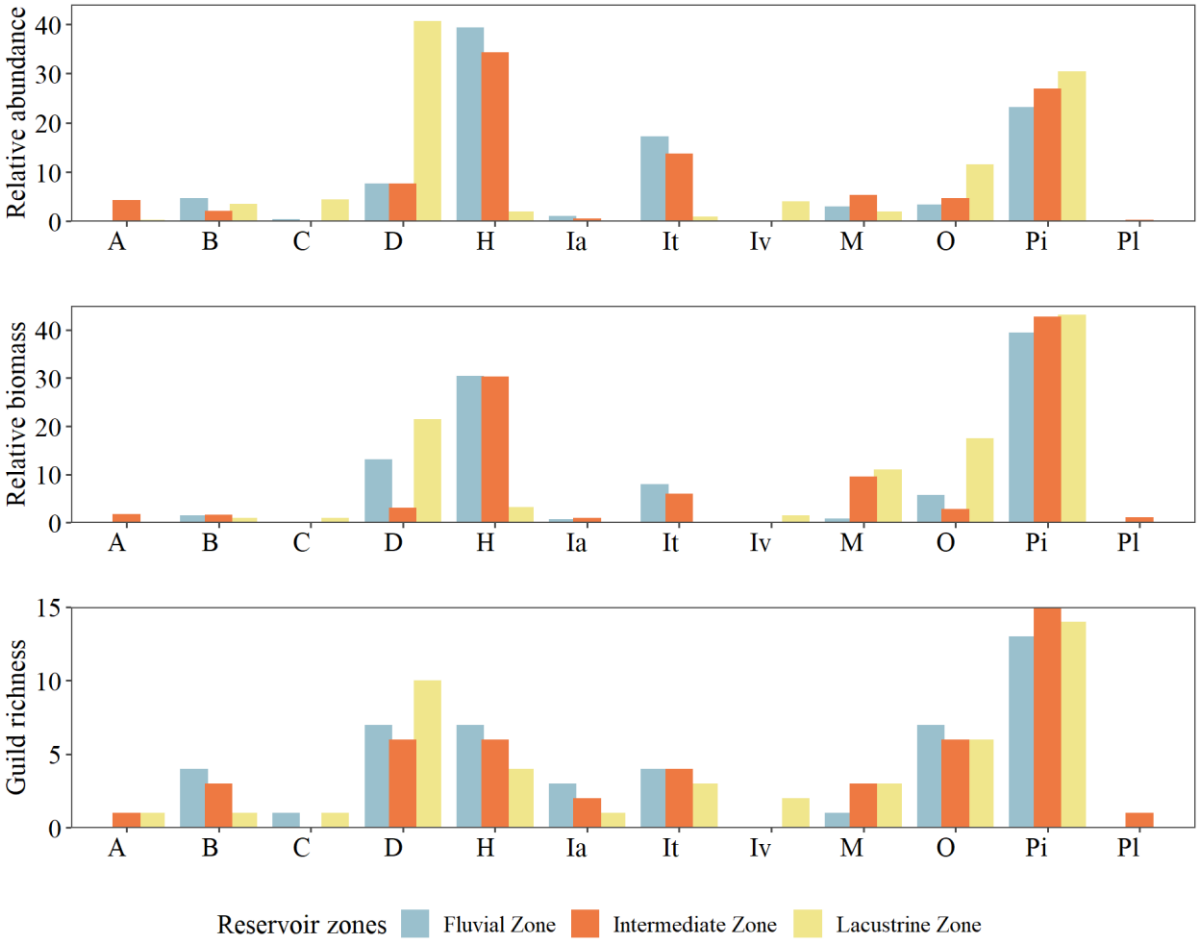

Figure 3. Longitudinal distribution of trophic guilds and their contributions (%) at each reservoir zone based on their a) relative abundance, b) relative biomass and c) guild richness. Each letter represents each trophic guild. A = algivore; B = benthophagous; C = carcinophagous; D = detritivore; H = herbivores; Ia= aquatic insectivore; It = terrestrial insectivore; Iv = invertivore; M = molluscivore; O = omnivore; Pi = piscivore; Pl= planktivore

2.3.5 Temporal changes on species trophic guilds and trophic structure

A detailed analysis of the trophic guilds and structure showed some notable differences when comparing the study carried out by Hahn et al. (1998) in the initial years of the Itaipu reservoir with the current fish community. Previously classified as piscivores, species such as *A. ucayalensis* and *G. gulo* have now been classified into the carcinophagus guild (Table 2). This shift was mainly due to their changing dietary preferences, as they now consume substantial quantities of Decapoda over fish, an alteration from their former diets. Another change was verified to some omnivores and detritivores species that now are classified as molluscivores. Species such as *L. friderici, Loricaria* sp., *M. parananus*, and *P. granulosus* now primarily feed on Bivalvia and Gastropoda (Table 2). Furthermore, the insectivore's fish in the early years were mainly aquatic insectivores. However, currently, most insectivores have shifted their diets to terrestrial insects (*A. osteomystax, P. galeatus* and *P. gracilis*) (Table 2). These changes were also highlighted in the trophic structure (Fig. 4, Table S5 and S6). Following the reservoir closure, the piscivores, aquatic insectivores, planktivores, bentophagous, and iliophagous guilds were the most important in abundance and biomass, considering all zones. Recently, only the piscivores remained as the most important guild in abundance and biomass across all zones. Detritivores were once more important in the fluvial zone, but now they are more expressive only in the lacustrine zone. A notable change was the absence of the planktivore guild in the fluvial and lacustrine zones, and a minimal catch in the intermediate zone (only two individuals) in the recent years when compared to its high abundance following the reservoir formation, especially in the lacustrine zone. Herbivores had a low importance in terms of abundance and biomass in the beginning, but now represent more than 30% in the fluvial and intermediate zones (Fig. 3 and Fig. 4). Terrestrial insectivores were also initially related only to the lacustrine zone, whereas nowadays they are third in abundance in the fluvial and intermediate zones.

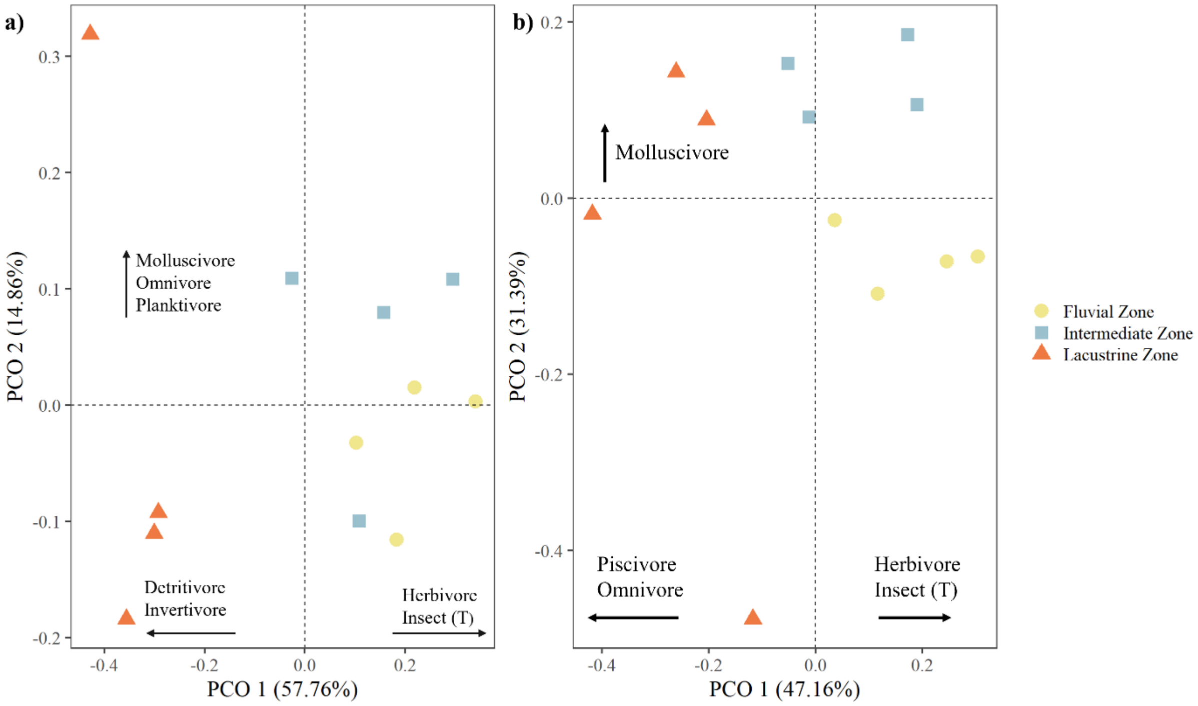

Figure 4 Principal Coordinate Analysis - PCoA showing the trophic structure of fish assemblages according to a) relative abundance and b) relative biomass of trophic guilds in the three zones of Itaipu reservoir.

2.4 Discussion

2.4.1 Longitudinal use of food resources

In the Itaipu reservoir, fish shifted their resource utilization from fluvial to lacustrine zones, likely due to distinct environmental conditions and resources availability (Filho et al., 2011). The fluvial section resembles the natural riverine ecosystem the most and receives direct influence from the upstream Paraná River and its floodplain (Oliveira et al., 2004; Agostinho et al., 2008). The connection of the riparian vegetation and floodplain ecotone in this zone leads to a higher spatial heterogeneity and productivity, offering a wide array of prey for fish (Agostinho & Zalewski, 1995). This diversity of prey arises from resources originating from two distinct sources: autochthonous and allochthonous. Prey consumed in this zone were decapods, fish, and terrestrial insects, making up to almost 70%. The presence of diverse stands of macrophytes and greater connection to floodplain forests in this upper section (Agostinho & Zalewski, 1995; Thomaz et al., 1999; Mormul et al., 2010) function as feeding grounds and shelter for associated fauna, like crustaceans, insects, and small fish for instance (Pelicice et al., 2008). This autochthonous fauna serves as food for fish inhabiting the fluvial zone and can be potential food sources for carcinophagus and omnivore species. Additionally, allochthonous prey, such as terrestrial insects, were very important for fish diets in the fluvial zone. Terrestrial insects from adjacent riparian forests are recognized as vital food sources for rheophilic fishes (Small et al., 2013; Šmejkal et al., 2023), and were exploited by fish the most in the fluvial zone, likely because the influx of terrestrial prey was higher in this section, contrasting their scarcity in the inner parts of the reservoir.

As distance to the dam decreased (intermediate to lacustrine zones), fish increased consumption of autochthonous resources, specifically of fish. Over time, in reservoirs, autochthonous production increases and establishes, increasing the contribution of these aquatic resources (aquatic macrophytes and forage fish) to fish assemblages (Mérona et al., 2003; Delariva et al., 2013). Superior plant was especially consumed in the intermediate zone. In Neotropical reservoirs, particularly in shallow environments (like those found in the fluvial and intermediate zones), colonization by macrophytes can be massive (Pringle et al., 2000) and herbivore species can be attracted, due the high availability of macrophytes in these shallow littoral areas in the intermediate zone (Mormul et al., 2010), attracting species such as *Schizodon borelli*, *Satanoperca* sp. and *Hemiodus orthonops*, suggesting that macrophytes provided a food subsidy to fish. Beyond serving as food itself, macrophytes play a key role on keeping biodiversity (Thomaz & Cunha, 2010; Yofukuji et al., 2021), and in the case of reservoirs, it can be the main habitat available for shelter and foraging sites for Neotropical fish fauna (Filho & Moura, 2021), which do not thrive in open pelagic areas (Gomes & Miranda, 2001). Generalist and sedentary small fish are positively associated with the vegetated areas of reservoirs (Pelicice et al., 2008; Santos et al., 2017) and can become abundant prey for piscivore fishes both in the intermediate and lacustrine zones (Pelicice et al., 2018; Bem et al., 2021). The highest consumption of fish in the lacustrine section can be also related to clearer waters as consequence of the sedimentation above (Filho et al., 2011; Cunha et al., 2016) favoring the visual predators.

The high proportion of mollusks in fish diets in our study can be explained by the massive proliferation of invading bivalves in Itaipu reservoir, which occurred in 1994 for *C.fluminea* and in 2001 for *L. fortunei* (Takeda et al., 2004; 2007). These mollusks have been reported as important and common to the diet of several fish species in Itaipu, in the years following the populational explosion of these non-native invertebrates (Luz et al, 2002; Oliveira et al., 2010). Particularly in the intermediate zone, where this resource was most consumed, this could be associated with submerged macrophytes, in which these mollusks use as substratum

(Michelan et al., 2014). Although patches of submerged macrophytes can develop in the lacustrine zone, fish in Itaipu usually explore the more developed littoral region, like those found in the intermediate zone in comparison to the lacustrine zone (Oliveira et al., 2004; Agostinho et al., 2016) where fish can feed heavily on these bivalves.

2.4.2 Longitudinal variations on fish species diet

As longitudinal changes are expected for prey communities (Santos et al., 2016; Santos et al., 2017), resources available for fish also vary among these environments (Wang et al., 2018) and can contribute to differences in diet as we found for some species. In the lacustrine zone, *G. sveni* and *H. orthonops* consumed predominantly detritus along with plants and invertebrates, while in the fluvial and intermediate zones, they relied mainly on plants. Opportunistic species with trophic plasticity like *G. sveni* and *H.orthonops* are not restricted to a single resource (Sampaio & Goulart, 2011; Agostinho et al., 2015; Tonella et al., 2017). Therefore, these species can consume large amounts of detritus mixed with other food sources, even in zones where detritus isn't typically abundant, whereas in the upper zones, these species can feed on the abundant vegetation, like macrophytes and the riparian vegetation surrounding the floodplain upstream. *Parauchenipterus galeatus* had different diets only between the lacustrine and fluvial zones. In the fluvial zone, *P. galeatus* fed mainly on terrestrial insects (reaching 90% of main food category), while in the lacustrine zone, in addition to terrestrial insects, its diet was complemented with Decapoda and higher plants. Although *P. galeatus* is considered an omnivore species (Tonella et al., 2017), it tends to insectivory, especially terrestrial invertebrates in the floodplain above (Bianchi-Costa et al., 2023), and therefore it can mimic its diet in the fluvial zone, where the inputs of terrestrial resources are greater compared to the other zones.

Overall, most species did not show significant differences in diet among zones. Some feeding strategies are highly specialized, like detritivory, herbivory, and benthophagous diets, because species need morphological preadaptations to capture, handle and digest these types of food (López-Fernández et al., 2014; Davis & Betancur-R, 2017). For instance, benthophagous species (i.e. *Hoplosternum littorale, Iheringichthys labrosus* and *Trachydoras paraguayensis*) present the position of their mouth and teeth suitable for obtaining food from the bottom (Fugi et al., 2001). For detritivore species, fish present adaptations in the digestive tracts, like long intestines (Fugi et al., 2001; Pouilly et al., 2003) to assimilate nutrients from detritus. Although predator fish can feed on several prey, piscivore species will not change their diet for alternate low energy resources (i.e detritus or plants) if preferential prey are highly available (Cantanhêde et al., 2008) being either fish or abundant decapods, which can fulfill their diets.

2.4.3 Trophic guilds and trophic structure of fish community

Freshwater ecosystems, due to their dynamic nature and susceptibility to anthropogenic influences, often struggle to establish clear trophic patterns, especially after river impoundment, which filter species and trophic guilds. Nevertheless, we identified 12 trophic guilds, with eight of them being common across reservoir zones, suggesting that most representative trophic guilds for freshwater were present. However, we found that some species exhibited variations in their trophic guild classifications, adapting their feeding behaviors according to changing environmental cues, such as resource availability.

The spatial distribution of dominant trophic guilds showed some distinct patterns, especially when comparing the fluvial and intermediate, where herbivores stood out in abundance, to the lacustrine zone. Particularly, high abundances of *H. cochliodon* and *H. orthonops* contributed to dominance in abundance of the herbivore guild. *H. cochliodon* occurred only in the fluvial zone and seems to thrive in this area, most likely because this species does not depend directly on riparian vegetation or macrophytes as direct food source, but rather it is adapted to ingest submerged woody materials (Armbruster, 2003; Tencatt et al., 2014). The presence of this abundant food source, coupled with the rarity of wood-eating behavior among this family, minimizes competition, turning the fluvial zone into a favorable environment for *H. cochliodon* dominance, consequently establishing herbivore high numbers. Meanwhile, *H. orthonops* is highly abundant in the Itaipu reservoir (Agostinho et al., 2015), and was indeed abundant in all zones. This can be related to some life history traits, like being able to consume plants and to colonize lentic and lotic biotopes (Agostinho et al., 2015).

Piscivores were the second most abundant guild across all zones, but consistently exhibited the highest relative biomass and richness. Piscivores are typically larger and hold higher biomasses in the assemblage, commonly dominating as the most abundant guild in reservoirs (Santos et al., 2017; Lima et al., 2018). Some distinct reasons can underlie this pattern. Firstly, the high abundance of forage fish and decapods that inhabit the littoral areas of the reservoir, serve as prey for piscivores (Agostinho et al., 2007; 2016; Arantes et al., 2019). Second, open water habitats and clearer waters facilitate these predators (Ortega et al., 2020).

Lastly, few pelagic species that were abundant are adapted to lacustrine environments (i.e. *Plagioscion squamosissimus*, *Raphiodon vulpinus;* Gomes & Miranda, 2001), which can limit competition and favors the success of this guild in numbers and in incorporating biomass.

Terrestrial insectivores were the third in abundance in the fluvial and intermediate zones. Species within this guild are smaller fish, sedentary, and forage on terrestrial insects that fall in the water. Additionally, these terrestrial insects can also use macrophyte stands, prevalent in the fluvial and intermediate sections of the reservoir, for oviposition and herbivory, further contributing to the diet of insectivorous fish. This set of characteristics (size and diet) allows these fish to successfully inhabit the upper zones of Itaipu reservoir (Pelicice et al., 2005; Santos et al., 2017). Although abundant, terrestrial insectivores did not contribute to overall biomass, primarily due to their small size.

Surprisingly, detritivores had a high abundance in the lacustrine section, even though it wasn't the primary resource consumed in any zone. The distribution of detritivore species is linked to the presence of detritus, and even though detritus seems to be unlimited, this scenario can change in reservoirs due to the intense oligotrophication (Lima et al., 2018; Santos et al., 2020). Specialized detritivores are highly selective and tend to feed on high protein detritus with higher organic matter (Fugi et al., 1996). However, the most abundant species caught in this zone and classified as detritivores were *G. sveni* and *H. orthonops*, opportunist species that can feed on detritus among other resources (plants and gastropods). Both species are not truly specialized detritivores as the species from the Loricariidae family (i.e *Hypostomus* and *Loricariichthys* species, that accounted for 25 individuals only), but contributed to the elevated detritivore abundance in the lacustrine zone. Lastly, although abundant, the smaller size of *G. seveni* did not contribute to greater biomass for this guild.

2.4.4 Temporal changes on species trophic guilds and trophic structure

Trophic dynamics of fish assemblages through time undergoes dramatic changes. Hahn et al. (1998) described the trophic structure of Itaipu reservoir immediately after its formation in 1982. The most meaningful alteration in the trophic structure from the early years was the massive proliferation of the planktivore *Hypophthalmus edentatus*, reclassified as *H. oreomaculatus* (Nani & Fuster, 1947, *comb. nov.*), the sole species in this trophic category in the inner zones of the reservoir. In our study, this species was nearly absent, with only two individuals caught in the intermediate zone. The initial surge in abundance and biomass of this species was expected due to heightened primary productivity following the transition from a lotic to a lentic environment, subsequently supporting higher trophic levels (Hahn et al., 1998; Abunjanra & Agostinho, 2002). *H. oremaculatus* is a specialist plankton feeder, and as the new lentic conditions did not limit the development of zooplankton, this reflected in the high abundance of this planktivore species. However, as the reservoir aged, reduction in primary productivity and zooplankton biomass, and overfishing of this species (Abujanra & Agostinho, 2002), led to a significant decline in the abundance of *H. oremaculatus* and almost its complete absence from the reservoir.

Another shift was the importance of aquatic insectivores in the beginning, to terrestrial insectivores in our study. Huge amounts of chironomids, ephemeropterans and odonats were found in fish diet post impoundment, contributing to high numbers and biomass of this guild (Hahn et al., 1998; Abes et al., 2001). These insects rapidly colonized the newly formed reservoir due to recent flooded areas and became highly available for fish, and not only insectivore species, but invertivore and omnivore species can take advantage of this abundant resource (Hahn & Fugi, 2007). Through time, however, the reservoir reaches a more stable state, primary production and the abundance of such organisms decline (Higuti et al., 2007). These opportunistic insects that were highly exploited by fish in the initial years, are replaced by the most profitable resources with the aging of reservoir.

We also observed a shift in the trophic guild of some species over time. The high trophic plasticity of species that established in the reservoir can explain such changes (Abelha et al., 2001). As fish can change preferred prey for those highly available (Fugi & Hahn, 2007), some species previously classified as omnivores and detritivores (Hahn et al., 1998), are now classified as carcinophagus and molluscivores, and this can be linked with the massive proliferation of some invertebrates in the Itaipu over the years, like the shrimp *Macrobrachium* that was possibly introduced accidentally together with the Amazonian fish *P. squamosissimus* (Bialetzki et al., 1997; Magalhães et al., 2005) and the mollusks *Corbicula fluminea* and *Limnoperna fortunei* that became important prey over the years (Takeda et al., 2004; 2007).

The results of our study show that fish diets and trophic structure changes following longitudinal gradients imposed by river damming. Particularly, we showed that the longitudinal use of resources transitioned from predominantly allochthonous (fluvial zone) to autochthonous resources (lacustrine zone). The alterations in prey consumption notably influenced the spatial distribution of distinct fish trophic guilds across the reservoir. The upper zones, fluvial and intermediate, shared a similar trophic structure characterized by herbivore, piscivore and terrestrial insectivore as the dominant guilds. In contrast, the lacustrine zone exhibited dominance by detritivore, piscivore, and omnivore guilds. High abundance within these guilds was likely due to the dominance of a few species that can take advantage of the most profitable resources. The changes in abundance and biomass of trophic guilds can result in severe modifications of ecosystem interactions and ultimately affect fishery yields and market values. Furthermore, we showed that as the reservoir aged, there was a shift in dominant guilds in terms of abundance and biomass, particularly the rise (early years) and fall of the planktivore group, and to a lesser extent, the fall of the aquatic insectivores. These changes highlight the complex dynamics and long-term effects of dams on aquatic ecosystems, emphasizing the importance of ongoing monitoring and adaptive management strategies to ensure the health and sustainability of these environments.

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3 MICROPLASTIC INGESTION BY FISH IN A NEOTROPICAL RESERVOIR: EFFECTS OF RESERVOIR DYNAMICS AND FISH TRAITS

ABSTRACT

Microplastic contamination poses a major threat in freshwaters, and rivers are considered sinks and pathways of plastic pollution to different ecosystems. Plastic abundance and concentration can be influenced by spatial factors, and artificial water bodies such as reservoirs can alter how plastics are distributed and interact with the biota. Additionally, biological traits like the trophic guilds and habitat use of animals can be important variables affecting plastic uptake. In this study, we investigated microplastic contamination in a fish community from a Neotropical reservoir. We assessed whether the distinct reservoir zones (fluvial, transitional, and lacustrine) had an influence on plastic ingestion by fish and also examined the effect of biological characteristics such as trophic guild and habitat use. Fibers and fragments of plastics were found in nine fish species and were identified as polyamide, polystyrene, and polyethylene. In general, plastic ingestion had a low incidence when compared to other reservoirs; however, we found that fish from the lacustrine zone, insectivores, and benthopelagic species showed a significant correlation with plastic ingestion. The findings presented here provide insights into the causes and the current state of microplastic pollution in Neotropical reservoirs.

Keywords: Trophic guild; Itaipu; Anthropic Pollution; Habitat Use

3.1 Introduction

Plastics have become a key cultural and economic component in recent decades, owing to their inherent features that allow them to be used in a broad range of applications. Because of their low cost and long-lasting characteristics, there has been a surge in manufacturing demand (Thompson et al., 2009; Zalasiewicz et al., 2016). However, the excessive use of these polymers, along with inadequate disposal management, limited reuse, and minimal recycling, has resulted in the ubiquitous presence and persistence of plastics in both terrestrial and aquatic environments, spanning from the poles to the equator (Barnes et al., 2009; Lusher et al., 2015). Plastic waste has been a growing concern in aquatic ecosystems due to the risks it poses to biodiversity and the environment (Eerkes-Medrano et al., 2015; Scherer et al., 2017; Wen et al., 2018). Although efforts were first concentrated on marine ecosystems, major rivers and lakes are gaining attention, following the discovery that they are polluted to the same extent by plastics (Biginagwa et al. 2016; Lebreton et al., 2017).

Freshwater habitats play an essential role in plastic transport from terrestrial environments to the seas (Lebreton et al., 2017). Tracking sources and sinks of plastics remains a challenge, although evidence suggests that plastic concentration is higher in urbanized watersheds that are often subjected to plastic pollution from terrestrial point sources (Huang et al., 2020; Wang et al., 2022). Because rivers or lakes can exhibit various physicochemical, hydrodynamic, and hydrological patterns, variations in the abundance and distribution of plastic particles can occur (Vayghan et al., 2022). After entering the environment, plastics can fragment due to weathering (i.e., mechanical abrasion or photodegradation) or interaction with animals, which can change their physical properties. The breakdown into countless smaller particles makes predicting concentrations and distribution of the so-called microplastics (particles with a size range from 1µm to 5mm; Barnes et al., 2009; O'Connor et al., 2022) even more challenging.

Along the longitudinal axis of a river, plastics concentrations are highly variable; areas of decreased flow velocity can enhance plastic settling, forming important deposition sites for plastic particles (Shen et al., 2023). The concentration of plastics can also be affected by the inflow of water from tributaries, being high near a point source of pollution while, conversely, the inflow of less polluted waters can dilute microplastic concentrations (Emmerik et al., 2022). Additional spatial variability needs to be assessed and can be further explored in artificial environments, such as reservoirs. As a distinct type of freshwater habitat, reservoirs have received little attention in terms of microplastic distribution, even though they can be a sink for plastic particles (Lebreton, 2017; Guo et al., 2021).

Reservoirs have distinct hydrodynamic patterns along the longitudinal axis, with lentic features in the portion close to the dam reservoir (lacustrine zone), intermediate stretches with lentic and lotic features (transitional zone), and the region upstream of the reservoir, with lotic characteristics (fluvial zone). These zones constitute a spatial gradient with varying flow velocity and sedimentation rate and may be further influenced by hydrological seasonality and dam operations (Thornton et al., 1990; Agostinho et al., 1994). These conditions within a reservoir, as well as the properties of microplastics such as density and shape, can affect transportation and consequently the spatial distribution of plastics. Once dammed, rivers can retain large amounts of suspended sediment, increasing the likelihood that they will form an effective trap for plastics and microplastics (Zhang et al., 2017; Guo et al., 2021).

Because of their small size, microplastics can be easily internalized by aquatic organisms, and so these animals can be a valuable indicator of the level of microplastics within an environment (Kukkola et al., 2021). Ingestion of plastics has been observed across a wide range of aquatic organisms, including several freshwater fish species (Azevedo-Santos et al., 2019; Müller, 2021). The wide range of colors, shapes, and sizes of the particles increases their potential availability, as these can be ingested accidentally or intentionally while feeding through the water column or benthos, for example (Roch et al., 2020). These particles, regardless of size, are linked to a series of detrimental impacts on fish in several ways: ingestion of plastic can lead fish to starve because it blocks the digestive tracts or otherwise impairs digestive function (Rummel et al., 2016; Cardozo et al., 2018); it can also affect reproduction, growth and eventually lead to death (Hossain & Olden, 2022).

Some recent hypotheses have proposed that the diverse properties associated with different feeding habits can enhance the likelihood of fish ingesting plastic (Mizraji et al., 2017; McNeish et al., 2018; Garcia et al., 2020). Fish feeding on detritus may randomly ingest plastics by disturbing the bottom layer and remobilizing denser particles embedded in the sediment, while visually orientated fish can actively ingest fibers or spheres that resemble their natural prey in size and/or color, like mosquito larvae or zooplankton (Roch et al., 2020; Ríos et al., 2022). Ingestion of microplastics adhered on the surface of plants or invertebrates is another potential source of accidental plastic intake by fish. (Kolandhasamy et al., 2018; Roy et al., 2023). Furthermore, species actively feeding and moving through the water column can be exposed to plastics present in all regions, i.e., at the surface, across the water column, and deposited in the benthic layer.

For fish inhabiting reservoirs, the longitudinal dynamics associated with feeding habits may help elucidate how spatial and biological factors can contribute to plastic intake by these aquatic animals. In this context, we reasoned that it would be valuable to investigate plastic intake along a longitudinal scale and with fish from multiple feeding guilds and habitat use, to better understand the impact of such factors at the community level. Moreover, understanding the presence of plastic in artificial freshwater habitats, such as reservoirs, is a pressing area of research. Following this rationale, we focused on investigating the following questions: (a) is there an intake of plastics by fish in the Itaipu reservoir? (b) does the longitudinal axis of the reservoir influence plastic ingestion by fish? and (c) is plastic ingestion related to fish feeding guilds and habitat use?

3.2 Material and Methods

3.2.1 Study area and sampling

This study was carried out in the Itaipu reservoir on the border between Brazil and Paraguay (24º15' and 25º33' S; 54º00 and 54º37' W), between March and December 2019. The reservoir is located downstream of many conservation areas on the Paraná River Basin, in addition to the constructed biological reserves created as the result of compensation measures (Ziober & Zanirato, 2014; Thieme et al., 2020). This reservoir, whose dam is located on the Paraná River, was closed in 1982. It has an area of 1350 km^2 and is approximately 150 km long. The average depth of the river is 22 m, reaching 170 m deep close to the dam, making it one of the largest hydroelectric power plants in the world (Silva et al., 2016). Besides its primary use, the Itaipu Reservoir is also used for navigation, recreation, tourism, fishing, and as a water supply for domestic and agricultural use.

Sampling was carried out quarterly over a period of 12 months at three stations: Guaíra (a fluvial zone), Santa Helena (transitional) and Foz do Iguaçu (lacustrine) (Fig. 1). At each sampling station, three batteries of gillnets of different mesh sizes (2.4, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15 and 16 cm) were installed and set for 24 hours, with inspections at 8:00 am, 4:00 pm, and 10:00 pm. Following the zonation approach of Thornton et al. (1990), nets were placed in three zones throughout the reservoir. In each zone, the nets were set in three strata (littoral, pelagic, and benthopelagic). Captured fish were anesthetized with benzocaine in accordance with ethical practice (Licença ICMBio- Número: 65850-1) and fixed (10% formalin). Subsequently, they were identified at the species level according to Ota et al. (2018), measured (total and standard length), weighed, eviscerated and the entire gastrointestinal tract (stomachs and intestines) was preserved in 4% formaldehyde for further analysis.

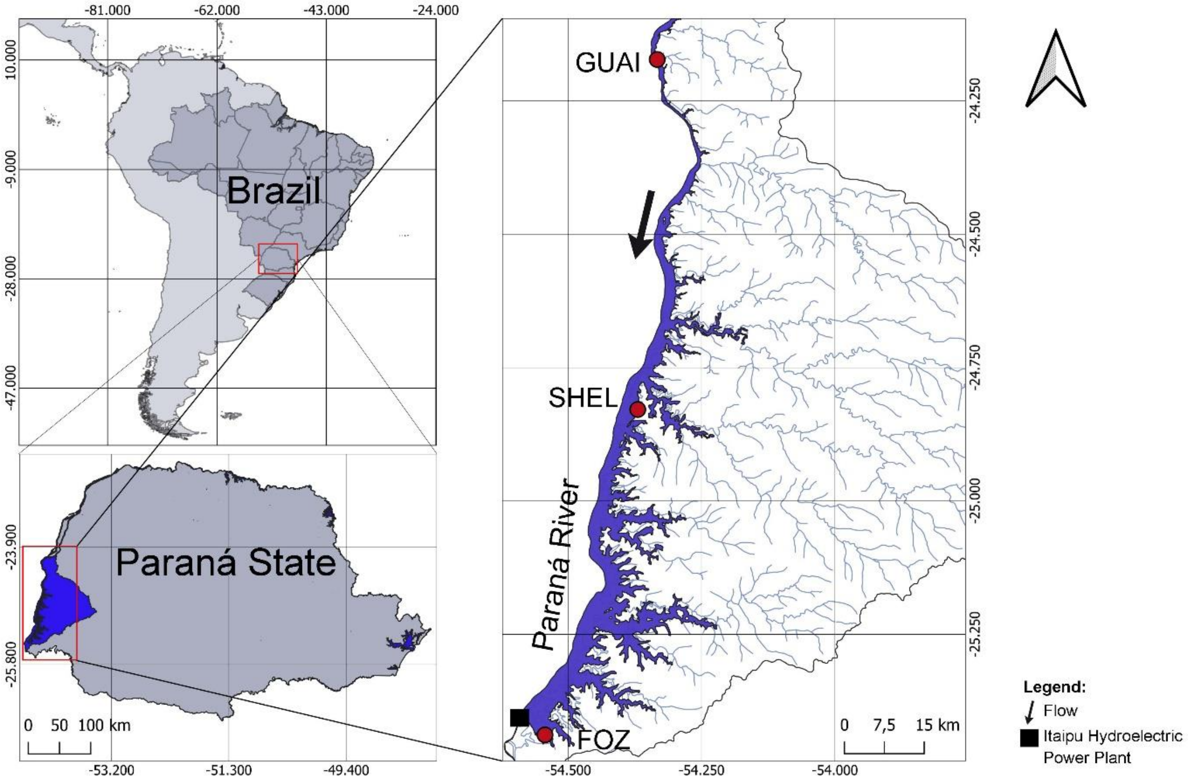

Fig. 1 Study area and sampling sites in the Itaipu Reservoir. Samplings were performed in the the fluvial zone (GUAI - Guaíra), the transitional zone (SHEL – Santa Helena) and the lacustrine zone (FOZ – Foz do Iguaçu)

3.2.2 Stomach content and plastics analysis

The gastrointestinal tract of the fish was analyzed under a stereoscopic microscope in order to determine the feeding guilds. Food items were identified to the lowest possible taxonomic level and quantified using the volumetric method (Hyslop, 1980). The fish gastrointestinal tract was analyzed for plastic particles and diet composition. All of the individual gastrointestinal tracts were analyzed, even those without food content since plastics can be present even if the other contents have already been digested. To extract all potentially remaining plastics, the desiccated gastrointestinal tract was chemically digested. To isolate plastic particles from residual organic matter and natural fibers, the desiccated gastrointestinal tract was placed in a solution of 10% potassium hydroxide (KOH) and incubated at 60°C for 48 h for chemical digestion (Rochman et al., 2015). After this period, the samples were filtered with a vacuum pump on a glass fiber filter (porosity of 1.2 µm) and dried for a period of 12 h at 60ºC. KOH digestion was chosen due to its efficiency in dissolving organic tissues and the fact that most polymers are resistant to KOH breakdown (Karami et al., 2017; Prata et al., 2019). For the quantification and characterization of plastic particles, the filters were inspected under a stereoscopic and optical microscope. Each plastic particle was classified according to its shape (fragment, line, or sphere), color, and size (microplastics, 1 µm−5 mm; mesoplastics, 5–20 mm; and macroplastics, ≥ 20 mm) (Barnes et al., 2009; O'Connor et al., 2022). All possible plastic particles were counted and stored in 70% alcohol for later analysis. To avoid cross-contamination, all samples were processed based on the method of Lusher et al. (2017). 100% cotton lab coats and disposable latex gloves were used, and the laboratory instruments were sanitized in distilled and filtered water. Finally, an assessment of airborne contamination was completed using control blanks prior to analysis. Petri dishes with microfiber filters were set up at the beginning of each work session, and particles similar to those identified within controls were disregarded from further analyses.

To identify the polymers, the spectrum of each sample was obtained and compared with the literature. Measurements for sample characterization were obtained using a Fourier transform infrared imaging microscope (LUMOS II, Bruker Optik GmbH). The spectra were acquired in Attenuated Total Reflectance (ATR) mode, in the spectral range of 4000-680 cm^{-1}, 8x objective, 4 cm^{-1} resolution, and 100 scans. The data were baseline corrected and the plastics were identified using the OPUS 8.5 software polymer library (Bruker Optik GmbH).

3.2.3 Data analysis

Fish trophic guilds were established from the matrix of stomach contents based on the Index of Alimentary Importance (Iai) (Kawakami & Vazzoler, 1980), which combines frequency of occurrence and volumetric approaches, providing an index that confirms the main food resources of the diet. Trophic guilds were then determined using an intermediate value (60%) of the main food item for each species. For the analysis of habitat use, fish were categorized into pelagic, benthopelagic, or demersal following Muniz et al. (2021). To assess whether reservoir zones (fluvial, transition, and lacustrine), trophic guilds, or habitat use (pelagic, benthopelagic, and demersal) influence the ingestion of plastic particles, we used a zero-inflated regression with negative binomial errors (ZINB) on the number of ingested plastics for each predictor variable. This approach is most suited for dealing with overdispersion issues and zeros in the response variable, as it models "zeros" and "counts" differently (Martin et al., 2005; Zeileis et al., 2008). Finally, for the trophic guild and habitat use analysis, we used only the categories in which at least one individual had ingested a plastic particle. All statistical analyses were performed using the software R 4.0.2 (R Core Team, 2022) using the packages “pscl” and “MASS”, and the graphics were made using the package “ggplot2”.

3.3 Results

We analyzed 552 individuals from the three reservoir zones (149 individuals in the fluvial zone, 216 in the transitional zone, and 187 in the lacustrine zone), belonging to 45 species (Table 1). Considering the major group of food resources based on the IAi, fish were classified into 10 trophic guilds: benthophagous, carcinophagous, detritivore, herbivore, insectivore, molluscivore, omnivore, piscivore, piscivore-carcinophagous and piscivore-insectivore. The herbivore guild was the most abundant in the fluvial and lacustrine zones, accounting for 21.73% and 25.92%, respectively, of the relative abundance among guilds, while in the transitional zone, the piscivores accounted for 34.48%. Regarding habitat use, all zones had a higher percentage of benthopelagic species, but in general, fish were evenly distributed with respect to water column position (Fig. 2).

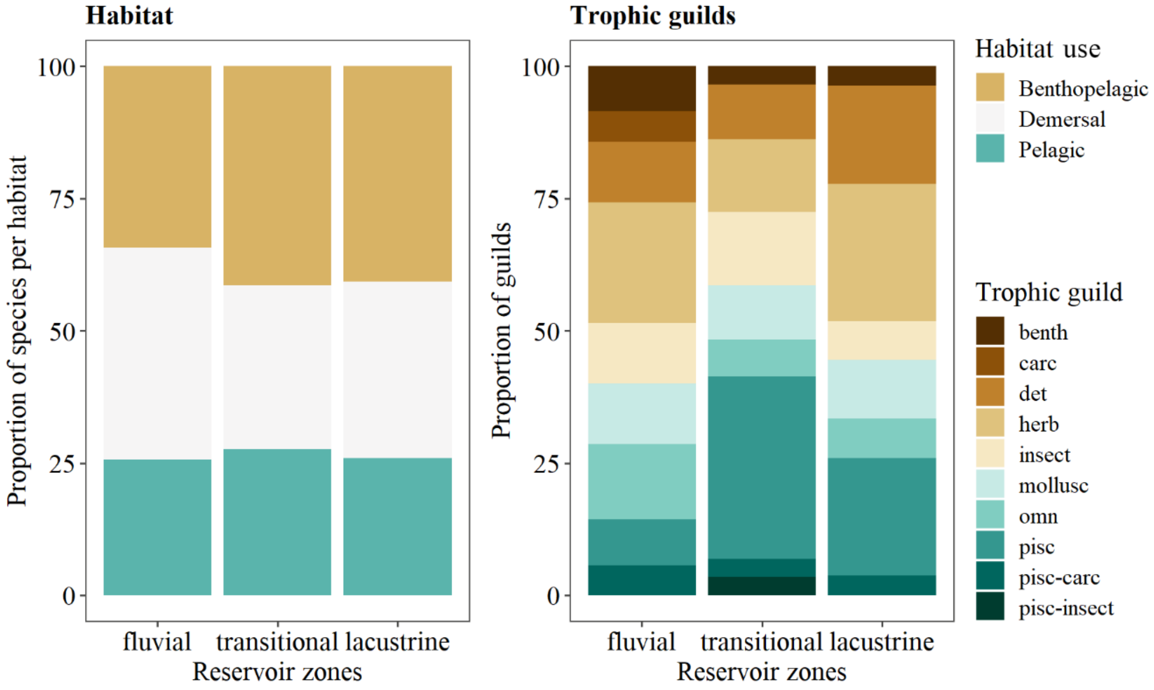

Fig. 2 Proportion of species of different habitat use and trophic guilds sampled and distributed among the Itaipu reservoir zones. Benth= benthophagous; carc= carcinophagous; det=

detritivore; her= herbivore; insect= insectivore; mollusc= molluscivore; omn= omnivore; pisc= piscivore; pisc-carc= piscivore-carcinophagous; pisc-insect= piscivore-insectivore

Table 1. Characterization of biological features of fish. Mean values of length and weight of fish collected from the Itaipu reservoir. * Only one individual; Ls, standard length; Wt, weight; SD, standard deviation

Species	Mean Ls	SD	Mean Wt	SD	Habitat	Trophic guild
Acestrorhynchus lacustris	11.57	6.70	47.33	50.00	benthopelagic	piscivore
Ageneiosus ucayalensis	16.2	3.74	86.03	30.15	pelagic	carcinophagous
Apareiodon affinis	8.59	4.53	8.59	28.19	benthopelagic	detritivore
Astyanax lacustris	10.70	4.01	32.82	22.15	pelagic	insectivore
Auchenipterus osteomystax	19.15	3.99	109.97	43.58	pelagic	insectivore
Cichla piquiti	25.45	2.67	419.85	129.28	benthopelagic	piscivore
Crenicichla britskii	12.08	2.52	52.52	37.54	benthopelagic	omnivore
Galeocharax gulo	13.89	5.02	55.61	34.86	benthopelagic	piscivore-carcinophagous
Geophagus sveni	12.31	3.24	83.29	62.21	demersal	omnivore
Hemiodus orthonops	16.42	3.89	105.30	88.23	pelagic	herbivore
Hoplias argentinensis	29.16	6.16	583.32	330.48	benthopelagic	piscivore
Hoplias mbigua	24.71	4.28	331.66	191.74	benthopelagic	piscivore
Hoplias sp.*	33.1		787.0		benthopelagic	piscivore
Hypostomus cf. *trigaticeps**	13		73.94		demersal	detritivore
Hypostomus cochliodon	17.03	2.28	150.75	51.71	demersal	herbivore
Hypostomus regani	18.20	31.08	132.04	31.08	demersal	detritivore
Iheringichthys labrosus	15.84	2.74	76.03	40.28	benthopelagic	benthophagous
Leporinus friderici	23.16	0.99	355.14	72.73	benthopelagic	molluscivore
Leporinus lacustris	15.48	2.40	162.87	78.01	benthopelagic	herbivore
Loricaria sp.	19.91	4.18	55.31	33.81	demersal	molluscivore
Loricariichthys platymetopon	21.91	3.46	96.78	39.92	demersal	detritivore
Loricariichthys rostratus	19.39	2.98	47.73	11.16	demersal	detritivore
Megalancistrus parananus	36.72	3.54	1849.25	393.32	demersal	molluscivore
Metynnis lippincottianus	11.26	1.23	76.11	25.35	pelagic	herbivore
Pimelodella gracilis	10.68	0.79	16.66	4.47	demersal	insectivore
Pimelodus maculatus	27.7	0	465.92	39.99	demersal	herbivore
Pimelodus mysteriosus	11.4	2.61	44.55	37.90	demersal	piscivore
Pinirampus pirinampu	27.6	1.20	314.85	74.03	demersal	piscivore-insectiovore
Plagioscion squamosissimus	21.28	5.84	250.05	220.72	pelagic	piscivore
*Potamotrygon amandae**	22.5		633.50		demersal	molluscivore
Potamotrygon cf. *falkneri*	59.2	8.76	7320	3450	demersal	piscivore
Prochilodus lineatus	37.33	4.84	1686.73	615.21	benthopelagic	detritivore
Pterodoras granulosus	34.48	3.79	1338.55	523.15	demersal	molluscivore
Pterygoplichthys ambrosettii	24.36	3.48	455.13	192.90	demersal	detritivore
Rhamphichthys hahni	55.0	5.37	333.50	71.55	benthopelagic	omnivore
Rhaphiodon vulpinus	34.23	5.85	283.74	175.50	pelagic	piscivore

Salminus brasiliensis	45.03	16.22	2321.37	15.84	benthopelagic	piscivore
Satanoperca sp.	14.72	1.92	136.63	63.33	benthopelagic	herbivore
Schizodon borellii	22.36	2.40	319.77	124.56	benthopelagic	herbivore
Serrasalmus maculatus	16.09	3.08	184.93	160.10	pelagic	piscivore
Serrasalmus marginatus	13.32	4.75	120.29	133.54	pelagic	piscivore
*Sorubim lima**	20.5		72.47		demersal	piscivore
*Steindachnerina brevipinna**	8.2		14.86		benthopelagic	detritivore
*Trachydoras paraguayensis**	8.3		28.66		demersal	benthophagous
Trachelyopterus galeatus	15.36	6.46	128.85	58.65	pelagic	insectivore

Our study found that all of the plastic particles recovered from fish were classified as microplastics (1 µm–5 mm) and were present in nine out of the 45 fish species studied, with 23 plastic particles recovered from 16 individual fish (2.89% of total fish) (Table 2). Analysis of the types of plastic ingested by fish revealed that the majority of the particles were fibers, with blue fibers being the most commonly found (18 particles) followed by black fibers (3 particles). Additionally, fragments of white (1 particle) and blue (1 particle) plastics were also recovered (Fig S1). The plastics were identified as being composed of polyamide (PA), polystyrene (PS), and polyethylene (PE) (Table 2; Fig. 3). The results showed that polyamide was the most common type of plastic in all fish samples, accounting for 82.60% of the total plastic particles recovered.

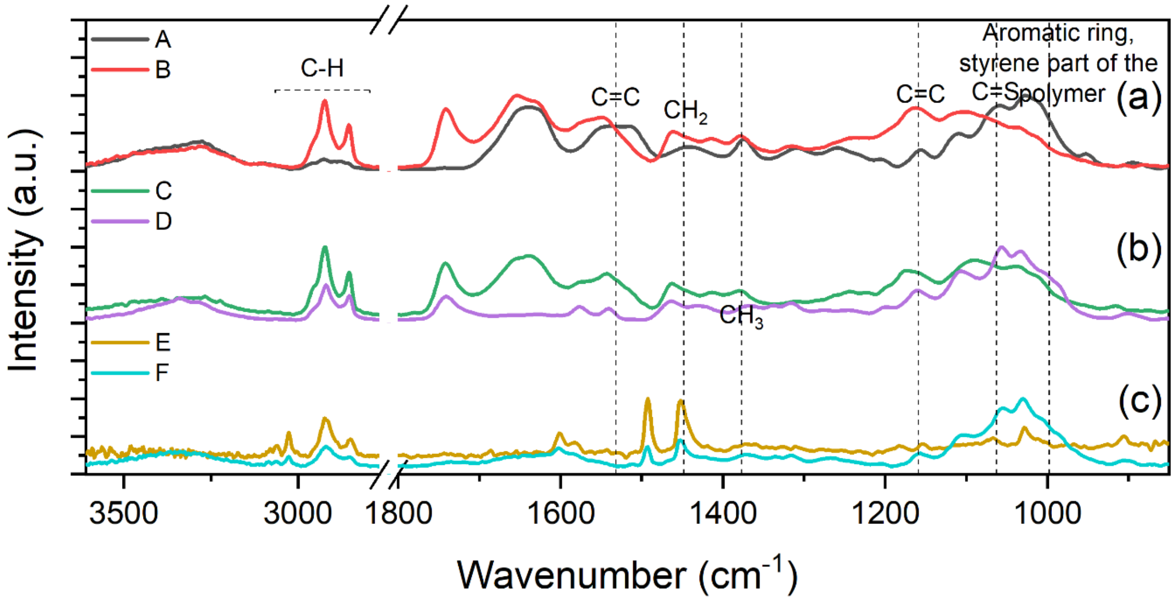

Fig. 3 Spectra of plastics identified using the polymer library in the OPUS 8.5 software (Bruker Optik GmbH). Samples A and B are polyamide, C and D are polyethylene and samples E and F are polystyrene

Table 2. Microplastics recovered from fish species in the different zones of the Itaipu reservoir. *n* = number of individuals that presented plastic particles in the gastrointestinal tract. PA- Polyamide; PS- Polystyrene; PE- Polyethylene

Zonation	**Species**	***n***	**PA**	**PS**	**PE**
Fluvial	*Hypostomus cochliodon*	3	2		1
Fluvial	*Iheringichthys labrosus*	1	1		1
Fluvial	*Trachelyopterus galeatus*	2	1		1
Transitional	*Auchenipterus osteomystax*	1	1		
Transitional	*Geophagus sveni*	1	1		
Transitional	*Iheringichthys labrosus*	1	1		
Transitional	*Metynnis lippincottianus*	1	1		
Transitional	*Trachelyopterus galeatus*	1	2		
Transitional	*Rhaphiodon vulpinus*	1	1		
Lacustrine	*Auchenipterus osteomystax*	1	1	1	
Lacustrine	*Galeocharax gulo*	1	2		
Lacustrine	*Iheringichthys labrosus*	1	4		
Lacustrine	*Leporinus lacustris*	1	1	1	

The results of our study indicate a significant effect of reservoir zonation on plastic ingestion by fish, as evaluated through the zero-inflated model (Count-model). Specifically, fish from the lacustrine zone of the reservoir had significantly higher ingestion of plastic particles compared to other zones ($p<0.001$). Conversely, fish in the fluvial zone, which mimics the natural river flow, demonstrated significantly lower ingestion of plastic particles in their gastrointestinal tracts (intercept; $p<0.001$). The absence of plastics (Zero-model) was not significant for any of the zones (Table 3). Among the various fish trophic guilds, only the insectivore guild had a significant, positive correlation with plastic ingestion ($p<0.05$). The position of the fish within the water column also had an effect; fish classified as benthopelagic were significantly more likely to exhibit plastic ingestion compared to other categories of habitat ($p=0.004$). The absence of plastics (Zero-model) was not significant for any of the trophic guilds or habitats (Table 3).

Table 3. Results of the zero-inflated GLM with negative binomial distribution for errors (ZINB) testing the relationship between total numbers of debris ingested and reservoir zones. The intercept represents the fluvial zone, which is used as a reference level. Significant values ($p<0.05$) are highlighted in bold

Count-model

	Estimate	**Std. Error**	**z value**	**p**
(Intercept)	**-3.2114**	**0.4157**	**-7.725**	**<0.001**
lacustrine	**3.83**	**0.558**	**6.864**	**<0.001**
transition	-0.3721	0.5827	-0.639	0.523
Log(theta)	10.691	180.4092	0.059	0.953
		Zero-model		
	Estimate	**Std. Error**	**z value**	**p**
(Intercept)	-7.173	102.484	-0.07	0.944
lacustrine	10.592	102.485	0.103	0.918
transition	-4.665	1280.435	-0.004	0.997

Table 4. Results of the zero-inflated GLM with negative binomial distribution for errors (ZINB) testing the relationship between total numbers of debris ingested and trophic guilds and habitat use. The intercept represents the demersal and herbivore traits, which are used as a reference level

		Count model – trophic guild		
	Estimate	**Std. Error**	**z value**	**p**
(Intercept)	-2.33238	0.57808	-4.035	<0.001
insectivore	**3.16748**	**1.39732**	**2.267**	**0.0234**
omnivore	-1.75584	1.42184	-1.235	0.21686
piscivore	0.13003	1.5131	0.086	0.93152
piscivore-carcinophagous	-0.07091	1.25103	-0.057	0.9548
bentophagous	-0.09608	0.98545	-0.097	0.92233
		Count model – Habitat Use		
pelagic	-1.98506	1.15505	-1.719	0.08569
benthopelagic	**2.86931**	**1.00772**	**2.847**	**0.00441**
Log(theta)	10.8075	359.2788	0.03	0.976

		Zero-model – Trophic Guild		
	Estimate	**Std. Error**	**z value**	**p**
(Intercept)	-11.37	165.057	-0.069	0.945
insectivore	27.9223	329.1325	0.085	0.932
omnivore	6.2889	101.5514	0.062	0.951
piscivore	20.89	230.4483	0.091	0.928
piscivore-carcinophagous	-0.0848	1.5305	-0.055	0.956
bentophagous	-1.3341	1.2612	-1.058	0.29
		Zero-model – Habitat Use		
pelagic	-15.607	284.754	-0.055	0.956
benthopelagic	14.7757	165.0553	0.09	0.929

3.4 Discussion

In this study, microplastics were found in nine out of the 45 fish species studied. Despite the low incidence, we found that the type of reservoir zone can influence the uptake of plastic particles, as well as the trophic guild and the position that fish occupy in the water column. Our results showed that fibers and polyamide were the most common shape and polymer type of microplastics found.

The prevalence of plastic ingestion was generally low, which is contrary to what was expected. Nonetheless, we found that the lacustrine zone of the reservoir can enhance the intake of microplastic, while the fluvial zone has the opposite effect. Within the aquatic ecosystem, plastic pollution can be considered to be omnipresent (Zalasiewicz et al., 2016; Kukkola et al., 2021) and there is a growing consensus that river damming creates retention sites for plastic particles (Guo et al., 2021; Dhivert et al., 2022). Our results demonstrate that the distinct zones of the reservoir can play a significant role in plastic ingestion by fish. Specifically, the fluvial zone, characterized by high water velocity and discharge that resembles a free-flowing river, showed a negative relationship with plastic intake by fish; plastic particles are more likely to be transported downstream rather than being trapped in this zone because of an imbalance between sedimentation and resuspension processes (Dhivert et al., 2022). Conversely, the lacustrine zone exhibited a positive relationship with plastic uptake, likely due to the tendency of microplastics to accumulate in static water bodies with low water flow and turbulence, which hinders resuspension and long-distance transport (Krause et al., 2021; Dhivert et al., 2022). This finding suggests that certain areas within the reservoir may accumulate more plastic particles than others, and fish ingestion becomes more likely. Furthermore, the presence of a cascade of dams upstream, such as the Porto Primavera dam, can act as microplastic sinks, which may be a critical factor for the lower number of plastics reported for the fluvial zone and the reservoir in general. Cascades of dams can intercept particles of different sizes; large particles settle in the upstream reservoirs, and smaller particles continue traveling downstream with the flow (Wu et al., 2022). It is important to note that only microplastics (small-sized fibers and fragments) were found in the gastrointestinal tracts of fish in our study, indicating that denser and larger-sized plastic particles may settle upstream of the reservoir or disintegrate into multiple smaller fragments before reaching downstream zones (Shen et al., 2023). This is reinforced by the study of Cardozo et al. (2023) that found mesoplastics in the GIT of fish in the upper Paraná River floodplain, the last relevant stretch of running water in the Paraná River restricted to 230 km between the Porto Primavera Dam and the Itaipu reservoir (Agostinho et al., 2008).

Beyond hydrodynamic characteristics, other factors associated with reservoir zones may also impact plastic distribution. The lacustrine zone is located near cities with denser populations and extensive agriculture and livestock raising (Ziober & Zanirato, 2014; Thieme et al., 2020). The higher number of particles ingested by fish in the lacustrine zone may reflect the activities surrounding this region and probably indicates higher availability when compared to the fluvial and transitional zones. The spatial variation of microplastics abundance is strongly driven by anthropogenic factors, such as nearby land use, agricultural activities, and population density relative to the river or dam location (McNeish et al., 2018; Huang et al., 2020; Li et al., 2020). Plastics and microfibers tend to be higher in these areas due to the prevalence of point and nonpoint sources, such as urban and agricultural runoff carried by stormwater, or airborne fibers from built-up areas (Wang et al., 2022; Österlund et al., 2023). As most studies conducted on reservoirs are inside large urban centers (e.g., Zhang et al., 2015; Huang et al., 2020; Shen et al., 2023), the direct inputs of MP from these point sources result in high abundances of these particles and may lead to higher detection frequencies. In contrast, the Itaipu dam, even though located proximate to urban centers, has protected areas at the margins in efforts to mitigate the ecological impacts from the construction and operation of the dam (Ziober & Zanirato, 2014; Thieme et al., 2020). Rivers and watersheds within forested areas have lower concentrations of microplastics than human-dominated landscapes (McNeish et al., 2018; Costa et al., 2023). These areas may receive fewer direct inputs of plastics, as well as a dilution effect from less polluted tributaries compared to other impounded systems, especially those located in Asia, that are commonly located inside populous cities and receive direct inputs from plastic production factories and wastewater from treatment plants (Huang et al., 2020; Li et al., 2020).

It is already recognized that some biotic factors are linked to potential routes of plastic ingestion, and so the habitat and trophic level occupied by fish are potentially important when investigating plastic uptake (Mizraji et al., 2017; Roch et al., 2020; Costa et al., 2023). Species with different diets can exhibit distinct levels of ingested particles (Garcia et al., 2020; Cardozo-Ferreira et al., 2021). Our results showed that insectivores are more likely to ingest microplastics than herbivores. Fish that feed on insects, especially terrestrial ones, tend to increase their chances of ingesting vulnerable and floating prey by actively swimming along the water column and rapidly attacking drifting particles (Brejão et al., 2013). Blue and black fibers were the predominant colors ingested by fish. Corroborating these results, Costa et al. (2023) identified that insectivorous fish also consumed higher amounts of black and blue plastics, which resemble the color and shape of their preferential food items. These colors seem to exert a stronger attraction than white or transparent fragments to visual predators (Ríos et al., 2022). In a natural setting, where a mixture of food and plastic particles is expected, plastic uptake by fish may increase due to greater voracity in the presence of food, leading to both active and accidental ingestion (Ríos et al., 2022). The use of trophic guild as a factor influencing plastic uptake in fish has produced mixed results. Different guilds have been considered more or less vulnerable to plastic ingestion (Andrade et al., 2019; Costa et al., 2023) while, in some cases, no effect has been observed (Pazos et al., 2017; Dantas et al., 2020). In general, species that forage and select animal prey items over plant or detritus seem to be more prone to plastic ingestion; such species can actively ingest particles without discriminating them from real food, or passively ingest them unintentionally (Mizraji et al., 2017; Wootton et al., 2021; Müller, 2021).

Recently, studies have reported high plastic detection frequencies in the interface between water and sediment, indicating that they may be hotspots for plastic accumulation (Frei et al., 2019; He et al., 2020). Therefore, it is expected that organisms that feed in or use this habitat are more susceptible to plastic ingestion (Drummond et al., 2022; Krause et al., 2021). Here, we found that benthopelagic species are more prone to having these particles in their GIT than demersal species. Compared to other reservoirs that are usually shallow (depths ranging to a maximum of 35.5 m) (Watkins et al., 2019; Hurt et al., 2020; Shen et al., 2023), the Itaipu reaches 170 m in depth close to the dam (Agostinho et al., 1994). This depth, together with other chemical and physical characteristics, makes occupation by fish difficult. In this zone, the benthopelagic species are foraging and mainly use the littoral areas of the reservoir (Oliveira et al., 2003), while the benthic layer is often underutilized. Benthopelagic species can swim and forage in both the pelagic and littoral areas, which probably increases their chances of encountering and ingesting particles such as settled or buoyant fibers or fragments that are present in the upper layers.

Certain physical properties of MPs (shape, size, or density) and their interactions with the surrounding environment affect the likelihood of their ingestion (Kooi et al., 2021; Fernandes et al., 2022). It is important to note that the analysis of the fish GIT offers only limited insight into the recent ingestion of an individual fish. Throughout their lifetime, fish will certainly consume microplastic, but depending on the size of the species, plastic fragments that are small enough will be egested and reduce the average microplastic burden. Synthetic fibers, however, can become tangled in the GIT and are potentially retained for longer periods, increasing the frequency of detection (Roch et al., 2020; Santana et al., 2021; Hou et al., 2022).

Blue fibers were the predominant type of microplastic found and originated from the breakdown of primary macro litter. In reservoirs, fibers can account for up to 90% of the microplastic shapes found in biotic tissues (Guo et al., 2022). The predominance of fibers can be related to freshwater environments that are often close to the discharge of point sources, such as domestic wastewater and runoff from pasture and agricultural lands, which are directly discharged into the environment (Sillanpää & Sainio, 2017). Fibers of polyamide most likely arise from the washing of clothes (Almroth et al., 2018), but can also be linked with two common activities carried out nearby: agriculture and fisheries (Lwanga et al., 2022; Cardozo et al., 2023). Contaminated waters from irrigation or contaminated fertilizers are known to contain high levels of microplastics, which can be washed into rivers or dams when it rains (Nizetto et al., 2016; Li et al., 2020), while synthetic fibers can be released from the weathering of nets from fisheries (Napper et al., 2022; Cardozo et al., 2023). Because of the reservoir dynamics, transport of microplastic is similar to that of sediments (Dhivert et al., 2022). Denser polymers such as PA (Erni-Cassola et al., 2019; PlasticsEurope, 2022) can be more easily trapped and begin to sink as a response to the sedimentation in the reservoir, potentially becoming available for fish foraging in the littoral areas.

Microplastic ingestion by fish in the Itaipu reservoir appears to be less common than expected. However, the lacustrine zone, the trophic guild, and habitat use were found to be significant factors affecting plastic uptake. The longitudinal characteristics of the reservoir were important in detecting microplastic uptake by fish, as well as the biological traits of these organisms. Insectivore and benthopelagic fish were traits suggested to increase susceptibility to MP ingestion compared to the others. The results presented here add further insight into the driving factors and current status of microplastic pollution in reservoirs in the Neotropical region. Our study highlights the urgent need to conduct studies on both the biota and the environment to better understand (i) the distribution of microplastics when subjected to non-natural environmental conditions, and (ii) the potential of such factors to act as predictors of microplastic entry into the food web. Overall, the implications of this study are important for environmental management and policy development, as well as for raising public awareness about the impacts of plastic pollution, especially those close to the main sources of MP input into freshwater ecosystems.

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4 PLASTIC POLLUTION: A GLOBAL SYNTHESIS ON FRESHWATER FISH AND INVERTEBRATES

ABSTRACT

Plastic contamination poses a widespread threat to aquatic wildlife, affecting numerous species, including fish and invertebrates. This is an ever-expanding area that requires ongoing assessments to effectively keep up with publications and guide toward comprehensive future work. This systematic review synthesized the literature focusing on the reports of plastic on freshwater fish and invertebrates. We assessed biological and ecological factors that can influence the presence of such pervasive pollutant across fish and invertebrates worldwide. Specifically, we evaluated the role of sampling environment, trophic guild, habitat use, body part assessed, body length and body weight on the occurrence of plastic for these animals. Our synthesis revealed that for freshwater biota, reporting on plastic occurrence predominantly still focuses on fish, but efforts have increased in recent years toward identifying this threat in invertebrates. Overall, biological and ecological traits did not strongly predict higher plastic occurrence neither for fish nor invertebrates, highlighting the vulnerability of both taxa to plastic pollution. By compiling global studies on plastic occurrence in freshwater biota, we identified some regional and other knowledge gaps that need to be further addressed to guide research strategies and public policies to address and mitigate this pressing environmental concern, ultimately safeguarding freshwater biodiversity.

Keywords: microplastic; Anthropogenic impact; Wildlife conservation; inland water

4.1 Introduction

Plastic pollution is a complex and multifaceted environmental issue of global urgency, and it is argued that it is irreversible and globally ubiquitous (Villarrubia-Gómez et al., 2018; Hale et al., 2020). This synthetic material is so pervasive in the environment that it is now regarded as a geological marker of the Anthropocene, an era characterized by the predominance of the anthropic footprint (Chen et al., 2022; Alves et al., 2023), and even an era referred to as the "Plastic Age" (Thompson et al., 2009). Concerns about plastic pollution in aquatic environments emerged as far back as the 1970s, primarily focusing on the conspicuous "macroplastic" pollution (Napper & Thompson, 2019). However, there is now a growing awareness of the problem of microplastics, which has gained significant attention in recent years within the scientific community and mainstream media (Catarino et al., 2021).

Most plastic is produced on land, and nearly all of the plastic is used and discarded on land. However, the focus and quantification of plastic debris have been carried out extensively only for marine environments (Blettler et al., 2018). Recent research has revealed that plastic pollution is not static but circulates from one ecosystem to another (Lebreton et al., 2017). Terrestrial and freshwater ecosystems, often overlooked, can be significant sources and conduits of plastic pollution in marine ecosystems. Existing research depicts an alarming parallel between plastic pollution levels in freshwater environments and those found in marine habitats (Lebreton et al., 2017; van Emmerik & Schwarz, 2019). Despite this crucial information, the assessment and quantification of plastic debris in freshwater environments remain lagged, and the specific interactions of plastics with the biota in freshwater ecosystems have yet to be fully understood (Granek et al., 2020; Azevedo-Santos et al., 2021).

The rising awareness of the negative consequences of plastic on aquatic life has prompted an upsurge in studies reporting the occurrence of plastic in freshwater animals (Granek et al., 2020; Catarino et al., 2021). The presence of plastic in freshwater organisms has emerged as a critical area of concern for a better understanding of the pervasive nature of plastic pollution and its associated risks. Aquatic organisms can interact with plastics due to entanglement or ingestion (Sigler, 2014; Blettler & Mitchell, 2021), and several studies have reported the occurrence of plastics on many species from different trophic levels and geographic areas (Garcia et al., 2020; Pastorino et al., 2021). Freshwater fishes are the group with the most extensive records on plastic occurrence up to now (Azevedo-Santos et al., 2021), particularly investigating the ingestion of microplastics, showcasing how widespread plastic ingestion is among these animals. Moreover, many studies have shown that other animal groups, from microscopic zooplankton to mammals, are at risk of ingesting or incorporating plastic particles within their bodies (Azevedo-Santos et al., 2021; Multisanti et al., 2022).

Plastic can harm freshwater animals and trigger negative ecological consequences in numerous ways. Among these negative consequences, large particles or tangled fibers can physically block the gastrointestinal tract, cause inflammation of tissues, reduce growth, and compromise reproductive success (Hodkovicova et al., 2022). Yet, plastic impacts can extend far beyond these effects. There is growing concern that the ingestion of plastic by wildlife moves through the food chain (Provencher et al., 2019). Although this topic is in its infancy and still gathering evidence, some studies have shown that predator species ingest more plastic because of feeding on already contaminated prey (Provencher et al., 2019; Justino et al., 2023). Currently, the mechanisms behind how animals “select” plastics and end up ingesting them are still incipient and lack solid conclusions regarding the influence of ecological and biological traits on plastic uptake.

Factors influencing animals’ exposure to plastic hazards can encompass environmental, biological, and behavioral aspects (Bertoli et al., 2022; Costa et al., 2023; Cardozo et al., 2023). Environmental factors can include the dynamics of water flow and sedimentation (D’Avignon et al., 2021), seasonality (van Emmerik et al., 2023) and whether the environment is natural or semi-natural (i.e., reservoirs) (Guo et al., 2021). Additionally, surface accumulation and the deposition of plastic in the shorelines and river bottoms can be different and alter the availability of plastics for organisms (D’Avignon et al., 2021). Regarding biological and ecological traits, morphology, feeding habits, and habitat use have been linked to the susceptibility to ingesting plastic. Species that forage using visual cues can be prone to ingesting plastic-like prey by mistake (de Sá et al., 2015; Ory et al., 2017; Roch et al., 2020), while those that rely more on chemosensory mechanisms can be better at discriminating plastic from actual food (Roch et al., 2020). Organisms inhabiting and foraging in specific habitats, such as benthic invertebrates, or demersal fish, can be highly vulnerable to plastic given the prevalent detection of microplastics in the bottom layers (Scherer et al., 2020; D’Avignon et al., 2021). Beyond ingesting plastic, these particles can be absorbed through the respiratory pathway (Roch et al., 2020; Ribeiro-Brasil et al., 2023; Shen et al., 2023). They seem to attach to gills during ventilation and may enter the circulatory system, being transported to other organs or tissues (Lu et al., 2016; Roch et al., 2020). While there is growing evidence that plastic can be consumed or otherwise uptake through different pathways (Roch et al., 2020), there is a general scarcity of studies on freshwater organisms linking biological and ecological traits to plastic occurrence, and it do not appear to be consistent across studies. Therefore, predicting the specific features in animals that make them more vulnerable or at higher risk becomes challenging.

We conducted a comprehensive global synthesis, both qualitative and quantitative, of the extent of plastic occurrence within freshwater biota (fish and invertebrates). We investigated several aspects that can influence the presence of plastics across diverse freshwater animals. Specifically, we evaluated the current knowledge on plastic reports regarding animal groups, sampling environment, trophic guild, habitat, body part assessed, body length, body weight and plastic size.

4.2 Materials and Methods

4.2.1 Data sampling

To synthesize the existing literature on the occurrence of plastic in freshwater fish and invertebrates, we conducted a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. We conducted a comprehensive search of scientific articles in two databases: Web of Science and Scopus. The search was conducted with no language restrictions. The following search terms were employed combined with Boolean arguments: ("micro-plastic*" OR microplastic* OR mesoplastic* OR macroplastic* OR "plastic debris" OR "plastic fragment" OR "plastic uptake" OR "plastic ingestion") AND ("fish* OR invertebrate* OR macroinvertebrate* OR zooplankton OR mussel* OR mollus? OR gastropod* OR bivalv* OR decapod* OR crustacea* OR larva* OR insect* OR biota OR animal") in April 2023. We did not restrict the search to specific keywords related to marine environments because excluding such keywords could potentially eliminate articles that might mention marine-related terms in their abstracts even when the primary focus is on freshwater environments.

The initial search yielded a total of 5082 records from Web of Science (WoS) and 4328 from Scopus. Following this, duplicates were removed, resulting in 9002 unique records. Most articles (*n* = 8582) were excluded because they were out of scope (mainly studies conducted on marine environments). The remaining 450 articles had their full text screened for eligibility. Several articles were excluded because they were still out of scope (the title or abstract did not provide enough information indicating whether the sampling location or species were from the freshwater realm; *n* = 251). Some studies did not provide sufficient data or details, even after thorough searches for online appendices or attempts to contact the authors for additional information (*n* = 19). Additionally, some studies (*n* = 4) were eliminated from the review as the full-texts were unavailable, hindering a comprehensive assessment of their content. Furthermore, articles in languages other than English, Portuguese, or Spanish were excluded (*n* = 6). Because different methodologies result in different ways of reporting the number of plastics, we included only studies that reported the mean number of plastics per individual in our analyses. This approach ensures that our results are consistent and can be effectively compared. This resulted in 114 studies included in our quantitative synthesis (Fig. 1).

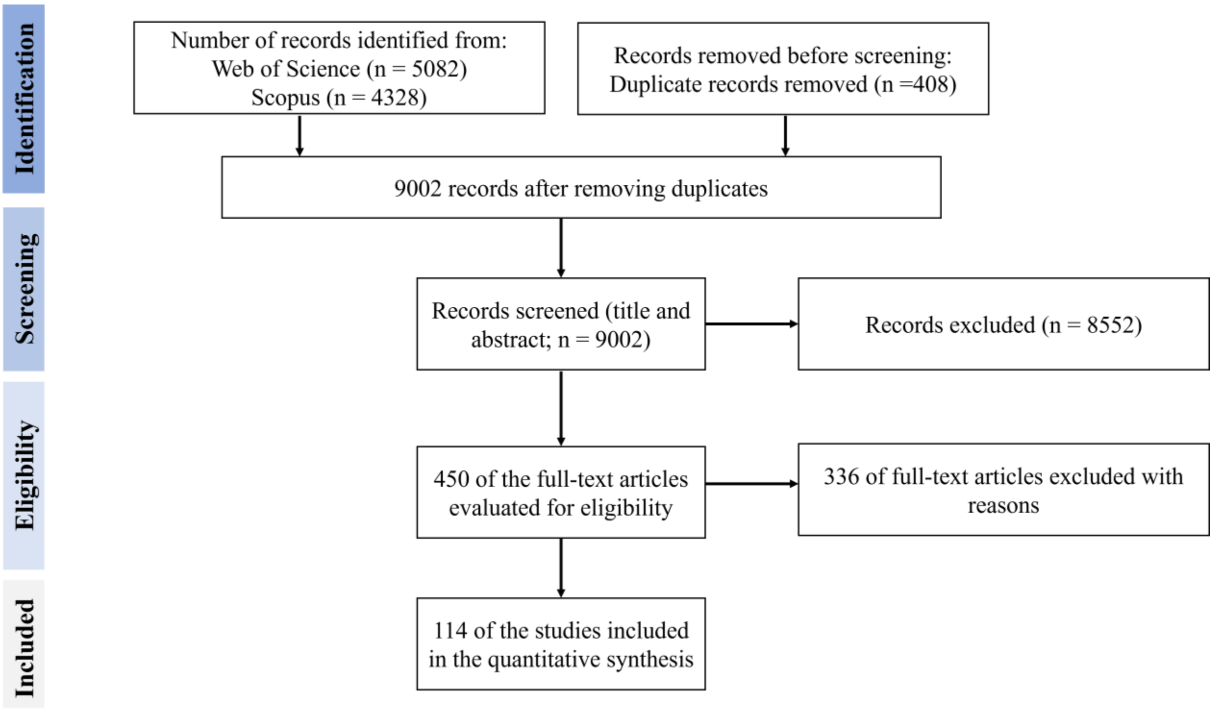

Fig. 1 A flowchart of the study selection process following the PRISMA (Preferred Reporting Items for Systematic Reviews) guidelines, outlining the criteria used for the systematic literature review.

From the selected studies, we extracted information directly from the text, data tables or graphs provided by the main text and supporting information. Data from graphs were extracted using the desktop version of WebPlotDigitizer (Rohatgi 2020). For every species included in each study, information obtained included: (1) animal group (which group the animal belongs to: invertebrates or fish); (2) name of species; (3) sampling environment (i.e., river, lake, stream, reservoir); (3) trophic guild; (4) habitat use (i.e., pelagic, benthopelagic or demersal/benthic); (5) body part assessed (stomach, whole gastrointestinal tract; gills; liver; muscle; whole body; soft tissue); (6) body length and body weight; (7) geographic location (country and geographical coordinates); (8) plastic size (micro, meso or macro) and (9) mean number of plastic per individual. Information on fish trophic guild and habitat were further sourced from FishBase website (Froese and Pauly, 2023) when not provided in the original article. When information about trophic guild and habitat was not provided for the invertebrates, it was sourced from other articles that included such information.

4.2.2 Synthesis design

In the first section of the results ("*Number of studies of plastic ingestion by freshwater fishes and invertebrates*"), we presented a comprehensive overview of the findings of all the studies within the scope included in our analysis (*n* = 179), primarily focusing on qualitative information (number of studies conducted per region and animal group). In this section, we summarized studies that reported the presence of plastic in freshwater biota, even when specific quantitative data may not have been available (mean number of plastics per individual). This qualitative assessment provides valuable insight into the widespread occurrence of plastic pollution across freshwater animal groups (Online Resource 1 Tables S1 and S2).

The second section of the results explores a statistical global analysis of plastic interaction by freshwater fish and invertebrate taxa ("*Drivers of plastic ingestion by freshwater fishes and invertebrates*"). Here, we presented quantitative and statistically analyzed data (mean number of plastic particles per individual), drawing upon the information collected from multiple distinct studies ($n_{\text{(fish)}} = 83$; $n_{\text{(invertebrates)}} = 31$; Online Resource 1 Tables S3 and S4) within these two major taxonomic groups, considering biological traits and environmental factors, detailed above, as potential influencers. This section provides a more in-depth examination of the relationships between these factors and the occurrence of plastics, allowing for a better understanding of the patterns and drivers of plastic pollution in freshwater ecosystems.

4.2.3 Data analysis

To comprehensively assess the global occurrence of plastic in distinct animal groups (as detailed for the second section above), species data extracted from the literature were grouped on fish and invertebrates. We applied a log + 1 transformation to the mean values of reported plastics per species to reduce data variation and improve model residuals. We used linear mixed-effects models (LMM) with Gaussian distribution to examine the relationship between biological and ecological traits (including trophic guild, habitat and body part assessed) and environmental factors (sampling environment) with the mean number of plastics reported within each taxonomic group (fish and invertebrates). However, due to incomplete data availability in certain studies, we conducted separate LMM analyses for body length and body weight, ensuring that our models accounted for the available information in each case. Linear mixed-effects models are particularly well-suited for our data because they account for the hierarchical structure of our dataset. Specifically, we used the study identity as a random effect for fish and invertebrates. This approach helps control for any unexplained variation and correlations that may exist within studies. Model selection and validation were conducted to ensure the models adequately represented the data. Model validation and selection included diagnostics such as residual plots (normality and heteroscedasticity), the variance inflation factors (VIFs) tests and the Akaike Criterion for candidate models, respectively.

We conducted all statistical analyses and graphs in R program 4.2.2 (R Core Team, 2022). We used the "lme" function for the linear mixed model from "lme4" package (Bates et al. 2015) and built figures using "ggplot2" (Wickham, 2016) and "maps" (Becker et al. 2018).

4.3 Results

4.3.1 Number of studies of plastic ingestion by freshwater fishes and invertebrates

The occurrence of plastic in freshwater fish and invertebrates from different geographical regions is widespread (Fig. 2), with reports across all continents (except Antarctica). Regionally, most of the studies included in our synthesis are concentrated in Asia (38.54%; *n* = 70), followed by Europe (24.02%; *n* = 43). Studies from South (14.52%; *n* = 26) and North America (11.17%; *n* = 20) have increased in the last years. Similarly, the African continent had 15 published articles (8.37%), most from the last three years. Studies from Central America and Oceania combined are less representative, summing less than 4% of all studies (*n* = 6 studies). The prevalence of plastic contamination in fish was evident across all continents. Notably, all articles from Central America belong to this group. As for invertebrates, there was an upward number of studies showcasing increasing recognition of their vulnerability to microplastics.

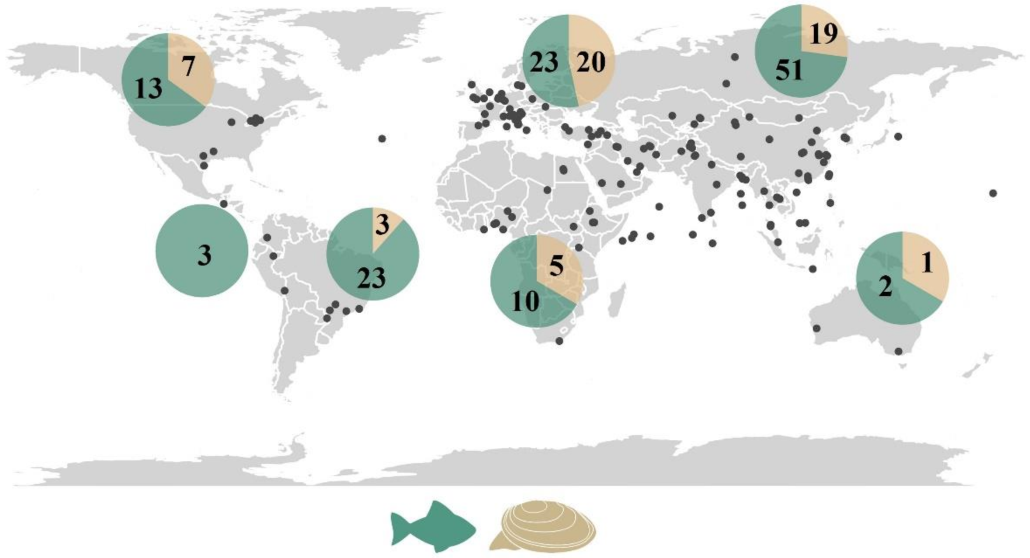

Fig. 2 Global overview of studies assessing plastic presence in various animal taxa. Each point represents one study, and the pie charts indicates the percentage of studies conducted on each taxon within different continents. Numbers inside each pie chart indicate the number of studies for each animal group.

The oldest report on plastics in freshwater biota included in our systematic review was from 2014. However, the following years showed an increasing effort in the number of published studies, and a more drastic increase in the last three years (Fig. 3), especially for fishes.

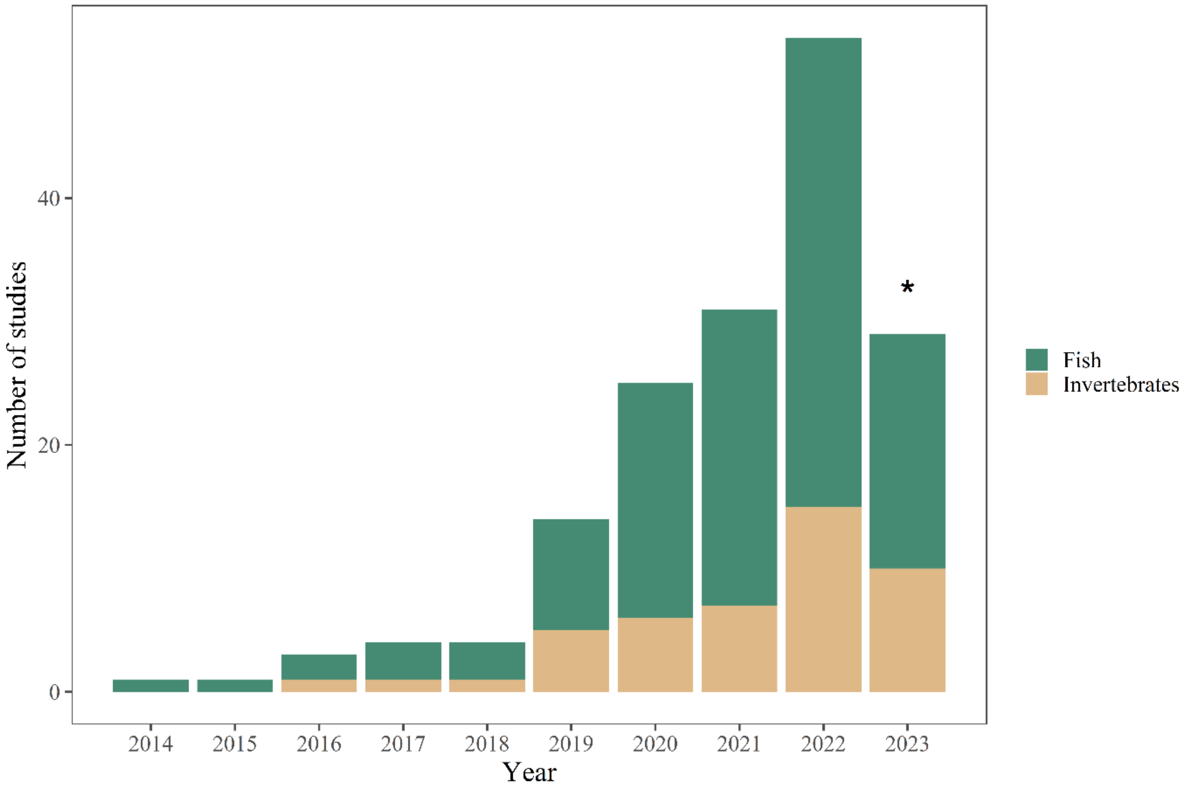

Fig. 3 Temporal trends in number of studies reporting plastic presence in freshwater fish and invertebrates worldwide. The asterisk represents the number of studies up to April 2023.

Worldwide, several freshwater species were investigated for plastic ingestion and most studies focused on fish (69.27%), with 411 distinct fish species assessed in our study, with records from all continents. Among these studies, there was one report for a lamprey and one on a stingray. More than 30% of studies were from the Cypriniformes order, followed by 20.32% from the Siluriformes (Fig. 4). The common carp, *Cyprinus carpio* (n = 20 studies), and the goldfish, *Carassius auratus* (n = 15 studies) were the most frequently studied species. The assessment of microplastic ingestion extended across diverse trophic guilds, including algivorous, carnivorous, detritivorous, herbivorous, omnivorous, and even one hematophagous species (*Vandellia cirrhosa*). Among the sampled fish species, the majority were wild caught (river, stream, lake, and wetlands), although there is an increasing body of research sampling from artificial reservoirs ($n = 6$), five of them in Asian countries, and only one in Fiji Islands.

Regarding fish organs assessed for the presence of plastic, the focus was on the stomach ($n = 10$) and the whole gastrointestinal tract ($n = 79$). However, recent studies have expanded their scope to investigate the occurrence of plastic in organs such as gills, liver, muscle, and skin, revealing a broader spectrum of potential pathways for plastic occurrence. When assessing individually, there was one paper each for muscle, liver, and gills. However, some studies assessed multiple organs together. In those cases, there were reports for muscle (5), liver (2), gills (12), stomach (3), gastrointestinal tract (11) and four for the entire fish body. Concerning the size of plastic found in freshwater biota, microplastic was prevalent in all species (fish and invertebrates), whereas meso and macroplastics were found only in fish (four studies) and the stingray.

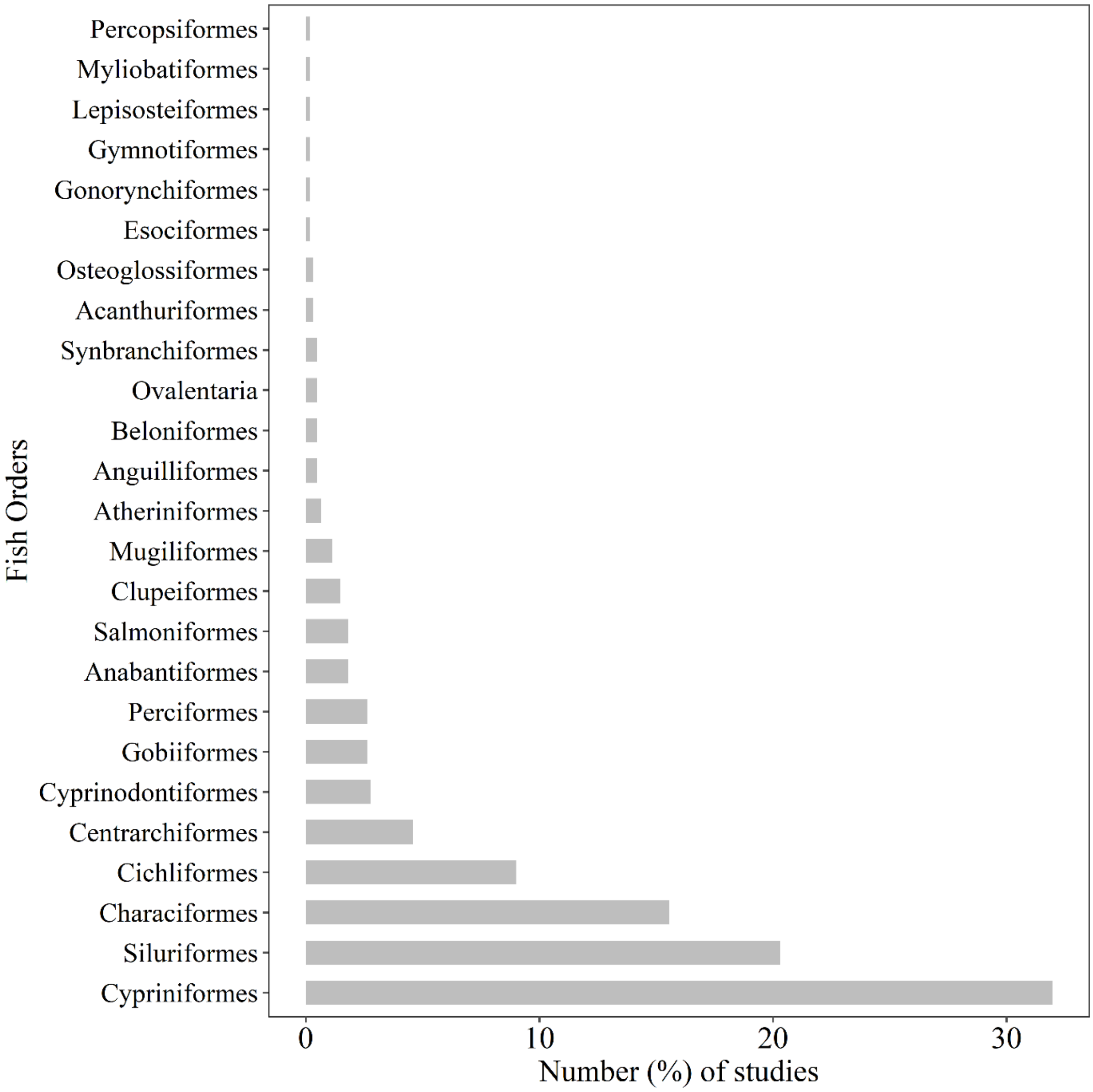

Fig. 4 Percentage number of studies conducted on distinct freshwater fish orders**.**

Invertebrates accounted for 30.73% of all studies, with most involving mollusks (Bivalvia and Gastropoda – Fig. 5) and larvae of Diptera, specifically the Chironomidae family. Other invertebrates such as crayfish, shrimp, amphipods, crab, and zooplankton have also been found to have plastic in their bodies. We accounted for 62 distinct freshwater species, but this number only refers to studies that presented information on specific taxonomic identification; eight other studies presented more broad information with lower taxonomic resolution (these studies did not provide species information, but information such as Nematoda, Zooplankton, Oligochaeta). Among the invertebrates that contain microplastics, the most common trophic guilds were detritivores, herbivores, and omnivores, sampled across diverse aquatic habitats encompassing rivers (25), lakes (15), streams (4), and reservoirs (4). For insect larvae, plastic presence was predominantly assessed in their entire body, but two studies focused on Trichoptera larval cases. The mollusks had their soft tissues chemically digested for microplastic occurrence. Regarding the size range of plastics, they were all microplastics.

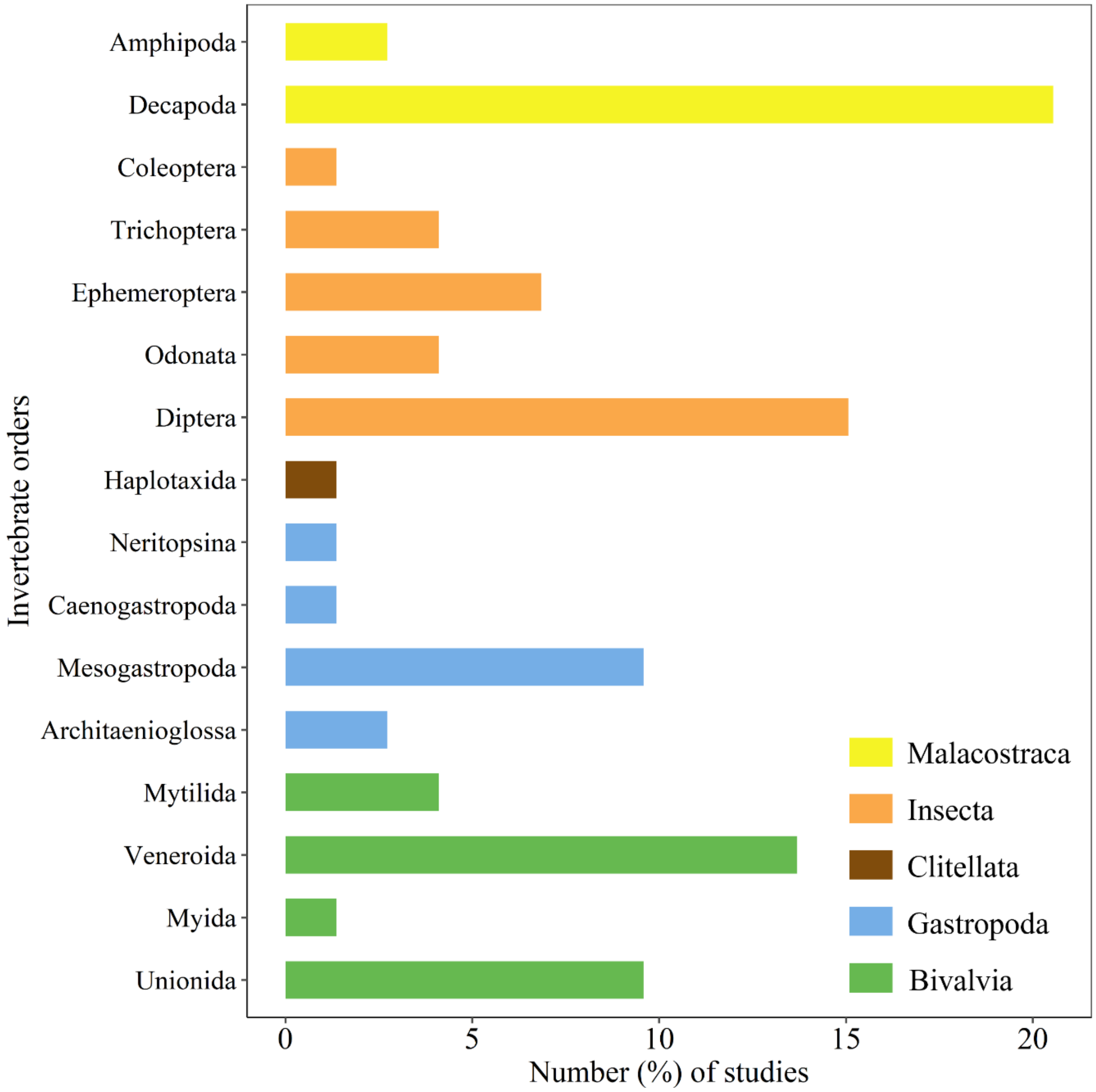

Fig. 5 Percentage number of studies conducted on distinct freshwater invertebrates' order. Orders are color grouped according to taxonomic class

4.3.2 Drivers of plastic ingestion by freshwater fishes and invertebrates

Fish

When analyzing studies per group, globally, there were 307 different species of fish compiled from 83 studies with quantitative data. The mean number of plastic particles found (5.96) varied between 0 to 62 particles per individual fish. Notably, it was observed that among these, 39 species did not have microplastic particles within their gastrointestinal tracts or any other body parts.

The quantity of plastic found in fish varied significantly depending on the specific body part examined. Fish that underwent a comprehensive examination of all their organs had, on average, a higher plastic content compared to when individual assessments were made for the gills, liver, muscle, stomach, or gastrointestinal tract only (Fig. 6; Online Resource 1 Table S5). We did not find evidence that trophic guilds influence the ingestion of microplastics by freshwater species. Also, the environment in which fish was sampled (lake, reservoir, river, stream and wetland) were not strong predictors of increasing amounts of plastic for freshwater fish. We also did not find evidence that increasing body length nor body weight can lead to a higher occurrence of plastic (Fig.7; Online Resource 1 Table S6). Regarding the variance explained within the model, the inclusion of random effects, specifically among-study variations, notably contributed to the overall model fit ($R^2m = 0.17$; $R^2c = 0.83$).

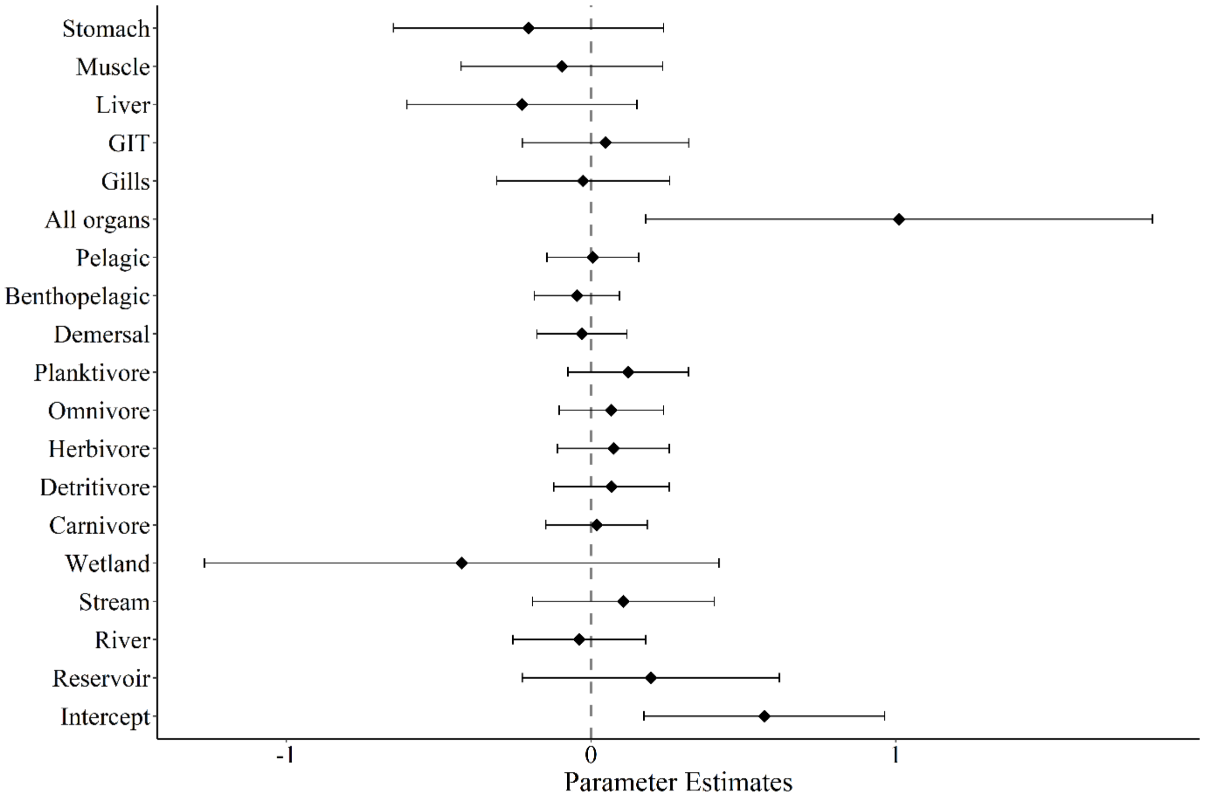

Fig 6. Parameter estimates of linear mixed models of mean plastic abundance in fishes in relation to explanatory variables (n = 83 studies). The intercept represents the environment “lake” which is used as a reference level. The gray line represents the confidence interval. The variables were significant if they did not present confidence intervals crossing the dashed line.

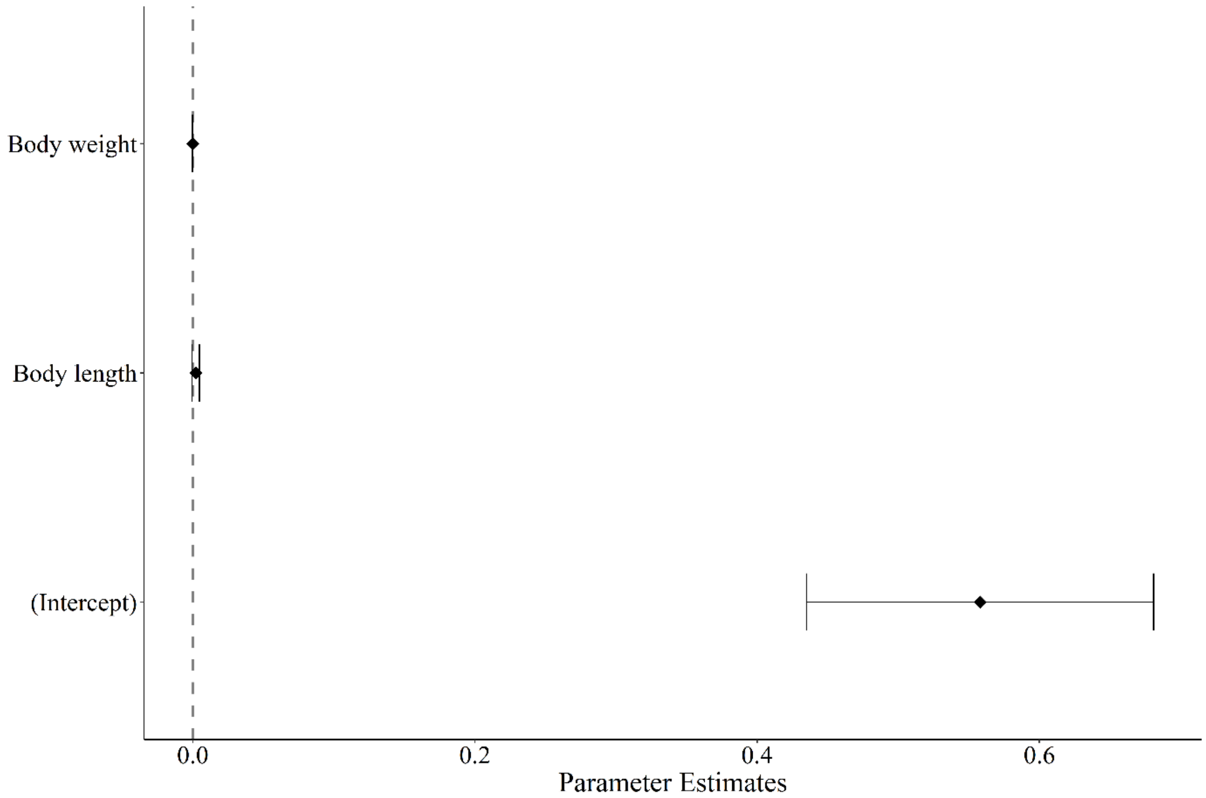

Fig 7. Parameter estimates of linear mixed models of mean plastic abundance in relation to body length and body weight in fishes of available studies (n = 60 studies). The gray line represents the confidence interval. The variables were significant if they did not present confidence intervals crossing the dashed line.

Invertebrates

When assessing invertebrates, we found a mean number of 0 to 29.17 microplastics per individual, and only four occurrences of plastic absence (n = four studies). However, there were two extreme outliers found in larvae of blackfly soldier, *Simulium* spp., from the same study, with a mean of 674.5 nanoplastics per individual (which were removed, considering it was the only study reporting presence of such small size of plastic). We found that the environment in which invertebrates were sampled strongly influenced plastic ingestion. Invertebrates collected from rivers exhibited, on average, higher quantities of microplastics compared to those from other environments (Fig.8; Online Resource 1 Table S7). The trophic guilds did not influence the mean number of plastic present. Regarding body parts assessed for the presence of plastic, we found that analyzing the whole body has a negative influence on detecting higher amounts of plastic (Fig 9). Regarding the variance explained within the model, the inclusion of random effects, specifically among-study variations, notably contributed to the overall model fit (R^2m = 0.33; R^2c = 0.93).

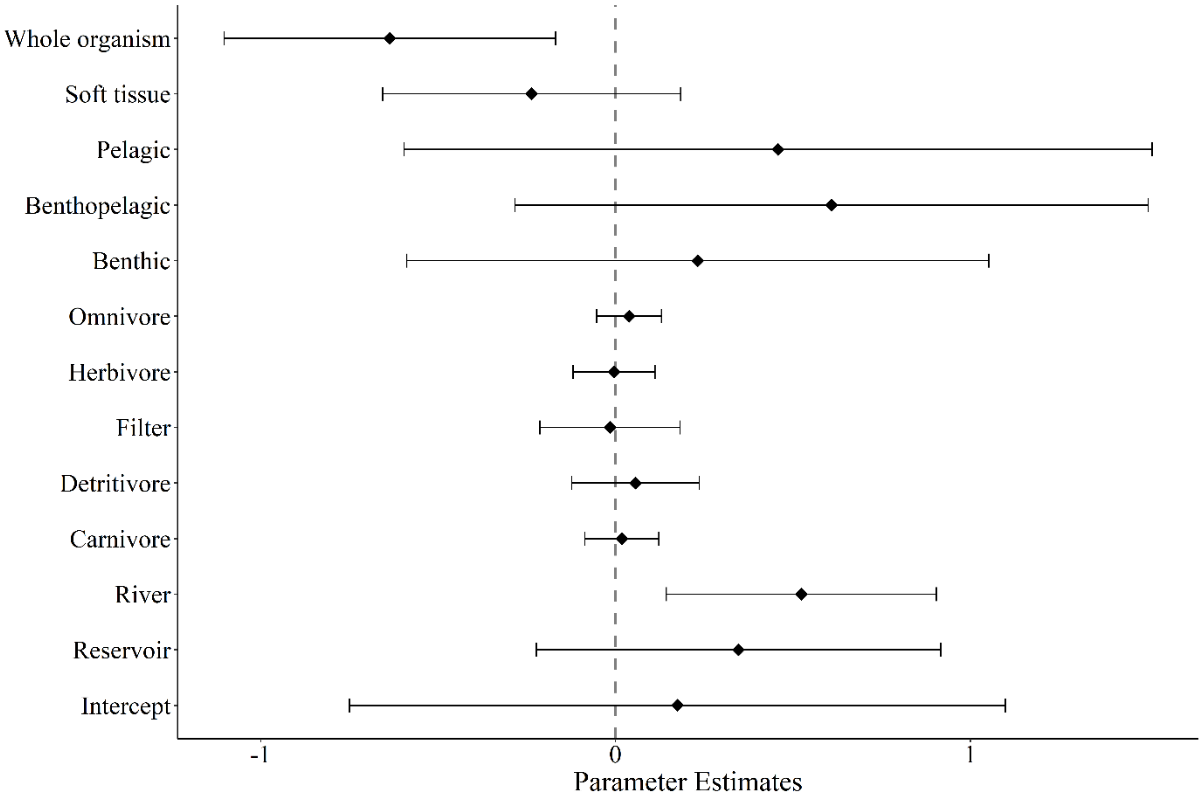

Fig 8. Parameter estimates of linear mixed models of mean plastic abundance in invertebrates in relation to explanatory variables (n = 31 studies). The intercept represents the environment "lake" which is used as a reference level. The gray line represents the confidence interval. The variables were significant if they did not present confidence intervals crossing the dashed line.

For length and weight, conducted on 16 individual studies that reported this data, we found no evidence indicating that longer and heavier animals tended to have higher plastic content (Fig 9; Online Resource 1 Table S8).

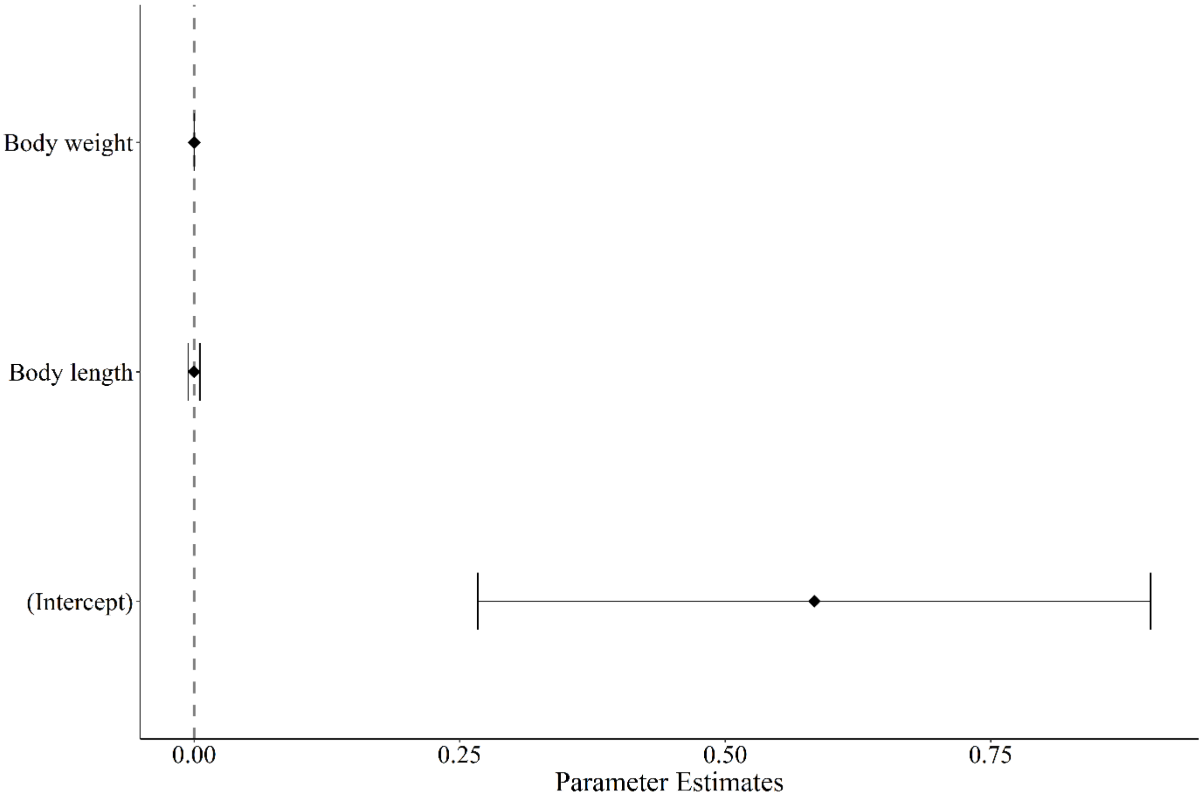

Fig 9. Parameter estimates of linear mixed models of mean plastic abundance in relation to body length and body weight of available studies (n = 16 studies). The gray line represents the confidence interval. The variables were significant if they did not present confidence intervals crossing the dashed line.

4.4 Discussion

4.4.1 Number of studies of plastic ingestion by freshwater fishes and invertebrates

Our findings show that plastic occurrence on freshwater biota is widespread, with studies for wild species of fish and invertebrates. Regionally, our compilation shows a bias on published studies towards Asia followed by Europe. The high number of studies on these continents can be attributed to a convergence of multifaceted factors. In the last decades, many Asian countries have undergone rapid economic growth, especially when it comes to plastic production, leading to increased consumption and disposal rates (Wu et al., 2017; Walther et al., 2020). Consequently, some Asian countries have started recognizing the urgency of addressing plastic pollution and started adopting policies to mitigate its effects (Wu et al., 2017; Akenji et al., 2020). Until 2018, only 16% of freshwater studies worldwide were from Asia (Blettler et al., 2018), but our results showed an increase in scientific efforts (almost 40% of studies). China is the most productive in the number of conducted studies on plastic pollution, as reported by Blettler et al. (2018) and Kumar et al. (2022) and in our ongoing study. Given that China is associated with some of the world’s most polluted waters, like the Yangtze River, and a major contributor to global pollution (Lebreton et al., 2017), the efforts on combating plastic issues surged with governmental monitoring programs, policies to ban importation of plastic waste from European countries and promoting research (Walther et al., 2020; Fürst & Feng, 2022). The presence of substantial polluted inland waters (Lebreton et al., 2017), like the Yangtze River, ranked as the third longest river globally (Huang et al., 2023), and the Yellow River, considered the sixth longest (Liu et al., 2021), has directed the focus on freshwater studies within the country, which ultimately increased documenting the occurrence of plastic on freshwater animals. Regarding Europe, the growing and historical awareness from the scientific community, coupled with societal and political initiatives on plastic research encouraged and supported research initiatives in this continent, where citizen awareness and activism create pressure for both governmental and scientific research to prioritize this issue (Catarino et al., 2021; Nelms et al., 2022; Oturai et al., 2023).

Data on freshwater animals and plastic occurrence have been scarcely investigated in countries from South and Central America, Africa, and Oceania, and only more recently efforts in South America and Africa have increased. As expected, most studies from South America and Africa are still far more advanced on marine ecosystems (Akindele & Alimba, 2021; Fernandes et al., 2022) and this could be influenced by some factors. Plastics were identified and studied firstly in the marine environment, setting the precedence for subsequent research. Additionally, the widespread awareness of marine litter and its negative effects on marine biota might have shaped public perception and funding opportunities, directing efforts primarily to marine studies. As a result, these regions have only recently started paying attention to plastic occurrence in freshwater animals (Akindele & Alimba, 2021; Orona-Návar et al., 2022). However, beyond the environment bias (marine or freshwater), low-income countries generally have limited research on plastic pollution (Blettler et al., 2018; Yao et al., 2020). This limitation seems to arise from financial constraints, especially when assessing biological samples that requires more expensive equipment (Browning et al., 2021; Vriend et al., 2021). Prioritizing international cooperation in these countries could be a way to advance in this field. Finally, the low number of studies reporting plastic interaction with the biota is still a relevant knowledge gap from Central America and Oceania. Addressing this gap is crucial to advance knowledge on the distribution and fate of plastics across freshwater animals.

Fish

Studies investigating the occurrence of plastic on freshwater biota are still incipient, and fish are the taxonomic group with most records across all continents. The reasons why fish are on the spotlight can be explained by their high ecological and economical value, reflected by their wide geographical distribution, feeding habits and habitat use (Fossi et al., 2022; Multisanti et al., 2022). Freshwater fish are extremely important as a widely consumed food in numerous countries, and inland fisheries are crucial to the economy, supporting livelihoods and ensuring food security, especially in developing countries (Funge-Smith & Bennett, 2019). This raises concerns of human exposure to ingestion of plastic-contaminated fish and the impacts on human health, which led to growing global interest in researching plastic pollution in fish. Moreover, the prevalence of reports for fish in comparison to invertebrates, can be linked to a more established methodology, and the visibility of ingested plastics in their digestive tracts, which makes research relatively easier, especially for countries facing challenges of limited investment and funding in scientific research (Granek et al., 2020).

A high number of fish species have been reported to interact with plastic, and as new studies are being continuously published, it's difficult to provide an exact number. Comparing with reviews conducted by Azevedo-Santos et al. (2019, 2021), the number of freshwater fish species analyzed for plastic occurrence increased from 75 in 2019 to 411 species in our study. This shows that freshwater species are as much contaminated as marine fishes, and the reporting of multiple species can broaden our knowledge to different biological and ecological traits represented by these organisms. The common carp (*Cyprinius carpio*) and the goldfish (*Carassius auratus*) were frequently the most studied species in our compilation. Their widespread occurrence across various freshwater habitats (Chan et al., 2019; Boston et al., 2023) and significance in fisheries (FAO, 2022), make them accessible for sampling and analyzing for plastic interaction. As many freshwater fish species face several challenges due to anthropic disturbances (Dudgeon, 2019; Yofukuji et al., 2023), poorly studied fish species as well as species of commercial importance are encouraged to be prioritized, for a better understanding of their vulnerability.

Several factors may influence fish's high variation in intra and interspecific interaction with plastics, which explains the widespread interest in understanding this through the lens of biological and ecological traits. The guild-based approach has been proven promising to detect changes caused by anthropic disturbances (Garcia et al., 2020; Cardozo et al., 2023; Costa et al., 2023) because this approach aggregates species from distinct taxonomic positions, allowing comparisons from different locations and environments. Some studies have suggested that fish are more likely to ingest plastic particles depending on their trophic guild or habitat preferences, but up to now, this has yielded multiple results (e.g. Garcia et al., 2020; Pastorino et al., 2021; Parker et al., 2022; da Costa et al., 2023).

Most studies still investigate the gastrointestinal tract for plastics, as it is one of the obvious routes from the environment to the organism. However, assessments of other organs have now been addressed, as they can contribute as a pathway of plastic into fish. The number of studies focusing on fish gills have increased due to the recognition that plastics can adhere to the gills through breathing or filtration, presenting a novel way for plastic uptake, beyond ingestion (Batel et al., 2018; Roch et al., 2020; Ribeiro-Brasil et al., 2023). Recent studies have investigated the occurrence of plastic in other organs such as liver, muscle, and skin. Assessment of fish internal organs is usually conducted under laboratory conditions (Avio et al., 2015; Collard et al., 2017; Roch et al., 2020), but analysis on wild freshwater fish suggested that small plastics could translocate from the gut to other organs (e.g. Collard et al. 2018; McIlwraith et al., 2021). However, a more holistic assessment of multiple organs is scarce and neglected for wild freshwater fish, and our study retrieved only a few studies for the liver, skin and muscle. Organs of fish are generally removed for human consumption, which can minimize the risk of plastic ingestion by humans, but the muscle is widely consumed, even raw. Records of plastic in the edible parts of fish have been reported for wild fish (Raza et al., 2022; Pandey et al., 2023; Shen et al., 2023) but is in its infancy, and because of the potential risks to human safety, increasing efforts to document its prevalence is necessary.

Considering the sampling environments, we focused on wild fish populations, with most of them being sampled from rivers, others on streams, lakes and wetlands, and semi-natural environment as reservoirs. Fate and interaction of plastic with the biota can be dependent on the hydrodynamics of the environment (Li et al., 2018; Yan et al., 2021). Rivers can be more important in transporting plastics, while lakes or reservoirs can be sinks, where it may accumulate at higher rates (Nava et al., 2023), ultimately changing fish vulnerability depending on its habitat preferences. Only more recently, fish inhabiting reservoirs have been assessed for plastic contamination (Guo et al., 2021). Only six studies were retrieved from our search, clearly showing a lack of studies focusing on plastic occurrence in animals from reservoirs. Given that wild populations of fish inhabit reservoirs and are important for fisheries, and the dynamics of this environment is remarkably distinct from natural rivers or lakes, more efforts are needed to elucidate whether fish are at higher risks in impounded systems. Overall, further insight on plastic contamination from streams, wetlands, and lakes is also needed, to direct and implement mitigation strategies towards the reduction of plastic in these specific environments.

Concerning plastic size, most studies reported the presence of microplastics across all species, and only five studies reported the occurrence for meso and macroplastics. Microplastics can be manufactured for the cosmetic industry, but they can also originate from the fragmentation of larger plastics, exponentially increasing their abundance in the environment (Barnes et al., 2021). Because of their small size, microplastics are available for a wider variety of animals and can be more easily mistaken by food, accidentally ingested, or filtered by gills for example, increasing the likelihood of reporting microplastic over meso or macro plastics. Furthermore, due to its omnipresence in the environment and the threat they pose, the focus has been on investigating microplastics. Finally, because larger plastics can affect fish, whether by ingestion, suffocation, or entanglement (Blettler & Mitchell, 2021; Andrades et al., 2021), we highlight the necessity to pay attention to design studies that fill this knowledge gap, also because larger plastics are source to the small sizes.

Invertebrates

We observed a major gap of research for freshwater invertebrates, with only 30% of studies focusing on these organisms sampled on natural or semi-natural environments. Only more recently, countries started including them as a target for research. The increasing number of studies from 2020 onwards can be related with advances in technical and scientific methodology, which allow for the detection and quantification of small plastic particles on these small animals, which facilitated their inclusion on studies (Browning et al., 2021; Vriend et al., 2021). Protocols for digesting the soft tissues or whole organisms have been proven to be efficient, making invertebrates another ideal group for assessments (Claessens et al., 2013; Nel et al., 2018). Likewise for fish, Asia and Europe had the most studies on invertebrates, and the other continents had at least one study retrieved in our search, except for Central America that had studies only for fish. As plastic pollution is recognized a ubiquitous particle in the environment (Villarrubia-Gómez et al., 2018; Hale et al., 2020), their presence in other organisms require further assessment.

We recorded 62 species of freshwater invertebrates that were assessed for plastic contamination, but this number is higher due to limited information. Unlike fish, some studies did not report species level information, which limits our knowledge on how widespread plastic is among specific taxa. This can implicate recovering basic biological and ecological information, impairing inferences using guild approaches (as discussed for fish). Nonetheless, mollusks were the group with the highest number of studies (more than 40% of studies focused on this group). The focus on these animals can be because they serve as food for human consumption (e.g Thamsenanupap et al., 2022) and for other animals, which places them as a concern on the plastic movement along the food chain (Provencher et al., 2019). They have also been historically used as effective bioindicators for monitoring pollution in inland waters because of their wide distribution, tolerance to different environmental conditions and most likely because of their feeding habits and habitat use (Bertoli et al., 2022) since numerous species are filter-feeders and use the benthic layer, where plastic can settle and accumulate (D'Avignon et al., 2021).

Insects from the Chironomidae family were the second most investigated (15% of studies). These insects can serve as bioindicators, especially in heavily disturbed environments. *Chironomus* spp. larvae are widely distributed and are often highly abundant in degraded habitats, once they can survive hypoxic aquatic environments (Carew et al., 2007; Lin et al., 2021). Nel et al. (2018) and Dahms et al. (2020) showed that these larvae can ingest plastic from the environment and reflect the levels of plastic from the sediments they were collected, providing insights into overall ecosystem health and location specific information on plastic levels.

Invertebrates can uptake plastics from other routes than solely by ingestion. Most studies digested the whole organism (i.e., insect larvae) or the soft tissues of mollusks, making it challenging to pinpoint the exact organ where plastics accumulate. However, some studies have shown that plastic can adhere to gills (e.g. Haque et al., 2023; Shen et al., 2023) or be incorporate into insect cases, as it is the case of Trichoptera insects (e.g. Ehlers et al., 2019; Windsor et al., 2019). Ultimately, because of their small size, dissecting organs for assessment of these invertebrates is not straightforward as on fish; it can be time consuming and increase costs, and therefore digesting the whole organism is relatively easier and more common.

Regarding sampling environments, most studies sampled riverine habitats, and to a lesser extent streams, lakes, and reservoirs. This emphasis on riverine ecosystems suggests a historical bias in research efforts, with limited attention directed to streams, lakes, and reservoirs until recently. This indicates a remaining gap in the literature, indicating a preliminary stage in the evaluation of invertebrates from these less-explored environments and from different regions of the globe.

For invertebrates we only found reports for microplastics, as this size range probably do not restrict uptake by animals from distinct body sizes. Plastic undergoes fragmentation into smaller pieces due to weathering effects, resulting in microplastics that can be ingested by invertebrates or incorporated into cases. Additionally, animals can also bite and shred larger particles, fragmenting them to microplastics (Zhang et al., 2021; So et al., 2022). As most studies were assessing filter-feeding mollusks, these animals can be restricted to filtering only small size particles present in the environment. Trichopteran insects for instance, can fragment larger plastic into the desirable shape and size to incorporate into its case (Valentine et al., 2022). Given that invertebrates can break down plastics into small sizes suitable for them, the risks extend beyond investigation of microplastics. Invertebrates can be susceptible to accumulating high burdens of nano plastics, a research area that needs to be prioritized.

4.4.2 Drivers of plastic ingestion by freshwater fishes and invertebrates

Fish

Globally, there were 307 different species of fish compiled from 83 studies with quantitative and comparable data. Several factors are thought to influence plastic uptake by organisms. However, for freshwater fish, we did not find supporting evidence that trophic guild, habitat use, sampling environment nor body length and weight influence animals on up taking more plastics.

However, we found that fish that underwent a comprehensive examination of all their organs had, on average, a higher plastic content than solely assessing each individual organ. While this finding emerged as statistically significant, it's crucial to note that it may not necessarily represent a broader trend across all studies. This outcome might be driven by a study that reported on average, high plastic uptake across all organs (esophagus, stomach, intestine, liver, gonads, pancreas, swim bladder and heart) of several fish species, and differences in sampling techniques, the environmental context, or other unaccounted factors could lead to the results reported. When analyzing only a specific body part, this may lead to underestimation of plastic particles, because plastic could be attached to gills or translocated from the gut to other organs like the liver, skin, or muscle tissue (e.g. Collard et al. 2018; McIlwraith et al. 2021). So, a thorough evaluation covering fish tissues and organs allows for a more accurate and realistic quantification of plastic accumulation in fish. Furthermore, studies focusing on detecting plastic into fish muscle and skin are of major importance, and efforts should increase towards whole body assessment, to ensure food safety and mitigate potential risks associated with plastic ingestion.

Surprisingly, biological and ecological traits were not strong predictors of plastic accumulation on fish. This unexpected finding challenges the common idea that specific feeding behaviors and habitat preferences significantly dictate the uptake of plastics among freshwater species. As a matter of fact, plastic was present across all studied trophic guilds and habitat use (pelagic, benthopelagic and demersal), gathering more evidence that fish in general are vulnerable to plastic contamination. Some of the most common assumptions is that fish ingest plastic actively, by mistaking particles with their natural prey or when foraging close to the sediment, where plastic abundance can be higher (Scherer et al., 2020) and therefore more available to individuals. In the case of top predators, for instance, they would be at higher risk because of trophic transfer and bioaccumulation, but this rarely holds true, once other unaccounted factors like egestion rates and plastic translocation have scarce evidence (Lusher et al., 2017; Gouin, 2020). Burden of plastic may also vary based on individual characteristics, but body size nor weight were relevant to predict higher rates of plastic in fish in our study. The importance of fish size and mass to predict plastic load is still highly uncertain and findings can be often contradicting (e.g. McNeish et al., 2018; Park et al., 2022; Wardlaw et al., 2022).

Although these speculations are prominent and try to unravel the dynamics of plastic interaction and its impacts on freshwater fish, we still lack a more robust dataset to draw these types of conclusions. Therefore, the lack of evidence in our study can arise from the fact plastic uptake can interact with other factors, resulting in the high variability among studies. Egestion rates on fish (Roch et al., 2020), metabolic activity, proximity to point sources (urbanized, densely populated regions) (e.g Lin et al., 2021; Thamsenanupap et al., 2022), environmental conditions (e.g Cardozo et al., 2023) and other methodological inconsistencies in quantifying plastic particles underscore the need for comprehensive and standardized approaches in future research. Finally, plastic occurrence in freshwater fish is ubiquitous and affects species indiscriminately. Furthermore, we were not able to use our whole dataset of studies because of absence of standardized reporting of plastic on organisms. We recommend providing the mean number of items found in the different organs and tissues in number of items/individual and items g/tissues. Also, some basic information regarding species characteristics (body size and weight, habitat use, feeding strategies) should be provided to increase comparability between studies.

Invertebrates

We did not record a substantial number of studies regarding freshwater invertebrates (34 individual studies) with comparable quantitative data as we did for fish, which shows that increased efforts targeting this group is necessary. We only found evidence that sampling environment, specifically invertebrates sampled from rivers had on average higher amounts of plastic, and that assessing the whole body of invertebrates does not predict higher amounts of plastic.

Rivers, similar to marine environments, accumulate plastics and are themselves threatened by plastics contamination (Lebreton et al., 2017). Several factors have been linked to the fate of plastic in rivers, including mobilization, transport, and accumulation (Yan et al., 2021), which is affected by river flow and velocity, wind, precipitation, and run off (van Emmerik et al., 2023). These variables determine whether plastics settle in riverbeds and floodplains, entangle in vegetation, or if get transported downstream (van Emmerik & Schwarz, 2019). The majority of landfill plastic waste ends up in rivers, where it can serve as a reservoir due to the significant amounts of plastic waste accumulating along their course, diverting a smaller fraction towards oceans than previously assumed (Meijer et al., 2021). Large plastic waste can remain intact in the environment for decades, while others can breakdown to smaller particles, the microplastics (Eerkes-Medrano et al., 2015). This fragmentation can occur because of abrasion, waves, or biological interactions (Wagner et al., 2014; Blettler & Mitchell, 2021). The newly fragmented plastics can be deposited along the sediment, resuspended during river turbulence, travel through the water column, and ultimately be ingested by animals (Lusher et al., 2017; D'avignon et al., 2021). Freshwater invertebrates can become highly vulnerable to plastic pollution, once plastic can disintegrate into different range sizes and shapes, accumulate in various compartments within the river, increasing the likelihood of invertebrates encounters with plastics. Nonetheless, there has been a limited number of studies conducted on other environments, which can constrain a more comprehensive analysis, reflecting the need for further exploration, particularly in the case of lakes and reservoirs. These environments exhibit unique dynamics compared to riverine habitats and demand additional assessment to elucidate their contribution to plastic availability for invertebrates.

Assessing the whole body of invertebrates did not reflect on quantifying higher amounts of plastic. Invertebrates may not accumulate plastic particles within their entire body and the retention can depend on the ability to excrete them or whether plastic could translocate membranes (Li et al. 2018). They can ingest plastic and transport it within their GITs; however, these organisms have evolved to protect themselves from mechanical damage caused by the ingestion of inorganic particles (Ward & Shumway, 2004), so the extent of plastic translocation within these organisms are yet to be understood (Lusher et al., 2017). They also can discriminate organic food from inorganic materials, and excrete them via pseudofaeces, minimizing the plastic burden within the whole individual (Gonçalves et al., 2019; Li et al., 2021). Furthermore, invertebrates' samples are pooled or analyzed as a whole, preventing a determination of where within the organism the particles were located, thus meaning that plastics are not necessarily distributed and accumulated through the whole body. Additionally, many small particles close to or smaller than the detection threshold of many studies can limit their detection.

We also found no significant relationship regarding trophic guild, habitat use, body length and weight for the invertebrates. The considerably lower number of studies with standardized quantitative data (mean number of items per individual) and the absence of basic information like body size and length, trophic guild, habitat preferences coupled with the high variability among studies, controlled by the random effects in our model, may account for the non-significant results. The lack of standardized research methods poses a central challenge in this field, owing to the complexity and early stage in this area, which impairs repeatability and comparability among studies, and by extension the review processes and knowledge building (Phuong et al., 2016; Hellevik & Cyvin, 2023). The interaction with other factors can be stronger in predicting such relationships and inconsistencies with digestion methods, variation in the filter pore sizes to filter digestate (that is not standard across studies), and environmental context can strongly influence microplastic particles that can be reported.

4.5 Conclusion

Our study gathered information demonstrating the pervasive presence of plastic among wild freshwater animals worldwide. Our synthesis revealed that for freshwater biota, reporting on plastic occurrence predominantly focuses on fish, but efforts have increased in recent years towards identifying this threat in invertebrates. Surprisingly, biological, and ecological traits did not strongly predict higher plastic occurrence neither for fish nor invertebrates, underscoring the vulnerability of both taxa to plastic pollution. Nonetheless, our understanding of patterns and drivers of plastic occurrence on freshwater animals remains limited. We strongly advocate for studies to provide basic species information (trophic guild, habitat preferences, size, and weight) alongside quantitative plastic data (average plastic count per individual and per gram). This will increase comparability among studies and foster a deeper comprehension of this threat for freshwater biodiversity. Further assessments are essential to evaluate the extent of plastic pollution in poorly studied environments like streams, lakes, and reservoirs, as well as the underexplored regions of the world. For this we encourage international cooperation among high income and low-income countries, that can lead to a more comprehensive and robust global database on the interaction of plastic and animals. These efforts will guide research strategies and public policies to address and mitigate this pressing environmental concern, ultimately safeguarding freshwater biodiversity.

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5 CONCLUDING REMARKS

Human society depends directly on services and goods provided by freshwater systems, such as drinking water, food, electricity, and transportation. Historically, human civilizations have always developed near freshwater ecosystems, impacting these environments. As human populations increases and so its demands, these impacts intensify. We conducted three independent studies aiming to evaluate (i) the effects of a Neotropical reservoir on the current fish trophic ecology and also a historical comparison with the fish community right after impoundment; (ii) the microplastic contamination in a fish community and the influence of longitudinal axis of a reservoir, trophic guild and habitat on plastic ingestion by fish; (iii) and a global synthesis concerning reports of plastic, encompassing all size fractions, for freshwater fish and invertebrates.

The results of the first study show that fish diets and trophic structure undergoes shifts following longitudinal gradients imposed by river damming. Specifically, the research demonstrates a transition in the longitudinal utilization of resources from predominantly allochthonous to autochthonous sources. This shift in prey consumption significantly influences the spatial distribution of distinct fish trophic guilds throughout the reservoir. Changing the abundance and biomass of trophic guilds has the potential to significantly alter ecosystem interactions, ultimately impacting fishery yields and market values. Furthermore, the findings show that the dominant trophic guilds change over time in terms of abundance and biomass as the reservoir ages.

Regarding plastic pollution, we found that microplastic ingestion by fish in the Itaipu reservoir appears to be less common than expected. Considering the longitudinal dynamics of the reservoir, we found that the lacustrine zone was important in detecting microplastic uptake by fish, suggesting that certain areas within the reservoir may accumulate more plastic particles than others, and plastic ingestion becomes more likely. We also showed that insectivore and benthopelagic fish were traits suggested to increase susceptibility to MP ingestion. The results presented herein provide further details on the factors influencing and the current state of microplastic pollution in Neotropical reservoirs. We highlight the critical need for comprehensive investigations into both biota and the environment. This approach is critical for gaining a deeper awareness of how microplastics are distributed and interact with animals in non-natural environments.

We synthesized literature on reports of plastic in freshwater fish and invertebrates, covering all size fractions, in order to keep up with emerging research and guide future work. Our findings show that while reporting on plastic occurrence in freshwater biota typically focuses on fish, recent efforts have expanded to recognize this threat in invertebrates. Notably, biological, and ecological traits had limited predictive power for increased plastic occurrence in either group, showcasing the vulnerability of both taxa to plastic pollution. Through a comprehensive compilation of global studies on plastic occurrence in freshwater biota, we point out regional and knowledge gaps that require further investigation.

Freshwater ecosystems are under multiple stressors and the extent to which these impacts synergize warrants further exploration. Together, our studies highlight that freshwater biota are directly impacted either by "macro" impacts, i.e. river impoundment, or by "micro" plastics. Finally, we advocate for the importance of continuous monitoring and the implementation of adaptive management strategies, to address and reduce these impacts, ensuring the long-term health and sustainability of freshwater environments.

APPENDIX A – Fish species captured in Itaipu reservoir

Table S1. Fish species captured in each reservoir zone. Lac = lacustrine; interm = intermediate and fluv = fluvial. The letter x denotes the presence of species.

Species	lac	interm	fluv
Acestrorhynchus lacustris	x	x	x
Ageneiosus ucayalensis			x
Apareiodon affinis	x	x	x
Astyanax aff. fasciatus	x		
Astyanax lacustris	x	x	x
Auchenipterus osteomystax	x	x	x
Brycon hilarii	x		
Brycon orbignyanus	x		
Cichla kelberi	x	x	x
Cichla piquiti	x	x	x
Crenicichla britskii	x		x
Eigenmannia virescens			x
Galeocharax gulo	x	x	x
Geophagus sveni	x	x	x
Gymnotus inaequilabiatus		x	x
Hemiodus orthonops	x	x	x
Hoplias argentinensis	x	x	
Hoplias mbigua	x	x	x
Hoplias sp.	x		
Hoplias sp. 2		x	
Hoplias spp	x		
Hoplosternum littorale		x	x
Hypophthalmus oremaculatus		x	
Hypostomus ancistroides	x		
Hypostomus cf. strigaticeps	x	x	
Hypostomus cochliodon			x
Hypostomus regani	x		x
Iheringichthys labrosus	x	x	x
Leporinus friderici	x	x	x
Leporinus lacustris	x	x	x

Leporinus octofasciatus		x	
Leporinus tigrinus		x	x
Leporinus unitaeniatus		x	x
Loricaria sp.	x	x	x
Loricariichthys platymetopon	x	x	x
Loricariichthys rostratus	x	x	x
Megalancistrus parananus	x		
Megaleporinus macrocephalus			x
Megaleporinus obtusidens	x		
Megaleporinus piavussu	x	x	
Metynnis lippincottianus	x	x	
Parauchenipterus galeatus	x	x	x
Pimelodella gracilis	x	x	x
Pimelodus maculatus	x	x	x
Pimelodus mysteriosus		x	x
Pimelodus ornatus			x
Pinirampus pirinampu	x	x	x
Plagioscion squamosissimus	x	x	x
Potamotrygon amandae	x	x	
Potamotrygon cf. falkneri		x	
Prochilodus lineatus	x	x	x
Pseudoplatystoma corruscans		x	
Pterodoras granulosus	x	x	
Pterygoplichthys ambrosettii		x	x
Rhamphichthys hahni		x	x
Rhaphiodon vulpinus	x	x	x
Roeboides descalvadensis	x	x	x
Salminus brasiliensis	x		
Satanoperca sp.	x	x	x
Schizodon borellii	x	x	x

Schizodon nasutus			x
Serrasalmus geryi			x
Serrasalmus maculatus	x	x	
Serrasalmus marginatus	x	x	x
Sorubim lima			x
Steindachnerina brevipinna	x		x
Synbranchus marmoratus			x
Trachydoras paraguayensis			x

APPENDIX B – Prey consumed by fish in categories

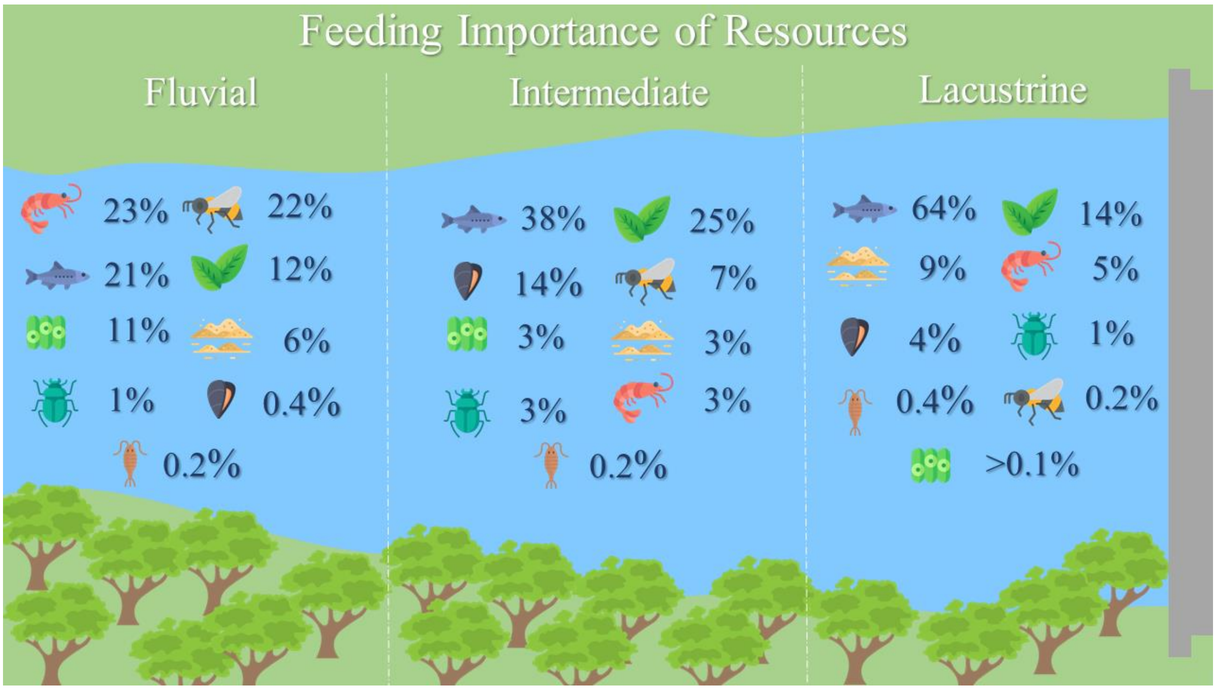

Figure S1 Schematic drawing of each prey categories consumed by fish assemblages and their percent contributions at each reservoir zone.

APPENDIX C – PERMANOVA results

Table S2. PERMANOVA results of fish diets among reservoir zones. Values in bold means statistically significant results. Lac = lacustrine; Int = intermediate; Flu = fluvial

Species	**pairs**	***Pseudo*-F**	**p**
Acestrorhynchus lacustris	lac - int	0.167417	0.89
Auchenipterus osteomystax	lac - fluv	2.067214	0.092
	lac - int	1.886791	0.074
	fluv - int	0.807993	0.488
Crenicichla britskii	lac - fluv	0.616633	1
Galeocharax gulo	lac - int	1.286785	0.223
Geophagus sveni	**lac - fluv**	2.51205	**0.013**
	lac - int	3.885719	**0.002**
	fluv - int	0.671979	0.651
Hemiodus orthonops	lac - fluv	0.898723	0.467
	lac - int	**2.183468**	**0.043**
	fluv - int	1.513003	0.154
Hoplias mbigua	lac - int	0.354028	0.87
Iheringichthys labrosus	lac - fluv	1.278794	0.245
	lac - int	1.572318	0.128
	fluv - int	0.601511	0.742
Loricaria sp.	fluv - int	1.135975	0.324
Loricariichthys platymetopon	lac - fluv	0.229478	0.95
	lac - int	1.383267	0.221
	fluv - int	0.801734	0.535
Loricariichthys rostratus	lac - int	2.941499	0.058
Parauchenipterus galeatus	**lac - fluv**	**2.869315**	**0.017**
	lac - int	1.611128	0.083
	fluv - int	1.073396	0.346
Plagioscion squamosissimus	lac - fluv	0.822861	0.487
	lac - int	0.715727	0.57
	fluv - int	0.734387	0.495
Rhaphiodon vulpinus	lac - int	0.357327	0.88
Satanoperca setepele	lac - int	0.754715	0.592
Serrasalmus marginatus	lac - fluv	0.86356	0.5
	lac - int	0.902682	0.623
	fluv - int	1.40182	0.249

APPENDIX D – Index of Alimentary Importance

Table S3. Index of Alimentary Importance (IAi) of prey resources in the diet of fish species in the Itaipu Reservoir. Lac = lacustrine; Int = intermediate; Flu = fluvial.

Species	Reservoir zone	Algae	Plants	Detritus	Decapoda	Fish	Mollusca	Insect (A)	Insect (T)	Microcrustacean
Acestrorhynchus lacustris	lac					100				
	int		2.04			97.96				
Ageneiosus ucayalensis	flu				98.27	1.73				
Apareiodon affinis	lac			100						
Astyanax lacustris	lac		90.91						9.09	
	int		3.03						96.97	
Auchenipterus osteomystax	lac		9.47						45.06	45.47
	flu							3.06	96.94	
	int		0.13					0.19	99.53	0.15
Cichla piquiti	int				35.40	63.92		0.68		
Crenicichla britskii	lac		41.57				51.25	0.02	7.17	
	flu		83.33						16.67	
Galeocharax gulo	lac				68.66	31.34				
	flu					100				
	int				39.85	60.10		0.05		
Geophagus sveni	lac		0.98	62.83			31.56	0.13		4.50
	flu		63.19	30.73			5.97	0.02		0.08
	int		60.73	19.28			19.59	0.40		
Hemiodus orthonops	lac	0.03	27.39	72.58						
	flu	10.32	62.30	27.16				0.22		
	int	16.21	63.19	16.28				0.44		3.88
Hoplias argentinensis	lac					100				
	int		3.86			96.14				
Hoplias mbigua	lac		19.80		1.49	78.71				
	int				2.53	96.55		0.92		
Hoplias sp.	lac					100				
Hoplias sp3	int					100				
Hypostomus cf. strigaticeps	lac			100						
Hypostomus cochliodon	flu		98.01	1.99						
Hypostomus regani	lac			100						
	flu		3.74	96.26						
Iheringichthys labrosus	lac			27.56	0.75		40.13	28.20	1.59	1.78
	flu			21.27			9.49	40.99		28.24
	int			34.29			11.19	42.32		12.20
Leporinus friderici	flu		85.71	14.29						
	int	0.01	4.12	0.82		9.80	85.19	0.02	0.03	
Leporinus lacustris	lac		85.36	0.16			6.84	5.76	1.89	
Loricaria sp.	flu		6.12	5.69			84.46	3.67		0.06

	int		0.09	35.92			63.90	0.04		0.04
Loricariichthys platymetopon	lac		3.71	82.41			1.24	0.02		12.62
	flu		0.25	97.02				0.02		2.70
	int		0.33	99.33						0.33
Loricariichthys rostratus	lac			87.93						12.07
	int			77.78						22.22
Megalancistrus parananus	lac			38.58			61.42			
Metynnis lippincottianus	lac		100							
	int	82.01	17.10	0.62			0.23	0.02	0.02	
Parauchenipterus galeatus	lac		19.06	1.06	25.41	0.25		5.00	49.23	
	flu		4.59		0.19	0.03	0.02	1.98	93.20	
	int		2.11		0.51	2.70	0.39	14.67	79.62	
Pimelodus maculatus	lac		94.09		5.90		0.01			
Pimelodella gracilis	flu		34.88	36.05				11.63		17.44
	int		27.99	5.21			2.19	2.27	62.14	0.20
Pimelodus mysteriosus	int		14.13	2.61		69.57	2.17	10.43	0.87	0.22
Pinirampus pirinampu	int					50.72		49.28		
Plagioscion squamosissimus	lac				27.10	69.87		3.03		
	flu		0.10		35.81	63.89		0.20		
	int				19.25	79.70		1.04		
Potamotrygon amandae	lac						99.74	0.26		
Potamotrygon cf. falkneri	int		0.81			95.16	4.03			
Prochilodus lineatus	lac			100						
	flu		0.22	99.78						
	int			100						
Pterodoras granulosus	lac		100							
	int						100			
Pterygoplichthys ambrosettii	flu		1.18	98.82						
Rhamphichthys hahni	flu			28.57				71.43		
	int		98.83					1.17		
Rhaphiodon vulpinus	lac				18.18	81.82				
	int				4.90	91.18		3.92		
Salminus brasiliensis	lac					100				
Satanoperca sp.	lac		98.53	0.43			0.94	0.02		0.09
	flu		95.65					4.35		
	int		82.12	11.46			5.01	0.08	1.33	
Schizodon borellii	flu	100								
	int	6.07	92.94	0.65			0.34			
Serrasalmus maculatus	lac		2.24			97.75			0.01	
Serrasalmus marginatus	lac					100				
	int		48.46	0.33	13.22	38.00				
Sorubim lima	flu					100				
Steindachnerina brevipinna	lac			100						
Trachydoras paraguayensis	flu			60				20.40		19.60

APPENDIX E – Kruskal-Wallis test results

Table S4. Results of Kruskal-Wallis Test for differences in abundance and biomass of fish trophic guilds among reservoir zones. Values in bold means statistically significant results. Lac = lacustrine; Int = intermediate; Flu = fluvial

Trophic guild	**Relative abundance**		**Relative biomass**	
	X^2	p	X^2	p
Benthophagous	0.83	0.65	2.46	0.291
Detritivore	4.83	0.08	2.14	0.34
Herbivore	**8.4**	**0.01**	2.86	0.23
Aquatic insectivore	0.74	0.38	0.2	0.65
Terrestrial insectivore	5.33	0.06	5.79	0.055
Molluscivore	4.52	0.1	3.25	0.19
Omnivore	2.54	0.28	3.4	0.18
Piscivore	2.64	0.26	0.42	0.8

APPENDIX F - Pearson correlation test results for abundance

Table S5. Pearson correlation test results between Axis 1 and Axis 2 of PCoA and abundance of fish trophic Guilds across Reservoir zones

Guild	Axis 1	Axis 2
Algivore	0.164115	0.261803
Bentophagous	-0.13357	0.428829
Carcinophagus	-0.38552	0.229474
Detritivore	-0.83916	0.097902
Herbivore	0.874126	0.447552
Insectivore (A)	0.366423	0.106873
Insectivore (T)	0.428073	0.3193
Invertivore	-0.76552	-0.34532
Molluscivore	0.01052638	0.575442
Omnivore	-0.54931	0.478885
Piscivore	-0.74606	0.269703
Planktivore	0	0.453425

APPENDIX G - Pearson correlation test results for biomass

Table S6. Pearson correlation test results between Axis 1 and Axis 2 of PCoA and biomass of fish trophic guilds across Reservoir zones

Guild	Axis1	Axis2
Algivore	0.315111	0.402965
Bentophagous	-0.4167	0.059589
Carcinophagus	-0.61197	-0.04331
Detritivore	-0.45891	-0.84815
Herbivore	0.774798	0.375388
Insectivore (A)	0.242946	0.170603
Insectivore (T)	0.622759	0.313847
Invertivore	-0.48219	0.152859
Molluscivore	-0.46691	0.431679
Omnivore	-0.71079	0.055005
Piscivore	-0.79884	0.545942
Planktivore	0.118214	0.239748

APPENDIX H – Microplastics recovered from fish

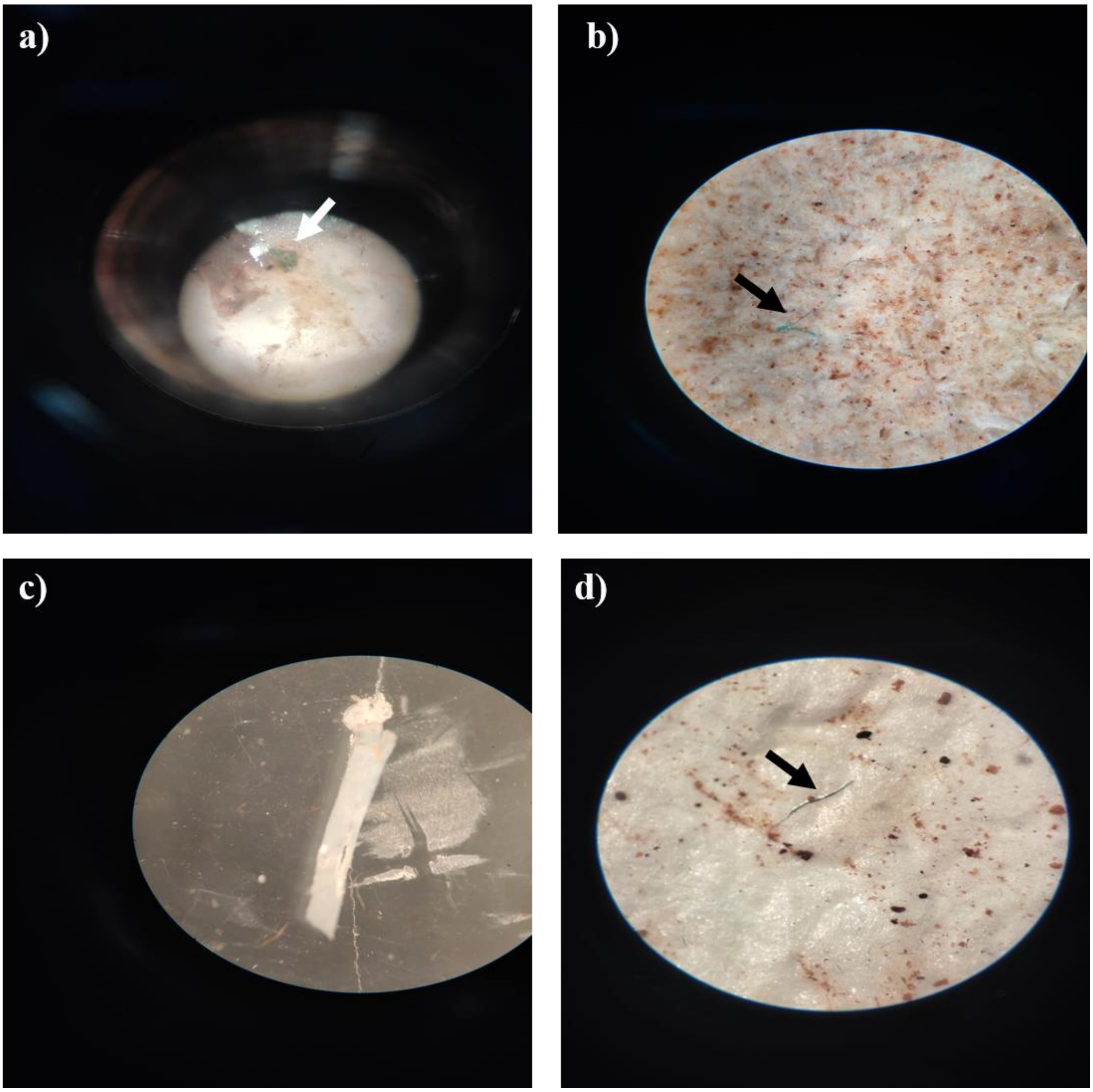

Fig. S1. Examples of microplastics recovered from the gastrointestinal tract of fish from the Itaipu reservoir. Arrows indicate the proximate location close to the plastic particle. A) Blue fragment of polyamide, b) blue fiber of polyamide, c) white fragment of polyethylene and d) black fiber of polyamide.

APPENDIX I – List of the studies included in the fish qualitative synthesis

Table S1. Key metadata of fish studies included in our qualitative synthesis. We used the abbreviation *et al.* for studies with 3 authors or more.

Authors	Publication Year	Country	doi
Adeogun et al.	2023	Nigeria	http://dx.doi.org/10.1007/s11356-020-09031-8
Adji et al.	2022	Indonesia	http://dx.doi.org/10.1007/s11270-022-05572-3
Adu-Boahen et al.	2022	Ghana	http://dx.doi.org/10.1007/s10708-020-10273-6
Andrade et al.	2019	Brazil	http://dx.doi.org/10.1016/j.envpol.2018.10.088
Bauer et al.	2022	Brazil	https://doi.org/10.1590/1519-6984.267886
Biginagwa et al.	2016	Tanzania	http://dx.doi.org/10.1016/j.jglr.2015.10.012
Buwono et al.	2021	Indonesia	http://dx.doi.org/10.1016/j.emcon.2021.08.002
Buwono et al.	2022	Indonesia	http://dx.doi.org/10.1016/j.envpol.2022.119958
Castillo et al.	2022	USA	http://dx.doi.org/10.1656/058.021.0407
Collard et al.	2018	France	http://dx.doi.org/10.1016/j.scitotenv.2018.06.313
Costa et al.	2023	Brazil	https://doi.org/10.1016/j.marpolbul.2023.114736
Devi et al.	2020	India	http://dx.doi.org/10.1016/j.marpolbul.2020.111637
Ditlhakanyane et al.	2022	Botswana	http://dx.doi.org/10.1007/s10661-022-10263-w
Dos Santos et al.	2020	Brazil	https://doi.org/10.1590/S2179-975X3020
Frank et al.	2020	Russia	http://dx.doi.org/10.17223/19988591/52/7
Garcia et al.	2021	Colombia	http://dx.doi.org/10.1007/s11356-020-11605-2
Garcia et al.	2020	Brazil	http://dx.doi.org/10.1007/s11270-020-04802-9
Garcia-Torne et al.	2023	Spain	http://dx.doi.org/10.3390/molecules28010239
Haque et al.	2023	Bangladesh	http://dx.doi.org/10.1016/j.scitotenv.2022.159344
Kim et al.		Korea	http://dx.doi.org/10.1007/s11356-023-26562-9
Li et al.	2020	China	http://dx.doi.org/10.1016/j.scitotenv.2020.138662
Lima et al.	2021	Brazil	http://dx.doi.org/10.1007/s11270-020-04964-6
Loayza et al.	2022	Bolivia	http://dx.doi.org/10.7717/peerj.14112
Makhdoumi et al.	2021	Iran	http://dx.doi.org/10.1016/j.marpolbul.2021.112915
Martinez-Tavera et al.	2021	Mexico	http://dx.doi.org/10.1016/j.chemosphere.2020.128968
Mazariegos-Ortiz et al.	2021	Guatemala	http://dx.doi.org/10.7818/ECOS.2188
McIlwraith et al.	2021	Canada	http://dx.doi.org/10.1021/acs.est.1c02922
Merga et al.	2020	Ethiopia	http://dx.doi.org/10.1016/j.scitotenv.2020.140527
Munno et al.	2022	Canada	http://dx.doi.org/10.1111/cobi.13794
Oliveira et al.	2020	Brazil	http://dx.doi.org/10.4136/ambi-agua.2551
Peters & Bratton	2016	USA	http://dx.doi.org/10.1016/j.envpol.2016.01.018
Phillips & Bonner	2015	USA	http://dx.doi.org/10.1016/j.marpolbul.2015.08.041
Pradit et al.	2021	Thailand	http://dx.doi.org/10.15666/aeer/1902_10851106
Qaiser et al.	2023	Pakistan	http://dx.doi.org/10.1016/j.chemosphere.2022.137177
Rahmayanti et al.	2022	Indonesia	http://dx.doi.org/10.32526/ennrj/20/202100200
Ramos et al.	2022	Brazil	https://doi.org/10.1590/S2179-975X0322
Raza et al.	2022	Pakistan	http://dx.doi.org/10.1007/s11356-022-22440-y
Rendell-Bhatti et al.	2023	UK	http://dx.doi.org/10.1016/j.envpol.2023.121267
Sanchez et al.	2014	France	http://dx.doi.org/10.1016/j.envres.2013.11.004

Sani et al.	2022	Nigeria	http://dx.doi.org/10.1080/15275922.2022.2125116
Wang et al.	2020	China	http://dx.doi.org/10.1016/j.chemosphere.2020.127345
Watiniasih et al.	2023	Indonesia	https://doi.org/10.12911/22998993/158819
Xu et al.	2021	China	http://dx.doi.org/10.1007/s11356-021-15338-8

APPENDIX J – List of the studies included in the invertebrates qualitative synthesis

Table S2. Key metadata of invertebrates studies included in our qualitative synthesis. We used the abbreviation *et al.* for studies with 3 authors or more.

Authors	Publication Year	country	doi
Adji et al.	2022	Indonesia	http://dx.doi.org/10.1007/s11270-022-05572-2
Akindele et al.	2020	Nigeria	http://dx.doi.org/10.1007/s11356-020-08763-8
Atici	2022	Turkey	http://dx.doi.org/10.1080/1354750X.2021.2020335
Baldwin et al.	2021	USA	http://dx.doi.org/10.1371/journal.pone.0228897
Battistin et al.	2023	Italy	http://dx.doi.org/10.1080/24750263.2022.2160019
Corami et al.	2022	Italy	https://doi.org/10.3390/toxics10070383 https://
Dahms et al.	2020	South Africa	http://dx.doi.org/10.1016/j.scitotenv.2020.138893
Di Lorenzo et al.	2023	Italy	http://dx.doi.org/10.1016/j.chemosphere.2022.136830
Ehlers et al.	2019	Germany	http://dx.doi.org/10.3354/ab00711
Gallitelli et al.	2020	Italy	http://dx.doi.org/10.3390/hydrology7040090
Haque et al.	2023	Bangladesh	http://dx.doi.org/10.1016/j.scitotenv.2022.159344
Khdre et al.	2023	Egypt	http://dx.doi.org/10.1007/s11270-023-06179-x
Lin et al.	2021	Taiwan	http://dx.doi.org/10.1038/s41598-020-79881-z
Lin et al.	2023	Taiwan	http://dx.doi.org/10.1016/j.jhazmat.2022.130272
López et al.	2023	Ecuador	http://dx.doi.org/10.3389/fenvs.2023.1028970
Maneechan et al.	2022	Thailand	http://dx.doi.org/10.7717/peerj.12902
Maneechan et al.	2022	Thailand	http://dx.doi.org/10.3390/insects13121131
Nel et al.	2018	Eastern Cape	http://dx.doi.org/10.1016/j.scitotenv.2017.08.298
Pan et al.	2021	Belgium	https://doi.org/10.1021/acs.est.1c03119
Rahmayanti et al.	2022	Indonesia	https://doi.org/10.32526/ennrj/20/202100200
Ribeiro et al.	2022	Portugal	http://dx.doi.org/10.3390/ijerph192315956
Su et al.	2016	China	http://dx.doi.org/10.1016/j.envpol.2016.06.036
Wardlaw & Prosser	2020	Canada	http://dx.doi.org/10.1007/s11270-020-04741-5
Windsor et al.	2019	Wales	http://dx.doi.org/10.1016/j.scitotenv.2018.07.271

APPENDIX K - List of the studies included in the fish quantitative synthesis

Table S3. Key metadata of fish studies included in our quantitative synthesis. We used the abbreviation *et al.* for studies with 3 authors or more. GIT – gastrointestinal tract

Authors	Year	Title	Country	Environment	Species	Trophic Guild	Habitat	Organ	Plastic Size	Obs	doi
Anandhan et al.	2022	Occurrence of Microplastics in the Gastrointestinal Tracts of Edible Fishes from South Indian Rivers	India	River	*Carangoides malabaricus*	Omnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1007/s00128-022-03595-3
Anandhan et al.	2022		India	River	*Chanda nama*	Carnivore	Benthopelagic	GIT	Micro	Only habitat use sourced from fishbase	https://doi.org/10.1007/s00128-022-03595-3
Anandhan et al.	2022	Occurrence of Microplastics in the Gastrointestinal Tracts of Edible Fishes from South Indian Rivers	India	River	*Chanos chanos*	Omnivore	Benthopelagic	GIT	Micro	Only habitat use sourced from fishbase	https://doi.org/10.1007/s00128-022-03595-3
Anandhan et al.	2022		India	River	*Chelon macrolepis*	Omnivore	Demersal	GIT	Micro	Only habitat use sourced from fishbase	https://doi.org/10.1007/s00128-022-03595-3
Anandhan et al.	2022		India	River	*Gerres filamentosus*	Omnivore	Demersal	GIT	Micro	Only habitat use sourced from fishbase	https://doi.org/10.1007/s00128-022-03595-3
Atamanalp et al.	2022	Interaction of Microplastic Presence and Oxidative Stress in Freshwater Fish: A Regional Scale Research, East Anatolia of Türkiye (Erzurum & Erzincan & Bingöl)	Turkey	Stream	*Atherina mochon*	Carnivore	Pelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.3390/su141912009
Atamanalp et al.	2022		Turkey	Stream	*Blicca bjoerkna*	Carnivore	Demersal	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.3390/su141912009
Atamanalp et al.	2022		Turkey	Stream	*Capoeta trutta*	Herbivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.3390/su141912009
Atamanalp et al.	2022		Turkey	Stream	*Capoeta umbla*	Herbivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.3390/su141912009
Atamanalp et al.	2022		Turkey	Stream	*Cyprinus carpio*	Omnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.3390/su141912009
Atamanalp et al.	2022		Turkey	Stream	*Garra rufa*	Herbivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.3390/su141912009
Atamanalp et al.	2022		Turkey	Stream	*Mugil cephalus*	Omnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.3390/su141912009
Atamanalp et al.	2022		Turkey	Stream	*Squalius squalus*	Omnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.3390/su141912009
Atamanalp et al.	2022	A new record for the presence of microplastics in dominant fish species of the Karasu River Erzurum, Turkey	Turkey	River	*Alburnus mossulensis*	Omnivore	Benthopelagic	GIT	Micro	Food and feeding habits of the Mossul bleak, Alburnus mossulensis Heckel, 1843 (Cyprinidae) in the Azad dam of Sanandaj, Iran	https://doi.org/10.1007/s11356-021-16243-w
Atamanalp et al.	2022		Turkey	River	*Cyprinus carpio*	Omnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1007/s11356-021-16243-w
Atamanalp et al.	2022		Turkey	River	*Squalius cephalus*	Omnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1007/s11356-021-16243-w

Atici et al.	2021	High levels of microplastic ingestion by commercial, planktivorous *Alburnus tarichi* in Lake Van, Turkey	Turkey	Lake	*Alburnus tarichi*	Planktivore	Pelagic	GIT	Micro		https://doi.org/10.1080/19440049.2021.1941304
Bilal et al.	2023	Microplastics in the Surface Water and Gastrointestinal Tract of Salmo trutta from the Mahodand Lake, Kalam Swat in Pakistan	Pakistan	Lake	*Salmo trutta*	Carnivore	Pelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.3390/toxics11010003
Bilal et al.	2023	Microplastics in water, sediments, and fish at Alpine River, originating from the Hindu Kush Mountain, Pakistan: implications for conservation	Pakistan	River	*Clupisoma naziri*	Omnivore	Demersal	GIT	Micro	Only habitat use sourced from fishbase	https://doi.org/10.1007/s11356-022-22212-8
Bilal et al.	2023		Pakistan	River	*Salmo trutta*	Carnivore	Pelagic	GIT	Micro	Only habitat use sourced from fishbase	https://doi.org/10.1007/s11356-022-22212-8
Bilal et al.	2023		Pakistan	River	*Schizothorax plagiostomus*	Herbivore	Benthopelagic	GIT	Micro	Only habitat use sourced from fishbase	https://doi.org/10.1007/s11356-022-22212-8
Bilal et al.	2023		Pakistan	River	*Wallago attu*	Carnivore	Demersal	GIT	Micro	Only habitat use sourced from fishbase	https://doi.org/10.1007/s11356-022-22212-8
Blankson et al.	2022	Microplastics prevalence in water, sediment and two economically important species of fish in an urban riverine system in Ghana	Ghana	River	*Chrysichthys nigrodigitatus*	Omnivore	Pelagic	GIT	Micro		https://doi.org/10.1371/journal.pone.0263196
Blankson et al.	2022		Ghana	River	*Sarotherodon melanotheron*	Omnivore	Demersal	GIT	Micro		https://doi.org/10.1371/journal.pone.0263196
Blettler et al.	2019	Massive plastic pollution in a mega-river of a developing country: Sediment deposition and ingestion by fish (*Prochilodus lineatus*)	Argentina	River	*Prochilodus lineatus*	Detritivore	Benthopelagic	GIT	Micro		https://doi.org/10.1016/j.envpol.2019.113348
Bosshart et al.	2020	Independence of microplastic ingestion from environmental load in the round goby (*Neogobius melanostomus*) from the Rhine River using high quality standards	Germany	River	*Neogobius melanostomus*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envpol.2020.115664
Cannon et al.	2016	Plastic ingestion by fish in the Southern Hemisphere: A baseline study and review of methods	Tasmania	Lake	*Paragalaxias dissimilis*	Carnivore	Demersal	GIT	Micro	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.marpolbul.2016.03.057
Cardozo et al.	2023	Plastic ingestion by carnivore fish in a neotropical floodplain: seasonal and interspecific variations	Brazil	River	*Acestrorhynchus lacustris*	Carnivore	Benthopelagic	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Ageneiosus inermis*	Carnivore	Pelagic	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Ageneiosus ucayalensis*	Carnivore	Pelagic	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Astronotus crassipinnis*	Carnivore	Benthopelagic	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Cichla kelberi*	Carnivore	Benthopelagic	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Cichlasoma paranaense*	Carnivore	Benthopelagic	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Crenicichla jaguarensis*	Carnivore	Benthopelagic	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Galeocharax gulo*	Carnivore	Benthopelagic	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0

Cardozo et al.	2023		Brazil	River	*Hemisorubim platyrhynchos*	Carnivore	Demersal	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Hoplerythrinus unitaeniatus*	Carnivore	Pelagic	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Hoplias spp.*	Carnivore	Benthopelagic	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Pinirampus pirinampu*	Carnivore	Demersal	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Plagioscion squamosissimus*	Carnivore	Benthopelagic	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Potamotrygon falkneri*	Carnivore	Demersal	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Pseudoplatystoma corruscans*	Carnivore	Demersal	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Rhamdia quelen*	Carnivore	Benthopelagic	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Rhaphiodon vulpinus*	Carnivore	Pelagic	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Salminus brasiliensis*	Carnivore	Benthopelagic	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Salminus hilarii*	Carnivore	Benthopelagic	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Serrasalmus maculatus*	Carnivore	Pelagic	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Serrasalmus marginatus*	Carnivore	Pelagic	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Sorubim lima*	Carnivore	Demersal	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cardozo et al.	2023		Brazil	River	*Zungaro jahu*	Carnivore	Benthopelagic	GIT	Micro-meso		https://doi.org/10.1007/s11356-023-25135-0
Cera et al.	2022	Microplastics distribution and possible ingestion by fish in lacustrine waters (Lake Bracciano, Italy)	Italy	Lake	*Atheryna boyeri*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1007/s11356-022-20403-x
Cera et al.	2022		Italy	Lake	*Coregonus lavaretus*	Carnivore	Pelagic	GIT	Micro		https://doi.org/10.1007/s11356-022-20403-x
Chen et al.	2022	Factors affecting microplastic accumulation by wild fish: A case study in the Nandu River, South China	China	River	*Carassius auratus*	Omnivore	Demersal	GIT	Micro	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.scitotenv.2022.157486
Chen et al.	2022		China	River	*Cirrhinus molitorella*	Omnivore	Benthopelagic	GIT	Micro	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.scitotenv.2022.157486
Chen et al.	2022		China	River	*Coptodon zillii*	Omnivore	Demersal	GIT	Micro	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.scitotenv.2022.157486
Chen et al.	2022		China	River	*Cranoglanis multiradiatus*	Carnivore	Benthopelagic	GIT	Micro	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.scitotenv.2022.157486
Chen et al.	2022		China	River	*Culter mongolicus*	Carnivore	Pelagic	GIT	Micro	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.scitotenv.2022.157486
Chen et al.	2022		China	River	*Hemibarbus medius*	Omnivore	Benthopelagic	GIT	Micro	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.scitotenv.2022.157486

Chen et al.	2022		China	River	*Hemiculter leucisculus*	Omnivore	Benthopelagic	GIT	Micro	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.scitotenv.2022.157486
Chen et al.	2022		China	River	*Microphysogobio kachekensis*	Carnivore	Demersal	GIT	Micro	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.scitotenv.2022.157486
Chen et al.	2022		China	River	*Misgurnus anguillicaudatus*	Omnivore	Demersal	GIT	Micro	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.scitotenv.2022.157486
Chen et al.	2022		China	River	*Opsariichthys hainanensis*	Omnivore	Benthopelagic	GIT	Micro	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.scitotenv.2022.157486
Chen et al.	2022		China	River	*Oreochromis niloticus*	Omnivore	Benthopelagic	GIT	Micro	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.scitotenv.2022.157486
Chen et al.	2022		China	River	*Oxyeleotris marmorata*	Carnivore	Demersal	GIT	Micro	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.scitotenv.2022.157486
Chen et al.	2022		China	River	*Parachromis managuensis*	Carnivore	Benthopelagic	GIT	Micro	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.scitotenv.2022.157486
Chen et al.	2022		China	River	*Spinibarbus hollandi*	Omnivore	Benthopelagic	GIT	Micro	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.scitotenv.2022.157486
Chen et al.	2022		China	River	*Squaliobarbus curriculus*	Omnivore	Benthopelagic	GIT	Micro	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.scitotenv.2022.157486
Chen et al.	2022		China	River	*Toxabramis houdermeri*	Omnivore	Benthopelagic	GIT	Micro	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.scitotenv.2022.157486
Chota-Macuyama et al.	2020	First record of microplastic ingestion by an important commercial fish in the city of Iquitos, peruvian Amazon	Peru	River	*Calophysus macropterus*	Carnivore	Demersal	Stomach	Micro		https://doi.org/10.24841/fa.v29i2.521
Chota-Macuyama et al.	2020		Peru	River	*Hydrolycus scomberoides*	Carnivore	Benthopelagic	Stomach	Micro		https://doi.org/10.24841/fa.v29i2.521
Chota-Macuyama et al.	2020		Peru	River	*Mylossoma albiscopum*	Omnivore	Pelagic	Stomach	Micro		https://doi.org/10.24841/fa.v29i2.521
Chota-Macuyama et al.	2020		Peru	River	*Osteoglossum bicirrhosum*	Omnivore	Benthopelagic	Stomach	Micro		https://doi.org/10.24841/fa.v29i2.521
Chota-Macuyama et al.	2020		Peru	River	*Pimelodus blochii*	Omnivore	Benthopelagic	Stomach	Micro		https://doi.org/10.24841/fa.v29i2.521
Chota-Macuyama et al.	2020		Peru	River	*Potamorhina altamazonica*	Detritivore	Benthopelagic	Stomach	Micro		https://doi.org/10.24841/fa.v29i2.521
Chota-Macuyama et al.	2020		Peru	River	*Prochilodus nigricans*	Detritivore	Benthopelagic	Stomach	Micro		https://doi.org/10.24841/fa.v29i2.521
Chota-Macuyama et al.	2020		Peru	River	*Pygocentrus nattereri*	Carnivore	Pelagic	Stomach	Micro		https://doi.org/10.24841/fa.v29i2.521
Chota-Macuyama et al.	2020		Peru	River	*Schizodon fasciatus*	Omnivore	Benthopelagic	Stomach	Micro		https://doi.org/10.24841/fa.v29i2.521

Chota-Macuyama et al.	2020		Peru	River	*Sorubim lima*	Carnivore	Demersal	Stomach	Micro		https://doi.org/10.24841/fa.v29i2.521
Chota-Macuyama et al.	2020		Peru	River	*Triportheus angulatus*	Omnivore	Benthopelagic	Stomach	Micro		https://doi.org/10.24841/fa.v29i2.521
Da Costa et al.	2023	Microplastics in fishes in Amazon riverine beaches: Influence of feeding mode and distance to urban settlements	Brazil	River	*Anchoviella juruasanga*	Carnivore	Pelagic	GIT	Micro	Only habitat use sourced from fishbase	http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Apareidon sp*	Detritivore		GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Astyanax elachylepis*	Omnivore		GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Bivibranchia fowleri*	Carnivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Brycon pesu*	Omnivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Bryconops caudomaculatus*	Carnivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Bryconops giacopinii*	Omnivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Creagrutus anary*	Omnivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Creagrutus sp*	Omnivore		GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Crenicicla santosi*	Carnivore		GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Cyphocharax spiluropsis*	Detritivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Deuterodon sp*	Omnivore		GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Geophagus sp*	Omnivore		GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Hemigrammus cf. Geisleri*	Carnivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Jupiaba zonata*	Omnivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Knodus heteresthes*	Omnivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Microschemobrycon callops*	Carnivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Moenkhausia collettii*	Carnivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Moenkhausia hasemani*	Omnivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Moenkhausia oligolepis*	Omnivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Moenkhausia rondoni*	Carnivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Myleinae sp*	Herbivore		GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934

Da Costa et al.	2023		Brazil	River	*Myleus sp*	Herbivore		GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Phenacogaster retropinnus*	Carnivore	Pelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Satanoperca jurupari*	Detritivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Serrapinnus notomelas*	Omnivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Serrapinus micropterus*	Omnivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Tetragonopterus argenteus*	Omnivore	Pelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Da Costa et al.	2023		Brazil	River	*Vandellia cirrhosa*	Hemtophage	Demersal	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.160934
Dahms et al.	2022	Gastric Microplastics in Clarias gariepinus of the Upper Vaal River, South Africa	South Africa	River	*Clarias gariepinus*	Omnivore	Demersal	GIT	Micro		10.3389/fenvs.2022.931073
Dehm et al.	2022	Occurrence of microplastics within a freshwater aquaculture system in the Pacific Islands, Viti Levu, Fiji	Fiji	Reservoir	*Oreochromis spp.*	Omnivore		GIT	Micro	*only wild fish species was considered in our study	https://doi.org/10.1007/s10661-022-10305-3
Driscoll et al.	2021	Presence of Microplastics in the Food Web of the Largest High-Elevation Lake in North America	USA	Lake	*Oncorhynchus clarkii bouvieri*	Carnivore	Demersal	Stomach	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.3390/w13030264
Driscoll et al.	2021		USA	Lake	*Salvelinus namaycush*	Carnivore	Benthopelagic	Stomach	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.3390/w13030264
Eppehimer et al.	2021	Impacts of baseflow and flooding on microplastic pollution in an effluent-dependent arid land river in the USA	USA	River	*Gambusia affinis*	Carnivore	Benthopelagic	Stomach	Micro		https://doi.org/10.1007/s11356-021-13724-w
Espiritu et al.	2023	Microplastics contamination in the fishes of selected sites in Pasig River and Marikina River in the Philippines	Philippines	River	*Arius manillensis*	Carnivore	Benthopelagic	GIT - gills	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1016/j.marpolbul.2023.114573
Espiritu et al.	2023		Philippines	River	*Oreochromis niloticus*	Omnivore	Benthopelagic	GIT - gills	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1016/j.marpolbul.2023.114573
Espiritu et al.	2023		Philippines	River	*Pterygoplichthys spp*	Detritivore	Demersal	GIT - gills	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1016/j.marpolbul.2023.114573
Forgione et al.	2023	Microplastics pollution in freshwater fishes in the South of Italy: Characterization, distribution, and correlation with environmental pollutants	Italy	River	*Barbus barbus*	Carnivore	Demersal	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.161032
Forgione et al.	2023		Italy	River	*Leuciscus cephalus*	Omnivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.161032
Forgione et al.	2023		Italy	River	*Rutilus rubilio*	Omnivore	Demersal	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.161032
Forgione et al.	2023		Italy	River	*Salmo trutta*	Carnivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.161032
Forgione et al.	2023		Italy	River	*Scardinius erythrophthalmus*	Omnivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.161032
Frank et al.	2023	Freshwater Fish Siberian Dace Ingest Microplastics in the Remote Yenisei Tributary	Russia	River	*Leuciscus baicalensis*	Omnivore	Benthopelagic	GIT	Micro		https://doi.org/10.3390/toxics11010038
Gad et al.	2023	Microplastics in mainstem Mississippi River fishes	USA	River	*Lepisosteus platostomus*	Carnivore	Demersal	Stomach	Micro	Information regarding trophic guild and habitat use sourced from fishbase	10.3389/fenvs.2022.1065583

Gad et al.	2023		USA	River	*Lepomis macrochirus*	Carnivore	Benthopelagic	Stomach	Micro	Information regarding trophic guild and habitat use sourced from fishbase	10.3389/fenvs.2022.1065583
Gad et al.	2023		USA	River	*Micropterus salmoides*	Carnivore	Benthopelagic	Stomach	Micro	Information regarding trophic guild and habitat use sourced from fishbase	10.3389/fenvs.2022.1065583
Gad et al.	2023		USA	River	*Pylodictis olivaris*	Carnivore	Demersal	Stomach	Micro	Information regarding trophic guild and habitat use sourced from fishbase	10.3389/fenvs.2022.1065583
Galafassi et al.	2021	Microplastic pollution in perch (*Perca fluviatilis*, Linnaeus 1758) from Italian south-alpine lakes	Italy	Lake	*Perca fluviatilis*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envpol.2021.117782
Garcia et al.	2021	Stable Isotope Insights into Microplastic Contamination within Freshwater Food Webs	France	River				GIT			https://dx.doi.org/10.1021/acs.est.0c06221
Heshmati et al.	2021	Occurrence and characterization of microplastic content in the digestive system of riverine fishes	Iran	River	*Alburnus chalcoides*	Carnivore	Pelagic	Stomach	Micro		https://doi.org/10.1016/j.jenvman.2021.113620
Heshmati et al.	2021		Iran	River	*Capoeta damascina*	Herbivore	Benthopelagic	Stomach	Micro	Trophic guild information retrieved from "Ayvazyan et al. 2018"; https://doi.org/10.1111/ jzs.12217	https://doi.org/10.1016/j.jenvman.2021.113620
Heshmati et al.	2021		Iran	River	*Capoeta trutta*	Herbivore	Benthopelagic	Stomach	Micro	Trophic guild information retrieved from "Ayvazyan et al. 2018"; https://doi.org/10.1111/ jzs.12218	https://doi.org/10.1016/j.jenvman.2021.113620
Heshmati et al.	2021		Iran	River	*Cyprinion macrostomus*	Herbivore	Benthopelagic	Stomach	Micro		https://doi.org/10.1016/j.jenvman.2021.113620
Heshmati et al.	2021		Iran	River	*Leuciscus cephalus*	Omnivore	Benthopelagic	Stomach	Micro		https://doi.org/10.1016/j.jenvman.2021.113620
Heshmati et al.	2021		Iran	River	*Luciobarbus capito*	Omnivore	Benthopelagic	Stomach	Micro		https://doi.org/10.1016/j.jenvman.2021.113620
Hossain et al.	2022	Surface water, sediment, and biota: The first multi-compartment analysis of microplastics in the Karnafully river, Bangladesh	Bangladesh	River	*Otolithoides pama*	Carnivore	Benthopelagic	GIT	Micro	Trophic guild information retrieved from " Bhakta et al. 2019"; https://doi.org/10.1016/j.rsma.2019.100860	https://doi.org/10.1016/j.marpolbul.2022.113820
Hossain et al.	2022		Bangladesh	River	*Polynemus paradiseus*	Carnivore	Demersal	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1016/j.marpolbul.2022.113820
Hossain et al.	2022		Bangladesh	River	*Setipinna phasa*	Carnivore	Pelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1016/j.marpolbul.2022.113820
Hou et al.	2021	A fish tale: a century of museum specimens reveal increasing microplastic concentrations in freshwater fish	USA	River	*Ictalurus punctatus*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1002/eap.2320
Hou et al.	2021		USA	Stream	*Micropterus salmoides*	Carnivore	Benthopelagic	GIT	Micro		https://doi.org/10.1002/eap.2320
Hou et al.	2021		USA	Lake	*Neogobius melanostomus*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1002/eap.2320
Hou et al.	2021		USA	Stream	*Notropis stramineus*	Omnivore	Benthopelagic	GIT	Micro		https://doi.org/10.1002/eap.2320
Jabeen et al.	2017	Microplastics and mesoplastics in fish from coastal and fresh waters of China	China	Lake	*Carassius auratus*	Omnivore	Benthopelagic	GIT	Micro-meso	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.envpol.2016.11.055
Jabeen et al.	2017		China	Lake	*Cyprinus carpio*	Omnivore	Benthopelagic	GIT	Micro-meso	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.envpol.2016.11.055
Jabeen et al.	2017		China	Lake	*Hemiculter bleekeri*	Planktivore	Benthopelagic	GIT	Micro-meso	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.envpol.2016.11.055

Jabeen et al.	2017		China	Lake	*Hypophthalmichthys molitrix*	Planktivore	Benthopelagic	GIT	Micro-meso	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.envpol.2016.11.055
Jabeen et al.	2017		China	Lake	*Megalobrama amblycephala*	Herbivore	Benthopelagic	GIT	Micro-meso	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.envpol.2016.11.055
Jabeen et al.	2017		China	Lake	*Pseudorasbora parva*	Omnivore	Benthopelagic	GIT	Micro-meso	*only freshwater fish species were considered for our study	http://dx.doi.org/10.1016/j.envpol.2016.11.055
Kasamesiri & Thaimuangphol	2020	Assessment on microplastics contamination in freshwater fish: a case study of the Ubolratana reservoir, Thailand	Thailand	Reservoir	*Barbobymus goniontus*	Omnivore	Benthopelagic	GIT	Micro		https://doi.org/10.21660/2020.77.6108
Kasamesiri & Thaimuangphol	2020		Thailand	Reservoir	*Clupeichtys aesarnensis*	Planktivore	Pelagic	GIT	Micro		https://doi.org/10.21660/2020.77.6108
Kasamesiri & Thaimuangphol	2020		Thailand	Reservoir	*Cyclocheilichthys repasson*	Omnivore	Benthopelagic	GIT	Micro		https://doi.org/10.21660/2020.77.6108
Kasamesiri & Thaimuangphol	2020		Thailand	Reservoir	*Hemibagrus spilopterus*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.21660/2020.77.6108
Kasamesiri & Thaimuangphol	2020		Thailand	Reservoir	*Henicorhynchus siamensis*	Herbivore	Benthopelagic	GIT	Micro		https://doi.org/10.21660/2020.77.6108
Kasamesiri & Thaimuangphol	2020		Thailand	Reservoir	*Labiobarbus leptocheilus*	Planktivore	Benthopelagic	GIT	Micro		https://doi.org/10.21660/2020.77.6108
Kasamesiri & Thaimuangphol	2020		Thailand	Reservoir	*Mystacoleucus marginatus*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.21660/2020.77.6108
Kasamesiri & Thaimuangphol	2020		Thailand	Reservoir	*Mystus mysticetus*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.21660/2020.77.6108
Kasamesiri & Thaimuangphol	2020		Thailand	Reservoir	*Osteochilus vittatus*	Omnivore	Benthopelagic	GIT	Micro		https://doi.org/10.21660/2020.77.6108
Kasamesiri & Thaimuangphol	2020		Thailand	Reservoir	*Paralaubuca harmandi*	Carnivore	Benthopelagic	GIT	Micro		https://doi.org/10.21660/2020.77.6108
Kasamesiri & Thaimuangphol	2020		Thailand	Reservoir	*Parambassis siamensis*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.21660/2020.77.6108
Kasamesiri & Thaimuangphol	2020		Thailand	Reservoir	*Pristolepis fasciatus*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.21660/2020.77.6108
Kasamesiri & Thaimuangphol	2020		Thailand	Reservoir	*Puntioplites proctozyson*	Omnivore	Benthopelagic	GIT	Micro		https://doi.org/10.21660/2020.77.6108
Kasamesiri & Thaimuangphol	2020		Thailand	Reservoir	*Rasbora aurotaenia*	Planktivore	Benthopelagic	GIT	Micro		https://doi.org/10.21660/2020.77.6108
Kasamesiri & Thaimuangphol	2020	Microplastics ingestion by freshwater fish in the Chi river, Thailand	Thailand	River	*Cyclocheilichthys repasson*	Omnivore	Benthopelagic	GIT	Micro		https://doi.org/10.21660/2020.67.9110
Kasamesiri & Thaimuangphol	2020		Thailand	River	*Hemibagrus spilopterus*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.21660/2020.67.9110
Kasamesiri & Thaimuangphol	2020		Thailand	River	*Henicorhynchus siamensis*	Omnivore	Benthopelagic	GIT	Micro		https://doi.org/10.21660/2020.67.9110
Kasamesiri & Thaimuangphol	2020		Thailand	River	*Labeo chrysophekadion*	Detritivore	Demersal	GIT	Micro		https://doi.org/10.21660/2020.67.9110
Kasamesiri & Thaimuangphol	2020		Thailand	River	*Labiobarbus siamensis*	Detritivore	Demersal	GIT	Micro		https://doi.org/10.21660/2020.67.9110
Kasamesiri & Thaimuangphol	2020		Thailand	River	*Laides longibarbis*	Detritivore	Benthopelagic		Micro		https://doi.org/10.21660/2020.67.9110

Kasamesiri & Thaimuangphol	2020		Thailand	River	*Mystus bocourti*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.21660/2020.67.9110
Kasamesiri & Thaimuangphol	2020		Thailand	River	*Puntioplites proctozyson*	Omnivore	Benthopelagic	GIT	Micro		https://doi.org/10.21660/2020.67.9110
Khan & Setu	2022	Microplastic Ingestion by Fishes from Jamuna River, Bangladesh	Bangladesh	River	*Ailia coila*	Carnivore	Pelagic	GIT	Micro		10.32526/ennrj/20/202100164
Khan & Setu	2022		Bangladesh	River	*Anguilla bengalensis*	Omnivore	Benthopelagic	GIT	Micro		10.32526/ennrj/20/202100164
Khan & Setu	2022		Bangladesh	River	*Cirrhinus reba*	Herbivore	Benthopelagic	GIT	Micro		10.32526/ennrj/20/202100164
Khan & Setu	2022		Bangladesh	River	*Clupisoma garua*	Omnivore	Demersal	GIT	Micro		10.32526/ennrj/20/202100164
Khan & Setu	2022		Bangladesh	River	*Labeo calbasu*	Omnivore	Demersal	GIT	Micro		10.32526/ennrj/20/202100164
Khan & Setu	2022		Bangladesh	River	*Ompok pabda*	Carnivore	Demersal	GIT	Micro		10.32526/ennrj/20/202100164
Khan & Setu	2022		Bangladesh	River	*Wallago attu*	Carnivore	Demersal	GIT	Micro		10.32526/ennrj/20/202100164
Khan et al.	2020	'The Plastic Nile': First Evidence of Microplastic Contamination in Fish from the Nile River (Cairo, Egypt)	Egypt	River	*Bagrus bayad*	Carnivore	Demersal	GIT	Micro		10.3390/toxics8020022
Khan et al.	2020		Egypt	River	*Oreochromis niloticus*	Omnivore	Benthopelagic	GIT	Micro		10.3390/toxics8020022
Khan et al.	2022	Exploration of microplastic pollution with particular focus on source identification and spatial patterns in riverine water, sediment and fish of the Swat River, Pakistan	Pakistan	River	*Schizothorax plagiostomus*	Detritivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	10.1039/d2ra00319h
Kılıç et al.	2022	First record of microplastic occurence at the commercial fish from Orontes River	Turkey	River	*Anguilla anguilla*	Carnivore	Demersal	GIT - gills	Micro		https://doi.org/10.1016/j.envpol.2022.119576
Kılıç et al.	2022		Turkey	River	*Carassius auratus*	Omnivore	Benthopelagic	GIT - gills	Micro		https://doi.org/10.1016/j.envpol.2022.119576
Kılıç et al.	2022		Turkey	River	*Carassius gibelio*	Omnivore	Benthopelagic	GIT - gills	Micro		https://doi.org/10.1016/j.envpol.2022.119576
Kılıç et al.	2022		Turkey	River	*Clarias gariepinus*	Carnivore	Benthopelagic	GIT - gills	Micro		https://doi.org/10.1016/j.envpol.2022.119576
Kılıç et al.	2022		Turkey	River	*Cyprinus carpio*	Omnivore	Benthopelagic	GIT - gills	Micro		https://doi.org/10.1016/j.envpol.2022.119576
Kılıç et al.	2022		Turkey	River	*Planiliza abu*	Herbivore	Pelagic	GIT - gills	Micro		https://doi.org/10.1016/j.envpol.2022.119576
Kusmierek & Popiolek	2020	Microplastics in freshwater fish from Central European lowland river (Widawa R., SW Poland)	Poland	River	*Gobio gobio*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1007/s11356-020-08031-9
Kusmierek & Popiolek	2020		Poland	River	*Rutilus rutilus*	Omnivore	Pelagic	GIT	Micro		https://doi.org/10.1007/s11356-020-08031-9
Mcneish et al.	2018	Microplastic in riverine fish is connected to species traits	USA	River	*Carpoides cyprinus*	Omnivore	Demersal	GIT		Only habitat use sourced from fishbase	10.1038/s41598-018-29980-9
Mcneish et al.	2018		USA	River	*Catostomus commersonii*	Detritivore	Demersal	GIT		Only habitat use sourced from fishbase	10.1038/s41598-018-29980-9
Mcneish et al.	2018		USA	River	*Cyprinella spiloptera*	Carnivore	Benthopelagic	GIT		Only habitat use sourced from fishbase	10.1038/s41598-018-29980-9

Mcneish et al.	2018		USA	River	*Dorosoma cepedianum*	Detritivore	Benthopelagic	GIT		Only habitat use sourced from fishbase	10.1038/s41598-018-29980-9
Mcneish et al.	2018		USA	River	*Fundulus diaphanus*	Carnivore	Benthopelagic	GIT		Only habitat use sourced from fishbase	10.1038/s41598-018-29980-9
Mcneish et al.	2018		USA	River	*Micropterus sp*	Carnivore		GIT		Only habitat use sourced from fishbase	10.1038/s41598-018-29980-9
Mcneish et al.	2018		USA	River	*Neogobius melanostomus*	Carnivore	Demersal	GIT		Only habitat use sourced from fishbase	10.1038/s41598-018-29980-9
Mcneish et al.	2018		USA	River	*Notropis atherinoides*	Carnivore	Benthopelagic	GIT		Only habitat use sourced from fishbase	10.1038/s41598-018-29980-9
Mcneish et al.	2018		USA	River	*Notropis hudsonius*	Omnivore	Benthopelagic	GIT		Only habitat use sourced from fishbase	10.1038/s41598-018-29980-9
Mcneish et al.	2018		USA	River	*Notropis stramineus*	Omnivore	Benthopelagic	GIT		Only habitat use sourced from fishbase	10.1038/s41598-018-29980-9
Mcneish et al.	2018		USA	River	*Pimephales promelas*	Omnivore	Demersal	GIT		Only habitat use sourced from fishbase	10.1038/s41598-018-29980-9
Mičušík et al.	2021	Plastic ingestion by the Wels catfish (*Silurus glanis* L.): detailed chemical analysis and degradation state evaluation	Slovakia	River	*Silurus glanis*	Carnivore	Benthopelagic	Stomach	Macro		https://doi.org/10.1016/j.toxrep.2021.11.006
O'Connor et al.	2020	Microplastics in brown trout (*Salmo trutta* Linnaeus, 1758) from an Irish riverine system	Ireland	River	*Salmo trutta*	Carnivore	Benthopelagic	GIT	Micro		https://doi.org/10.1016/j.envpol.2020.115572
Oliva-Hernández et al.	2021	Microplastics in nile tilapia (*Oreochromis niloticus*) from lake Amatitlán	Guatemala	Lake	*Oreochromis niloticus*	Omnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	10.4136/ambi-agua.2754
Pandey et al.	2023	Abundance, characteristics, and risk assessment of microplastics in indigenous freshwater fishes of India	India	River	*Channa punctatus*	Carnivore	Demersal	GIT - gills - muscle	Micro		https://doi.org/10.1016/j.envres.2022.115011
Pandey et al.	2023		India	River	*Labeo bata*	Omnivore	Benthopelagic	GIT - gills - muscle	Micro	Trophic guild information retrieved from Rao & Simhachalam, 2018: "FOOD AND FEEDING HATBITS OF FRESH WATER FISH LABEO BATA (HAMILTON, 1822) FROM THE RIVER GODAVARI"	https://doi.org/10.1016/j.envres.2022.115011
Pandey et al.	2023		India	River	*Labeo rohita*	Herbivore	Benthopelagic	GIT - gills - muscle	Micro	Trophic guild information retrieved from "Majumder et al. 2018"; https://doi.org/10.26438/ijsrbs/v5i4.9296	https://doi.org/10.1016/j.envres.2022.115017
Pandey et al.	2023		India	River	*Puntius amphibius*	Omnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1016/j.envres.2022.115020
Pandey et al.	2023		India	River	*Salmostoma bacaila*	Carnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1016/j.envres.2022.115020
Park et al.	2022	Occurrence and characteristics of microplastics in fish of the Han River, South Korea: Factors affecting microplastic abundance in fish	Korea	River	*Carassius auratus*	Omnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2022		Korea	River	*Carassius cuvieri*	Omnivore	Pelagic	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2022		Korea	River	*Chelon haematocheila*	Herbivore	Pelagic	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2022		Korea	River	*Coreoperca herzi*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647

Park et al.	2022		Korea	River	*Cyprinus carpio*	Omnivore	Benthopelagic	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2022		Korea	River	*Erythroculter erythropterus*	Carnivore	Pelagic	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2022		Korea	River	*Hamibarbus labeo*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2022		Korea	River	*Hemibarbus longirostris*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2022		Korea	River	*Leiocassis ussuriensis*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2022		Korea	River	*Lepomis macrochirus*	Carnivore	Pelagic	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2022		Korea	River	*Micropterus salmoides*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2022		Korea	River	*Odontobutis interrupta*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2022		Korea	River	*Opsarichthys uncirostris amurensis*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2022		Korea	River	*Pseudogobio esocinus*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2022		Korea	River	*Pungtungia herzi*	Carnivore	Pelagic	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2022		Korea	River	*Sarcocheilichthys nigripinnis morii*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2022		Korea	River	*Sarcocheilichthys variegatus wakiyae*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2022		Korea	River	*Silurus asotus*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2022		Korea	River	*Siniperca scherzeri*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2022		Korea	River	*Squalidus japonicus coreanus*	Omnivore	Pelagic	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2022		Korea	River	*Tachysurus fulvidraco*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2022		Korea	River	*Zacco platypus*	Omnivore	Pelagic	GIT	Micro		https://doi.org/10.1016/j.envres.2021.112647
Park et al.	2020	Distributions of Microplastics in Surface Water, Fish, and Sediment in the Vicinity of a Sewage Treatment Plant	Korea	Stream	*Carassius auratus*	Omnivore	Benthopelagic	GIT	Micro	Only habitat use sourced from fishbase	10.3390/w12123333
Park et al.	2020		Korea	Stream	*Cyprinus carpio*	Omnivore	Benthopelagic	GIT	Micro	Only habitat use sourced from fishbase	10.3390/w12123333
Park et al.	2020		Korea	Stream	*Micropterus salmoides*	Carnivore	Benthopelagic	GIT	Micro	Only habitat use sourced from fishbase	10.3390/w12123333
Park et al.	2020		Korea	Stream	*Pseudogobio esocinus*	Carnivore	Benthopelagic	GIT	Micro	Only habitat use sourced from fishbase	10.3390/w12123333
Park et al.	2020		Korea	Stream	*Zacco platypus*	Omnivore	Benthopelagic	GIT	Micro	Only habitat use sourced from fishbase	10.3390/w12123333

Parker et al.	2022	Microplastic loads within riverine fishes and macroinvertebrates are not predictable from ecological or morphological characteristics	England	River	*Alburnus alburnus*	Omnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	http://dx.doi.org/10.1016/j.scitotenv.2022.156321
Parker et al.	2022		England	River	*Barbatula barbatula*	Carnivore	Demersal	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	http://dx.doi.org/10.1016/j.scitotenv.2022.156321
Parker et al.	2022		England	River	*Cottus gobio*	Carnivore	Demersal	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	http://dx.doi.org/10.1016/j.scitotenv.2022.156321
Parker et al.	2022		England	River	*Gasterosteus aculeatus*	Carnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	http://dx.doi.org/10.1016/j.scitotenv.2022.156321
Parker et al.	2022		England	River	*Leuciscus leuciscus*	Carnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	http://dx.doi.org/10.1016/j.scitotenv.2022.156321
Parker et al.	2022		England	River	*Perca fluviatilis*	Carnivore	Demersal	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	http://dx.doi.org/10.1016/j.scitotenv.2022.156321
Parker et al.	2022		England	River	*Phoxinus phoxinus*	Omnivore	Demersal	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	http://dx.doi.org/10.1016/j.scitotenv.2022.156321
Parker et al.	2022		England	River	*Rutilus rutilus*	Carnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	http://dx.doi.org/10.1016/j.scitotenv.2022.156321
Parker et al.	2022		England	River	*Squalius cephalus*	Omnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	http://dx.doi.org/10.1016/j.scitotenv.2022.156321
Parker et al.	2022	Distinct microplastic patterns in the sediment and biota of an urban stream	England	River	*Barbatula barbatula*	Carnivore	Demersal	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	http://dx.doi.org/10.1016/j.scitotenv.2022.156477
Parker et al.	2022		England	River	*Gasterosteus aculeatus*	Carnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	http://dx.doi.org/10.1016/j.scitotenv.2022.156477
Parker et al.	2022		England	River	*Phoxinus phoxinus*	Omnivore	Demersal	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	http://dx.doi.org/10.1016/j.scitotenv.2022.156477
Parker et al.	2022		England	River	*Rutilus rutilus*	Carnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	http://dx.doi.org/10.1016/j.scitotenv.2022.156477
Parker et al.	2022		England	River	*Squalius cephalus*	Omnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	http://dx.doi.org/10.1016/j.scitotenv.2022.156477
Parvin et al.	2021	Abundance, characteristics and variation of microplastics in different freshwater fish species from Bangladesh	Bangladesh	River	*Anabas testudineus*	Omnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.scitotenv.2021.147137
Parvin et al.	2021		Bangladesh	River	*Awaous grammepomus*	Omnivore	Benthopelagic	GIT	Micro		https://doi.org/10.1016/j.scitotenv.2021.147137
Parvin et al.	2021		Bangladesh	River	*Cirrhinus reba*	Omnivore	Benthopelagic	GIT	Micro		https://doi.org/10.1016/j.scitotenv.2021.147137
Parvin et al.	2021		Bangladesh	River	*Cyprinus carpio*	Omnivore	Benthopelagic	GIT	Micro		https://doi.org/10.1016/j.scitotenv.2021.147137
Parvin et al.	2021		Bangladesh	River	*Eutropiichthys vacha*	Carnivore	Pelagic	GIT	Micro		https://doi.org/10.1016/j.scitotenv.2021.147137
Parvin et al.	2021		Bangladesh	River	*Heteropneustes fossilis*	Omnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.scitotenv.2021.147137
Parvin et al.	2021		Bangladesh	River	*Labeo bata*	Herbivore	Benthopelagic	GIT	Micro		https://doi.org/10.1016/j.scitotenv.2021.147137
Parvin et al.	2021		Bangladesh	River	*Labeo calbasu*	Omnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.scitotenv.2021.147137
Parvin et al.	2021		Bangladesh	River	*Labeo rohita*	Herbivore	Benthopelagic	GIT	Micro		https://doi.org/10.1016/j.scitotenv.2021.147137
Parvin et al.	2021		Bangladesh	River	*Mastacembelus armatus*	Omnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.scitotenv.2021.147137

Parvin et al.	2021		Bangladesh	River	*Mystus cavasius*	Omnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.scitotenv.2021.147137
Parvin et al.	2021		Bangladesh	River	*Mystus vittatus*	Omnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.scitotenv.2021.147137
Parvin et al.	2021		Bangladesh	River	*Nandus meni*	Omnivore	Pelagic	GIT	Micro		https://doi.org/10.1016/j.scitotenv.2021.147137
Parvin et al.	2021		Bangladesh	River	*Notopterus notopterus*	Omnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.scitotenv.2021.147137
Parvin et al.	2021		Bangladesh	River	*Ompok bimaculatus*	Omnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.scitotenv.2021.147137
Parvin et al.	2021		Bangladesh	River	*Oreochromis mossambicus*	Omnivore	Benthopelagic	GIT	Micro		https://doi.org/10.1016/j.scitotenv.2021.147137
Parvin et al.	2021		Bangladesh	River	*Puntius sophore*	Omnivore	Benthopelagic	GIT	Micro		https://doi.org/10.1016/j.scitotenv.2021.147137
Parvin et al.	2021		Bangladesh	River	*Silonia silondia*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.scitotenv.2021.147137
Pastorino et al.	2023	Microplastics in biotic and abiotic compartments of high-mountain lakes from Alps	Italy	Lake	*Salvelinus fontinalis*	Carnivore	Benthopelagic	GIT	Micro		https://doi.org/10.1016/j.ecolind.2023.110215
Pastorino et al.	2021	First insights into plastic and microplastic occurrence in biotic and abiotic compartments, and snow from a high-mountain lake (Carnic Alps)	Italy	Lake	*Cottus gobio*	Carnivore	Demersal	Stomach	Micro		https://doi.org/10.1016/j.chemosphere.2020.129121
Pazos et al.	2017	Microplastics in gut contents of coastal freshwater fish from Rio de la Plata estuary	Argentina	River	*Fish*	Carnivore		GIT	Micro	*information regarding plastic was available for species pooled as trophic guilds	http://dx.doi.org/10.1016/j.marpolbul.2017.06.007
Pazos et al.	2017		Argentina	River	*Fish*	Planktivore		GIT	Micro	*information regarding plastic was available for species pooled as trophic guilds	http://dx.doi.org/10.1016/j.marpolbul.2017.06.007
Pazos et al.	2017		Argentina	River	*Fish*	Omnivore		GIT	Micro	*information regarding plastic was available for species pooled as trophic guilds	http://dx.doi.org/10.1016/j.marpolbul.2017.06.007
Pazos et al.	2017		Argentina	River	*Fish*	Detritivore		GIT	Micro	*information regarding plastic was available for species pooled as trophic guilds	http://dx.doi.org/10.1016/j.marpolbul.2017.06.007
Pittura et al.	2022	Microplastics and Brominated Flame Retardants in Freshwater Fishes From Italian Lakes: Implication for Human Health	Italy	Lake	*Anguilla anguilla*	Carnivore	Demersal	GIT	Micro		10.3389/frwa.2022.902885
Pittura et al.	2022		Italy	Lake	*Carassius auratus*	Omnivore	Benthopelagic	GIT	Micro		10.3389/frwa.2022.902885
Pittura et al.	2022		Italy	Lake	*Perca fluviatilis*	Carnivore	Demersal	GIT	Micro		10.3389/frwa.2022.902885
Pittura et al.	2022		Italy	Lake	*Rutilus rutilus*	Omnivore	Benthopelagic	GIT	Micro		10.3389/frwa.2022.902885
Raza et al.	2022	Characterization and implication of microplastics on riverine population of the River Ravi, Lahore, Pakistan	Pakistan	River	*Cirrhinus mrigala*	Detritivore	Demersal	GIT - gills - muscle - liver	Micro		https://doi.org/10.1007/s11356-022-22440-y
Raza et al.	2022		Pakistan	River	*Labeo rohita*	Herbivore	Benthopelagic	GIT - gills -	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1007/s11356-022-22440-y

								muscle - liver			
Raza et al.	2022		Pakistan	River	*Sperata seenghala*	Carnivore	Demersal	GIT - gills - muscle - liver	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1007/s11356-022-22440-y
Ribeiro-Brasil et al.	2020	Contamination of stream fish by plastic waste in the Brazilian Amazon	Brazil	Stream	*Aequidens tetramerus*	Carnivore	Benthopelagic	GIT - gills	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1016/j.envpol.2020.115241
Ribeiro-Brasil et al.	2020		Brazil	Stream	*Bryconops melanurus*	Carnivore	Benthopelagic	GIT - gills	Micro	Trophic guild information retrieved from "Brejão et al. 2013"; https://doi.org/10.1590/S1679-62252013005000006	https://doi.org/10.1016/j.envpol.2020.115241
Ribeiro-Brasil et al.	2020		Brazil	Stream	*Carnegiella strigata*	Carnivore	Pelagic	GIT - gills	Micro	Trophic guild information retrieved from "Brejão et al. 2013"; https://doi.org/10.1590/S1679-62252013005000006	https://doi.org/10.1016/j.envpol.2020.115241
Ribeiro-Brasil et al.	2020		Brazil	Stream	*Copella arnoldi*	Carnivore	Benthopelagic	GIT - gills	Micro	Trophic guild information retrieved from "Brejão et al. 2013"; https://doi.org/10.1590/S1679-62252013005000006	https://doi.org/10.1016/j.envpol.2020.115241
Ribeiro-Brasil et al.	2020		Brazil	Stream	*Crenicichla regani*	Carnivore	Benthopelagic	GIT - gills	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1016/j.envpol.2020.115241
Ribeiro-Brasil et al.	2020		Brazil	Stream	*Hemigrammus unilineatus*	Carnivore	Benthopelagic	GIT - gills	Micro	Trophic guild information retrieved from "Brejão et al. 2013"; https://doi.org/10.1590/S1679-62252013005000006	https://doi.org/10.1016/j.envpol.2020.115241
Ribeiro-Brasil et al.	2020		Brazil	Stream	*Hoplias malabaricus*	Carnivore	Benthopelagic	GIT - gills	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1016/j.envpol.2020.115241
Ribeiro-Brasil et al.	2020		Brazil	Stream	*Iguanodectes rachovii*	Carnivore	Benthopelagic	GIT - gills	Micro	Trophic guild information retrieved from "Brejão et al. 2013"; https://doi.org/10.1590/S1679-62252013005000006	https://doi.org/10.1016/j.envpol.2020.115241
Ribeiro-Brasil et al.	2020		Brazil	Stream	*Laimosemion strigatus*		Benthopelagic	GIT - gills	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1016/j.envpol.2020.115241
Ribeiro-Brasil et al.	2020		Brazil	Stream	*Mastiglanis asopos*	Carnivore	Demersal	GIT - gills	Micro	Trophic guild information retrieved from "Brejão et al. 2013"; https://doi.org/10.1590/S1679-62252013005000006	https://doi.org/10.1016/j.envpol.2020.115241
Ribeiro-Brasil et al.	2020		Brazil	Stream	*Megalechis thoracata*	Carnivore	Demersal	GIT - gills	Micro	Trophic guild information retrieved from "Brejão et al. 2013"; https://doi.org/10.1590/S1679-62252013005000006	https://doi.org/10.1016/j.envpol.2020.115241
Ribeiro-Brasil et al.	2020		Brazil	Stream	*Nannacara taenia*		Benthopelagic	GIT - gills	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1016/j.envpol.2020.115241
Ribeiro-Brasil et al.	2020		Brazil	Stream	*Pimelodella geryi*	Carnivore	Demersal	GIT - gills	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1016/j.envpol.2020.115241
Ribeiro-Brasil et al.	2020		Brazil	Stream	*Polycentrus schomburgkii*		Benthopelagic	GIT - gills	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1016/j.envpol.2020.115241

Rios et al.	2022	Occurrence of microplastics in Fish from Mendoza River: First Insights into Plastic Pollution in the Central Andes, Argentina	Argentina	River	*Hatcheria macraei*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.3390/w14233905
Rios et al.	2022		Argentina	River	*Oncorhynchus mykiss*	Carnivore	Benthopelagic	GIT	Micro		https://doi.org/10.3390/w14233905
Rios et al.	2022		Argentina	River	*Salmo trutta*	Carnivore	Benthopelagic	GIT	Micro		https://doi.org/10.3390/w14233905
Roch et al.	2019	A systematic study of the microplastic burden in freshwater fishes of south-western Germany - Are we searching at the right scale?	Germany	River - lake	*Fish*			GIT	Micro	Not enough info per species	https://doi.org/10.1016/j.scitotenv.2019.06.404
Rojas et al.	2023	Microplastic occurrence in fish species from the Iquitos region in Peru, western Amazonia	Peru	River	*Ageneiosus inermis*	Carnivore	Pelagic	All organs	Micro		http://dx.doi.org/10.1590/1809-4392202201212
Rojas et al.	2023		Peru	River	*Anodus elongatus*	Omnivore	Pelagic	All organs	Micro		http://dx.doi.org/10.1590/1809-4392202201212
Rojas et al.	2023		Peru	River	*Astronotus ocellatus*	Omnivore	Benthopelagic	All organs	Micro		http://dx.doi.org/10.1590/1809-4392202201212
Rojas et al.	2023		Peru	River	*Brycon amazonicus*	Omnivore	Benthopelagic	All organs	Micro		http://dx.doi.org/10.1590/1809-4392202201212
Rojas et al.	2023		Peru	River	*Calophysus macropterus*	Carnivore	Demersal	All organs	Micro		http://dx.doi.org/10.1590/1809-4392202201212
Rojas et al.	2023		Peru	River	*Cichla monoculus*	Carnivore	Benthopelagic	All organs	Micro		http://dx.doi.org/10.1590/1809-4392202201212
Rojas et al.	2023		Peru	River	*Hoplias malabaricus*	Carnivore	Benthopelagic	All organs	Micro		http://dx.doi.org/10.1590/1809-4392202201212
Rojas et al.	2023		Peru	River	*Megaleporinus trifasciatus*	Omnivore	Benthopelagic	All organs	Micro		http://dx.doi.org/10.1590/1809-4392202201212
Rojas et al.	2023		Peru	River	*Myleus schomburgkii*	Herbivore	Benthopelagic	All organs	Micro		http://dx.doi.org/10.1590/1809-4392202201212
Rojas et al.	2023		Peru	River	*Pseudoplatystoma tigrinum*	Carnivore	Demersal	All organs	Micro		http://dx.doi.org/10.1590/1809-4392202201212
Rojas et al.	2023		Peru	River	*Pseudoplatystoma fasciatum*	Carnivore	Demersal	All organs	Micro		http://dx.doi.org/10.1590/1809-4392202201212
Rojas et al.	2023		Peru	River	*Pterygoplichthys pardalis*	Detritivore	Demersal	All organs	Micro		http://dx.doi.org/10.1590/1809-4392202201212
Rojas et al.	2023		Peru	River	*Pygocentrus nattereri*	Carnivore	Pelagic	All organs	Micro		http://dx.doi.org/10.1590/1809-4392202201212
Rojas et al.	2023		Peru	River	*Satanoperca jurupari*	Omnivore	Benthopelagic	All organs	Micro		http://dx.doi.org/10.1590/1809-4392202201212
Rojas et al.	2023		Peru	River	*Sorubim lima*	Carnivore	Demersal	All organs	Micro		http://dx.doi.org/10.1590/1809-4392202201212
Ryan et al.	2019	Hudson River juvenile Blueback herring avoid ingesting microplastics	USA	Stream	*Alosa aestivais*	Carnivore	Pelagic	Stomach	Micro	Blue herring is a marine species when adult, but all fish collected for this study were juveniles in freshwater streams	https://doi.org/10.1016/j.marpolbul.2019.07.004
Saad et al.	2022	First biomonitoring of microplastic pollution in the Vaal River using Carp fish (*Cyprinus carpio*) as a bio-indicator	South Africa	River	*Cyprinus carpio*	Omnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	http://dx.doi.org/10.1016/j.scitotenv.2022.155623

Sarijan et al.	2019	Ingestion of microplastics by commercial fish in Skudai river, Malaysia	Malaysia	River	*Anabas testudineus*	Omnivore	Pelagic	GIT	Micro		10.14456/ea.2019.47
Sarijan et al.	2019		Malaysia	River	*Clarias gariepinus*	Omnivore	Benthopelagic	GIT	Micro		10.14456/ea.2019.47
Sarijan et al.	2019		Malaysia	River	*Cyclocheilichthys apogon*	Herbivore	Benthopelagic	GIT	Micro		10.14456/ea.2019.47
Sarijan et al.	2019		Malaysia	River	*Oreochromis mossambicus*	Herbivore	Benthopelagic	GIT	Micro		10.14456/ea.2019.47
Sarijan et al.	2019		Malaysia	River	*Oxyeleotris marmorata*	Carnivore	Demersal	GIT	Micro		10.14456/ea.2019.47
Sarijan et al.	2019		Malaysia	River	*Pangasianodon hypophthalmus*	Omnivore	Benthopelagic	GIT	Micro		10.14456/ea.2019.47
Shen et al.	2023	Damming has changed the migration process of microplastics and increased the pollution risk in the reservoirs in the Shaying River Basin	China	Reservoir	*Carassius auratus*	Omnivore	Benthopelagic	GIT - gills - muscle - skin	Micro		https://doi.org/10.1016/j.jhazmat.2022.130067
Shen et al.	2023		China	Reservoir	*Channa argus*	Carnivore	Benthopelagic	GIT - gills - muscle - skin	Micro		https://doi.org/10.1016/j.jhazmat.2022.130067
Shen et al.	2023		China	Reservoir	*Hemiculter leucisculus*	Carnivore	Benthopelagic	GIT - gills - muscle - skin	Micro		https://doi.org/10.1016/j.jhazmat.2022.130067
Shen et al.	2023		China	Reservoir	*Misgurnus anguillicaudatus*	Carnivore	Demersal	GIT - gills - muscle - skin	Micro		https://doi.org/10.1016/j.jhazmat.2022.130067
Shen et al.	2023		China	Reservoir	*Opsariichthys bidens*	Carnivore	Benthopelagic	GIT - gills - muscle - skin	Micro	Trophic guild information retrieved from "Rådman et al. 2006"; https://doi.org/10.1007/s10228-005-0316-0	https://doi.org/10.1016/j.jhazmat.2022.130067
Shen et al.	2023		China	Reservoir	*Rhinogobius giurinus*	Carnivore	Demersal	GIT - gills - muscle - skin	Micro		https://doi.org/10.1016/j.jhazmat.2022.130067
Shen et al.	2023		China	Reservoir	*Rhodeus ocellatus*	Omnivore	Benthopelagic	GIT - gills - muscle - skin	Micro		https://doi.org/10.1016/j.jhazmat.2022.130067
Shen et al.	2023		China	Reservoir	*Tachysurus nitidus*	Omnivore	Demersal	GIT - gills - muscle - skin	Micro	Trophic guild information retrieved from " Liu et al. 2009"; https://doi.org/10.1002/rra.3519	https://doi.org/10.1016/j.jhazmat.2022.130067
Shukla et al.	2022	Occurrence of Microplastics in Riverine Fishes Sold for Human Consumption in Chhattisgarh, India	India	River	*Amblypharyngodon mola*	Omnivore	Benthopelagic	GIT	Micro		https://doi.org/10.1007/s11270-022-05976-0
Shukla et al.	2022		India	River	*Mystus tengara*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1007/s11270-022-05976-0

Shukla et al.	2022		India	River	*Puntius ticto*	Carnivore	Benthopelagic	GIT	Micro		https://doi.org/10.1007/s11270-022-05976-0
Silburn et al.	2022	A baseline study of macro, meso and micro litter in the Belize River basin, from catchment to coast	Belize	River	*Cichlasoma synspilum*	Herbivore	Benthopelagic	GIT	Micro	Trophic guild information retrieved from Valtierra-Veja & Schmitter-Soto, 2000: "Feeding habits of cichlid species (Perciformes: Cichlidae) in Caobas lake, Quintana Roo, Mexico"	https://doi.org/10.1093/icesjms/fsab268
Silva-Cavalcanti et al.	2017	Microplastics ingestion by a common tropical freshwater fishing resource	Brazil	River	*Hoplosternum littorale*	Omnivore	Demersal	GIT	Micro-meso		http://dx.doi.org/10.1016/j.envpol.2016.11.068
Slootmaekers et al.	2019	Microplastic contamination in gudgeons (*Gobio gobio*) from Flemish rivers (Belgium)	Belgium	River	*Gobio gobio*	Carnivore	Benthopelagic	GIT	Micro		https://doi.org/10.1016/j.envpol.2018.09.136
Su et al.	2019	Microplastics biomonitoring in Australian urban wetlands using a common noxious fish (*Gambusia holbrooki*)	Australia	Wetland	*Gambusia holbrooki*	Carnivore	Benthopelagic	GIT - gills	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1016/j.chemosphere.2019.04.114
Sultana et al.	2023	Microplastics in freshwater wild and farmed fish species of Bangladesh	Bangladesh	River	*Gibelion catla*	Omnivore	Benthopelagic	GIT	Micro	*only wild fish species was considered in our study	https://doi.org/10.1007/s11356-023-26512-5
Sultana et al.	2023		Bangladesh	River	*Heteropneustes fossilis*	Omnivore	Demersal	GIT	Micro	*only wild fish species was considered in our study	https://doi.org/10.1007/s11356-023-26512-5
Sultana et al.	2023		Bangladesh	River	*Labeo rohita*	Herbivore	Benthopelagic	GIT	Micro	*only wild fish species was considered in our study	https://doi.org/10.1007/s11356-023-26512-5
Sultana et al.	2023		Bangladesh	River	*Mystus tengara*	Omnivore	Demersal	GIT	Micro	*only wild fish species was considered in our study	https://doi.org/10.1007/s11356-023-26512-5
Sultana et al.	2023		Bangladesh	River	*Ompok pabda*	Omnivore	Demersal	GIT	Micro	*only wild fish species was considered in our study	https://doi.org/10.1007/s11356-023-26512-5
Sun et al.	2021	Characterization and spatial distribution of microplastics in two wild captured economic freshwater fish from north and west rivers of Guangdong province	China	River	*Cirrhinus molitorella*	Omnivore	Benthopelagic	GIT - gills	Micro		https://doi.org/10.1016/j.ecoenv.2020.111555
Sun et al.	2021		China	River	*Oreochromis niloticus*	Omnivore	Benthopelagic	GIT - gills	Micro		https://doi.org/10.1016/j.ecoenv.2020.111555
Tariq et al.	2022	Barrages influencing microplastics distribution and in-gestion; a case study	Pakistan	Reservoir				GIT	Micro		10.26471/cjees/2022/017/212
Tien et al.	2020	Microplastics in water, sediment and fish from the Fengshan River system: Relationship to aquatic factors and accumulation of polycyclic aromatic hydrocarbons by fish	Taiwan	River	*Carassius auratus*	Omnivore	Benthopelagic	GIT	Micro		https://doi.org/10.1016/j.envpol.2020.114962
Tien et al.	2020		Taiwan	River	*Leiognathus equulus*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envpol.2020.114962
Tien et al.	2020		Taiwan	River	*Oreochromis niloticus*	Herbivore	Benthopelagic	GIT	Micro		https://doi.org/10.1016/j.envpol.2020.114962
Tien et al.	2020		Taiwan	River	*Pomadasys argenteus*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envpol.2020.114962
Tien et al.	2020		Taiwan	River	*Pterygoplichthys pardalis*	Detritivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envpol.2020.114962
Toner & Midway	2021	Historic fish samples from the Southeast USA lack microplastics	USA	River	*Dorosoma cepedianum*	Omnivore	Pelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishes of texas	https://doi.org/10.1016/j.scitotenv.2021.145923

Toner & Midway	2021		USA	River	*Fundulus olivaceus*	Omnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishes of texas	https://doi.org/10.1016/j.scitotenv.2021.145923
Toner & Midway	2021		USA	River	*Gambusia affinis*	Carnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishes of texas	https://doi.org/10.1016/j.scitotenv.2021.145923
Toner & Midway	2021		USA	River	*Lepomis macrochirus*	Carnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishes of texas	https://doi.org/10.1016/j.scitotenv.2021.145923
Toner & Midway	2021		USA	River	*Micropterus salmoides*	Carnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishes of texas	https://doi.org/10.1016/j.scitotenv.2021.145923
Toner & Midway	2021		USA	River	*Notropis longirostris*	Omnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishes of texas	https://doi.org/10.1016/j.scitotenv.2021.145923
Toner & Midway	2021		USA	River	*Pimephales vigilax*	Omnivore	Demersal	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishes of texas	https://doi.org/10.1016/j.scitotenv.2021.145923
Trindadeet al.	2023	First record of plastic ingestion by a freshwater stingray	Brazil	River	*Potamotrygon leopoldi*	Carnivore	Demersal	GIT	Micro-meso		http://dx.doi.org/10.1016/j.scitotenv.2023.163199
Turhan	2022	Evaluation of Microplastics in the Surface Water, Sediment and Fish of Surgu Dam Reservoir (Malatya) in Turkey	Turkey	Reservoir	*Alburnus mossulensis*	Planktivore	Benthopelagic	GIT	Micro	Trophic guild information retrieved from Bandpei et al. 2017: "Food and feeding habits of the Mossul bleak, Alburnus mossulensis Heckel, 1843 (Cyprinidae) in the Azad dam of Sanandaj, Iran."	http://doi.org/10.4194/trjfas20157
Turhan	2022		Turkey	Reservoir	*Cyprinus carpio*	Omnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	http://doi.org/10.4194/trjfas20157
Urbanski et al.	2020	First record of plastic ingestion by an important commercial native fish (*Prochilodus lineatus*) in the middle Tiete River basin, Southeast Brazil	Brazil	River	*Prochilodus lineatus*	Herbivore	Benthopelagic	GIT	Micro		https://doi.org/10.1590/1676-0611-bn-2020-1005
Vidal et al.	2021	Incidence of Watershed Land Use on the Consumption of Meso and Microplastics by Fish Communities in Uruguayan Lowland Streams	Uruguay	Stream	*Ancistrus taunayi*	Detritivore	Demersal	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Astyanax spp.*	Omnivore	Pelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Australoheros facetus*	Carnivore	Benthopelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Australoheros scitulus*	Carnivore	Pelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Bryconamericus iheringii*	Omnivore	Benthopelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Characidium rachovii*	Carnivore	Benthopelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Charax stenopterus*	Carnivore	Benthopelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Cheirodon interruptus*	Omnivore	Benthopelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Cnesterodon decemmaculatus*	Omnivore	Benthopelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Corydoras paleatus*	Omnivore	Demersal	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575

Vidal et al.	2021		Uruguay	Stream	*Crenicichla scottii*	Carnivore	Benthopelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Ectrepopterus uruguayensis*	Carnivore	Benthopelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Gymnogeophagus mekinos*	Omnivore	Benthopelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Gymnogeophagus terrapurpura*	Omnivore	Benthopelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Gymnotus omarorum*	Carnivore	Pelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Heptapterus mustelinus*	Carnivore	Demersal	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Hisonotus nigricauda*	Detritivore	Benthopelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Hoplias argentinensis*	Carnivore	Benthopelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Hyphessobrycon meridionalis*	Omnivore	Benthopelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Hypostomus commersoni*	Detritivore	Demersal	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Jenynsia lineata*	Omnivore	Benthopelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Oligosarcus jenynsii*	Carnivore	Benthopelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Otocinclus arnoldi*	Detritivore	Demersal	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Phalloceros caudimaculatus*	Omnivore	Pelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Pseudocorynopoma doriae*	Carnivore	Benthopelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Rhamdia quelen*	Omnivore	Benthopelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Rineloricaria sp*	Detritivore	Demersal	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Steindachnerina biornata*	Detritivore	Benthopelagic	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Vidal et al.	2021		Uruguay	Stream	*Synbranchus marmoratus*	Carnivore	Demersal	GIT	Micro-meso	Only habitat use sourced from fishbase	https://doi.org/10.3390/w13111575
Wardlaw et al.	2022	Factors influencing the variation of microplastic uptake in demersal fishes from the upper Thames River Ontario	Canada	River	*Catostomus commersonii*	Carnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envpol.2022.120095
Wardlaw et al.	2022		Canada	River	*Cyprinus carpio*	Omnivore	Demersal	GIT	Micro		https://doi.org/10.1016/j.envpol.2022.120095
Winkler et al.	2022	Following the fate of microplastic in four abiotic and biotic matrices along the Ticino River (North Italy)	Italy	River	*Silurus glanis*	Carnivore	Benthopelagic	GIT	Micro		http://dx.doi.org/10.1016/j.scitotenv.2022.153638
Wu et al.	2021	Microplastic contamination assessment in water and economic fishes in different trophic	China	Reservoir	*Carassius auratus*	Omnivore	Demersal	GIT - gills	Micro		https://doi.org/10.1016/j.jenvman.2021.113667

		guilds from an urban water supply reservoir after flooding								
Wu et al.	2021		China	Reservoir	*Ctenopharyngodon idella*	Herbivore	Benthopelagic	GIT - gills	Micro	https://doi.org/10.1016/j.jenvman.2021.113667
Wu et al.	2021		China	Reservoir	*Culter mongolicus*	Carnivore	Benthopelagic	GIT - gills	Micro	https://doi.org/10.1016/j.jenvman.2021.113667
Wu et al.	2021		China	Reservoir	*Hypophthalmichthys nobilis*	Planktivore	Pelagic	GIT - gills	Micro	https://doi.org/10.1016/j.jenvman.2021.113667
Wu et al.	2021		China	Reservoir	*Megalobrama amblycephala*	Herbivore	Benthopelagic	GIT - gills	Micro	https://doi.org/10.1016/j.jenvman.2021.113667
Wu et al.	2021		China	Reservoir	*Tachysurus fulvidraco*	Carnivore	Demersal	GIT - gills	Micro	https://doi.org/10.1016/j.jenvman.2021.113667
Wu et al.	2022	Seasonal variation and ecological risk assessment of microplastics ingested by economic fishes in Lake Chaohu, China	China	Lake	*Carassius auratus*	Omnivore	Benthopelagic	GIT - gills	Micro	http://dx.doi.org/10.1016/j.scitotenv.2022.15518
Wu et al.	2022		China	Lake	*Culter alburnus*	Carnivore	Benthopelagic	GIT - gills	Micro	http://dx.doi.org/10.1016/j.scitotenv.2022.15518
Wu et al.	2022		China	Lake	*Cyprinus carpio*	Omnivore	Benthopelagic	GIT - gills	Micro	http://dx.doi.org/10.1016/j.scitotenv.2022.15518
Wu et al.	2022		China	Lake	*Hypophthalmichthys molitrix*	Planktivore	Pelagic	GIT - gills	Micro	http://dx.doi.org/10.1016/j.scitotenv.2022.15518
Wu et al.	2022		China	Lake	*Hyporhamphus intermedius*	Planktivore	Pelagic	GIT - gills	Micro	http://dx.doi.org/10.1016/j.scitotenv.2022.15518
Xiong et al.	2018	Sources and distribution of microplastics in China's largest inland lake - Qinghai Lake	China	Lake	*Gymnocypris przewalskii*	Omnivore	Benthopelagic	GIT	Micro	https://doi.org/10.1016/j.envpol.2017.12.081
Yasaka et al.	2022	Bioaccumulation of Microplastics in Fish and Snails in the Nam Pong River, Khon Kaen, Thailand	Thailand	River	*Barbonymus altus*	Omnivore	Pelagic	GIT	Micro	10.14456/ea.2022.8
Yasaka et al.	2022		Thailand	River	*Laides longibarbis*	Carnivore	Benthopelagic	GIT	Micro	10.14456/ea.2022.8
Yin et al.	2022	Accumulation of microplastics in fish guts and gills from a large natural lake: Selective or non-selective?	China	Lake	*Carassius auratus*	Omnivore	Benthopelagic	GIT - gills	Micro	https://doi.org/10.1016/j.envpol.2022.119785
Yin et al.	2022		China	Lake	*Coilia brachygnathus*	Planktivore	Pelagic	GIT - gills	Micro	https://doi.org/10.1016/j.envpol.2022.119785
Yin et al.	2022		China	Lake	*Culter alburnus*	Carnivore	Benthopelagic	GIT - gills	Micro	https://doi.org/10.1016/j.envpol.2022.119785
Yin et al.	2022		China	Lake	*Culter dabryi*	Carnivore	Benthopelagic	GIT - gills	Micro	https://doi.org/10.1016/j.envpol.2022.119785
Yin et al.	2022		China	Lake	*Culter mongolicus*	Carnivore	Benthopelagic	GIT - gills	Micro	https://doi.org/10.1016/j.envpol.2022.119785
Yin et al.	2022		China	Lake	*Cyprinus carpio*	Omnivore	Benthopelagic	GIT - gills	Micro	https://doi.org/10.1016/j.envpol.2022.119785
Yin et al.	2022		China	Lake	*Hypophthalmichthys molitrix*	Planktivore	Benthopelagic	GIT - gills	Micro	https://doi.org/10.1016/j.envpol.2022.119785
Yin et al.	2022		China	Lake	*Hypophthalmichthys nobilis*	Planktivore	Benthopelagic	GIT - gills	Micro	https://doi.org/10.1016/j.envpol.2022.119785

Yin et al.	2022		China	Lake	*Hyporhamphus intermedius*	Planktivore	Pelagic	GIT - gills	Micro		https://doi.org/10.1016/j.envpol.2022.119785
Yin et al.	2022		China	Lake	*Pseudolaubuca sinensis*	Omnivore	Benthopelagic	GIT - gills	Micro		https://doi.org/10.1016/j.envpol.2022.119785
Yin et al.	2022		China	Lake	*Tachysurus fulvidraco*	Carnivore	Demersal	GIT - gills	Micro		https://doi.org/10.1016/j.envpol.2022.119785
Yuan et al.	2019	Microplastic abundance, distribution and composition in water, sediments, and wild fish from Poyang Lake, China	China	Lake	*Carassius auratus*	Omnivore	Benthopelagic	GIT	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1016/j.ecoenv.2018.11.126
Zhang et al.	2021	Microplastics in freshwater and wild fishes from Lijiang River in Guangxi, Southwest China	China	River	*Cyprinus carpio*	Omnivore	Demersal	GIT - gills	Micro	Information regarding trophic guild and habitat use sourced from fishbase	https://doi.org/10.1016/j.scitotenv.2020.142428
Zhang et al.	2021		China	River	*Mystus macropterus*	Carnivore	Demersal	GIT - gills	Micro		https://doi.org/10.1016/j.scitotenv.2020.142428
Zhang et al.	2021		China	River	*Pelteobagrus fulvidraco*	Omnivore	Demersal	GIT - gills	Micro		https://doi.org/10.1016/j.scitotenv.2020.142428
Zhang et al.	2021		China	River	*Pelteobagrus vachelli*	Omnivore	Demersal	GIT - gills	Micro	Trophic guild information retrieved from "Li et al. 2022"; https://doi.org/10.3389/fgene.2022.1050192	https://doi.org/10.1016/j.scitotenv.2020.142428
Zheng et al.	2019	Occurrence and Species-Specific Distribution of Plastic Debris in Wild Freshwater Fish from the Pearl River Catchment, China	China	River	*Carassius gibelio*	Omnivore	Demersal	GIT	Micro		10.1002/etc.4437
Zheng et al.	2019		China	River	*Channa maculata*	Carnivore	Demersal	GIT	Micro		10.1002/etc.4437
Zheng et al.	2019		China	River	*Cirrhinus molitorella*	Omnivore	Demersal	GIT	Micro		10.1002/etc.4437
Zheng et al.	2019		China	River	*Coptodon zillii*	Omnivore	Demersal	GIT	Micro		10.1002/etc.4437
Zheng et al.	2019		China	River	*Ctenopharyngodon idella*	Herbivore	Benthopelagic	GIT	Micro		10.1002/etc.4437
Zheng et al.	2019		China	River	*Cyprinus carpio*	Omnivore	Benthopelagic	GIT	Micro		10.1002/etc.4437
Zheng et al.	2019		China	River	*Hypophthalmichthys molitrix*	Planktivore	Pelagic	GIT	Micro		10.1002/etc.4437
Zheng et al.	2019		China	River	*Megalobrama hoffmanni*	Omnivore	Benthopelagic	GIT	Micro		10.1002/etc.4437
Zheng et al.	2019		China	River	*Squaliobarbus curriculus*	Omnivore	Benthopelagic	GIT	Micro		10.1002/etc.4437

APPENDIX L - List of the studies included in the invertebrates quantitative synthesis

Table S4. Key metadata of invertebrates studies included in our quantitative synthesis. We used the abbreviation *et al.* for studies with 3 authors or more. GIT – gastrointestinal tract

Authors	Year	Title	country	Enviro	Study_Object	species	Trophic guild	Habitat	organ	plastic_size	obs	doi
Akindele et al.	2019	First empirical study of freshwater microplastics in West Africa using gastropods from Nigeria as bioindicators	Nigeria - Germany	river	gastropod	*Lanistes varicus*	herbivore	benthic	soft tissue	micro	trophic guild information retrieved from " Raw et al. 2016" DOI:10.1093/mollus/eyv070	https://doi.org/10.1016/j.limno.2019.125708
Akindele et al.	2019		Nigeria - Germany	river	gastropod	*Melanoides tuberculata*	algivore	benthic	soft tissue	micro	trophic guild information retrieved from " Meshack et al. 2020" DOI:10.30574/gscbps.2020.11.2.0119	https://doi.org/10.1016/j.limno.2019.125708
Akindele et al.	2019		Nigeria - Germany	river	gastropod	*Theodoxus fluviatilis*	herbivore	benthic	soft tissue	micro	trophic guild information retrieved from "Kirkegaard, 2006" DOI: 10.1016/j.limno.2005.11.002	https://doi.org/10.1016/j.limno.2019.125708
Almeshal et al.	2022	Comparison of Freshwater Mussels *Unio tumidus* and *Unio crassus* as Biomonitors of Microplastic Contamination of Tisza River (Hungary)	Hungary	river	mussel	*Unio crassus*	omnivore	benthic	soft tissue	micro		https://doi.org/10.3390/environments9100122
Almeshal et al.	2022		Hungary	river	mussel	*Unio tumidus*	omnivore	benthic	soft tissue	micro		https://doi.org/10.3390/environments9100122
An et al.	2022	A case study on small size microplastics in water and snails in an urban river	China	river	snail	*Bellamya aeruginosa*	algivore	benthic	soft tissue	micro	trophic guild information retrieved from "Wang et al. 2023" DOI: 10.1016/j.ecoenv.2023.114596	http://dx.doi.org/10.1016/j.scitotenv.2022.157461
Atamanalp et al.	2023	The Use of Zebra Mussel (*Dreissena polymorpha*) as a Sentinel Species for the Microplastic Pollution of Freshwater: The Case of Beyhan Dam Lake, Turkey	Turkey	reservoir	mussel	*Dreissena polymorpha*	filter	benthic	soft tissue	micro	trophic guild information retrieved from "Ludovisi et al. 2022" DOI:10.1007/s10750-022-04846-4	
Berglund et al.	2019	Microplastics in a freshwater mussel (*Anodonta anatin*a) in Northern Europe	Sweden	river	mussel	*Anodonta anatina*	algivore	benthic	soft tissue	micro		https://doi.org/10.1016/j.scitotenv.2019.134192
Bertoli et al.	2022	Microplastics accumulation in functional feeding guilds and functional habit groups of freshwater macrobenthic invertebrates: Novel insights in a riverine ecosystem	Italy	river	Hirudinea	Hemiclepsis	carnivore	benthic	soft tissue	micro		https://doi.org/10.1016/j.scitotenv.2021.150207

Bertoli et al.	2022	Italy	river	Oligochaeta	Lumbriculidae	omnivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Gastropoda	Gammarus	herbivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Gastropoda	Theodoxus	algivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Gastropoda	Bithynia	algivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Gastropoda	Valvata	algivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Gastropoda	Gyraulus	algivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Ephemeroptera	Dryopidae	omnivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Ephemeroptera	Dytiscidae	omnivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Ephemeroptera	Baetis	omnivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Ephemeroptera	Heptagenidae	omnivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Diptera	Atherix ibis	carnivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Diptera	Simulidae	omnivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Diptera	Limonidae	carnivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Heteroptera	Aphelocheirus	carnivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Trichoptera	Rhyacophila	carnivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Trichoptera	Lepidostoma	herbivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Plecoptera	Leuctra	herbivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Trichoptera	Hydropsyche	omnivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Coleoptera	Oulimnius	omnivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Malacostraca	Asellus	herbivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Odonata	Calopteryx	carnivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Arachnida	Hydracarina	carnivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Ephemeroptera	Caenis	omnivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022	Italy	river	Odonata	Gomphidae	carnivore	benthic	soft tissue	micro	https://doi.org/10.1016/j.scitotenv.2021.150207

Bertoli et al.	2022		Italy	river	Diptera	Chironomidae	omnivore	benthic	soft tissue	micro		https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022		Italy	river	Coleoptera	Elmis	omnivore	benthic	soft tissue	micro		https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022		Italy	river	Odonata	Coenagrionidae	carnivore	benthic	soft tissue	micro		https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022		Italy	river	Coleoptera	Stenelmis	omnivore	benthic	soft tissue	micro		https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022		Italy	river	Gastropoda	Lymnaea	algivore	benthic	soft tissue	micro		https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022		Italy	river	Diptera	Potamanthus	omnivore	benthic	soft tissue	micro		https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022		Italy	river	Coleoptera	Limnius	omnivore	benthic	soft tissue	micro		https://doi.org/10.1016/j.scitotenv.2021.150207
Bertoli et al.	2022		Italy	river	Ephemeroptera	Ephemera	omnivore	benthic	soft tissue	micro		https://doi.org/10.1016/j.scitotenv.2021.150207
Doucet et al.	2021	Microfiber Content in Freshwater Mussels from Rural Tributaries of the Saint John River, Canada	Canada	river	mussel	*Margaritifera margaritifera*	omnivore	benthic	soft tissue	micro		https://doi.org/10.1007/s11270-020-04958-4
Driscoll et al.	2021	Presence of Microplastics in the Food Web of the Largest High-Elevation Lake in North America	USA	lake	amphipod	*Gammarus lacustris*	detritivorous	benthic	GIT	micro	trophic guild information retrieved from "Matafonov, 2007" DOI:10.1134/S1062359007020070	
Garcia et al.	2021	Stable Isotope Insights into Microplastic Contamination within Freshwater Food Webs	France	river	invertebrate		detritivorous	benthic	whole			https://dx.doi.org/10.1021/acs.est.0c06221
Garcia et al.	2021		France	river	invertebrate		carnivore	benthic	whole			https://dx.doi.org/10.1021/acs.est.0c06221
Garcia et al.	2021		France	river	invertebrate		algivore	benthic	whole			https://dx.doi.org/10.1021/acs.est.0c06221
Garcia et al.	2021		France	river	invertebrate		herbivore	benthic	whole			https://dx.doi.org/10.1021/acs.est.0c06221
Gedik & Atasaral	2022	The microplastic pattern in Turkish lakes: sediment and bivalve samples from Cildir Lake, Almus Dam Lake, and Kartalkaya Dam Lake	Turkey	reservoir	mussel	*Dreissena polymorpha*	filter	benthic	soft tissue	micro		10.55730/1300-0179.3093
Gedik & Atasaral	2022		Turkey	reservoir	mussel	*Unio damescensis*	filter	benthic	soft tissue	micro		10.55730/1300-0179.3093
Gedik & Atasaral	2022		Turkey	reservoir	mussel	*Anodonta* sp.	filter	benthic	soft tissue	micro		10.55730/1300-0179.3093
Guimaraes et al.	2023	Microplastic contamination in the freshwater shrimp *Macrobrachium amazonicum* in Itacoatiara, Amazonas, Brazil	Brazil	river	shrimp	*Macrobrachium amazonicum*	carnivore	benthic	whole	micro		http://dx.doi.org/10.1007/s10661-023-11019-w

Hoellein et al.	2021	Microplastics in Invasive Freshwater Mussels (*Dreissena* sp.): Spatiotemporal Variation and Occurrence with Chemical Contaminants	USA	lake	mussel	*Dreissena* spp.	filter	benthic	soft tissue	micro		10.3389/fmars.2021.690401
Hossain et al.	2022	Surface water, sediment, and biota: The first multi-compartment analysis of microplastics in the Karnafully river, Bangladesh	Bangladesh	river	prawn	*Macrobrachium rosenbergii*	omnivore	benthic	GIT	micro		https://doi.org/10.1016/j.marpolbul.2022.113820
Hurley et al.	2017	Ingestion of Microplastics by Freshwater Tubifex Worms	England	river	anellida	*Tubifex tubifex*	detritivorous	benthic	whole	micro		10.1021/acs.est.7b03567
Jitkaew et al.	2023	Occurrence of microplastics in freshwater gastropods from a tropical river U-Taphao, southern Thailand	Thailand	river	gastropod	*Filopaludina sumatrensis*	filter	benthic	soft tissue	micro		10.7717/peerj.14861
Jitkaew et al.	2024		Thailand	river	gastropod	*Pomacea canaliculata*	herbivore	benthic	soft tissue	micro		10.7717/peerj.14861
Kallenbach et al.	2022	Anthropogenically impacted lake catchments in Denmark reveal low microplastic pollution	Denmark	lake	mussel	*Dreissena polymorpha*	filter	benthic	soft tissue	micro		https://doi.org/10.1007/s11356-022-19001-8
Mulayim et al.	2022	Microplastic Accumulation in Crayfish *Astacus leptodactylus* (Eschscholtz 1823) and Sediments of Durusu (Terkos) Lake (Turkey)	Turkey	lake	crayfish	*Astacus leptodactylus*	omnivore	benthic	stomach*	micro		https://doi.org/10.1007/s11270-022-05908-y
Nan et al.	2020	Identification of microplastics in surface water and Australian freshwater shrimp *Paratya australiensis* in Victoria, Australia	Australia	stream - wetland	prawn	*Paratya australiensis*	filter	benthic	whole	micro	trophic guild information retrieved from "Moulton et al. 2012" DOI:10.1071/MF12063	https://doi.org/10.1016/j.envpol.2019.113865
Parker et al.	2022	Distinct microplastic patterns in the sediment and biota of an urban stream	England	river	invertebrates	Amphipoda	omnivore		whole	micro		http://dx.doi.org/10.1016/j.scitotenv.2022.156477
Parker et al.	2022		England	river	invertebrates	Annelida	detritivorous		whole	micro		http://dx.doi.org/10.1016/j.scitotenv.2022.156477
Parker et al.	2022		England	river	invertebrates	Diptera	herbivore		whole	micro		http://dx.doi.org/10.1016/j.scitotenv.2022.156477
Parker et al.	2022		England	river	invertebrates	Ephemeroptera	herbivore		whole	micro		http://dx.doi.org/10.1016/j.scitotenv.2022.156477
Parker et al.	2022		England	river	invertebrates	Gastropoda	detritivorous		whole	micro		http://dx.doi.org/10.1016/j.scitotenv.2022.156477
Parker et al.	2022		England	river	invertebrates	Hemiptera	herbivore		whole	micro		http://dx.doi.org/10.1016/j.scitotenv.2022.156477
Parker et al.	2022		England	river	invertebrates	Hemiptera	carnivore		whole	micro		http://dx.doi.org/10.1016/j.scitotenv.2022.156477

Parker et al.	2022		England	river	invertebrates	Isopoda	herbivore		whole	micro		http://dx.doi.org/10.1016/j.scitotenv.2022.156477
Parker et al.	2022		England	river	invertebrates	Odonata	carnivore		whole	micro		http://dx.doi.org/10.1016/j.scitotenv.2022.156477
Parker et al.	2022		England	river	invertebrates	Trichoptera	omnivore		whole	micro		http://dx.doi.org/10.1016/j.scitotenv.2022.156477
Pastorino et al.	2023	Microplastics in biotic and abiotic compartments of high-mountain lakes from Alps	Italy	lake	zooplankton	copepods	omnivore	pelagic	whole	micro		https://doi.org/10.1016/j.ecolind.2023.110215
Pastorino et al.	2021	First insights into plastic and microplastic occurrence in biotic and abiotic compartments, and snow from a high-mountain lake (Carnic Alps)	Italy	lake	insect	Chironomidae	detritivorous	benthic	whole	micro		https://doi.org/10.1016/j.chemosphere.2020.129121
Pastorino et al.	2021	Use of the Zebra Mussel *Dreissena polymorpha* (Mollusca, Bivalvia) as a Bioindicator of Microplastics Pollution in Freshwater Ecosystems: A Case Study from Lake Iseo (North Italy)	Italy	lake	mussel	*Dreissena polymorpha*	filter	benthic	soft tissue	micro		https://doi.org/10.3390/w13040434
Pazos et al.	2020	First record of microplastics in the mussel *Limnoperna fortunei*	Argentina	river	mussel	*Limnoperna fortunei*	filter	benthic	soft tissue	micro		http://dx.doi.org/10.1016/j.rsma.2020.101360
Pittura et al.	2022	Microplastics and Brominated Flame Retardants in Freshwater Fishes From Italian Lakes: Implication for Human Health	Italy	lake	crayfish	*Procambarus clarkii*	omnivore	benthic	soft tissue	micro	trophic guild information retrieved from "Alcorlo et al. 2004" DOI:10.1163/1568540041643283	10.3389/frwa.2022.902885
Pradit et al.	2021	Occurrence of microplastics and trace metals in fish and shrimp from Songkhla lake, Thailand during the COVID-19 pandemic	Thailand	lake	shrimp	*Parapenaeopsis hardwickii*	carnivore	pelagic	GIT	micro		http://dx.doi.org/10.15666/aeer/1902_10851106
Pradit et al.	2021		Thailand	lake	shrimp	*Metapenaeus brevicornis*	omnivore	pelagic	GIT	micro	trophic guild information retrieved from Patkar et al. 2022: Study of food preference of *Metapenaeus brevicornis* (H. MILNE EDWARDS) in different areas of Mumbai coast.	http://dx.doi.org/10.15666/aeer/1902_10851106
Schessl et al.	2019	Microbeads in Sediment, Dreissenid Mussels, and Anurans in the Littoral Zone of the Upper St. Lawrence River, New York	USA	river	mussel	*Dreissena* sp	filter	benthic	soft tissue	micro		10.22059/poll.2018.257596.468

Shen et al.	2023	Damming has changed the migration process of microplastics and increased the pollution risk in the reservoirs in the Shaying River Basin	China	reservoir	crab	*Eriocheir sinensis*	omnivore	benthic	GIT*	micro	trophic guild information retrieved from "Czerniejewski et al. 2010” DOI:10.1163/001121609X12591347509202	https://doi.org/10.1016/j.jhazmat.2022.130067
Shen et al.	2023		China	reservoir	crab	*Sinopotamon honanense*	omnivore	benthic	GIT*	micro		https://doi.org/10.1016/j.jhazmat.2022.130067
Shen et al.	2023		China	reservoir	prawn	*Macrobrachium* sp.	omnivore	benthic	GIT*	micro		https://doi.org/10.1016/j.jhazmat.2022.130067
Shen et al.	2023		China	reservoir	crayfish	*Procambarus clarkii*	omnivore	benthic	GIT*	micro		https://doi.org/10.1016/j.jhazmat.2022.130067
Shen et al.	2023		China	reservoir	prawn	*Caridina* sp.	algivore	benthic	GIT*	micro	trophic guild information retrieved from "Yam & Dudgeon, 2005" DOI:10.1899/0887-3593(2005)024<0068: SIIOFU>2.0.CO;2	https://doi.org/10.1016/j.jhazmat.2022.130067
Shen et al.	2023		China	reservoir	prawn	*Neocaridina denticulata sinensis*	omnivore	benthic	GIT*	micro	trophic guild information retrieved from " Ye et al. 2019" DOI:10.1051/kmae/2019025	https://doi.org/10.1016/j.jhazmat.2022.130067
Shen et al.	2023		China	reservoir	gastropod	*Cipangopaludina cathayensis*	algivore	benthic	GIT*	micro	trophic guild information retrieved from " Liet al. 2020" DOI:10.15666/aeer/1901_279292	https://doi.org/10.1016/j.jhazmat.2022.130067
Shen et al.	2023		China	reservoir	gastropod	*Bellamya purificata*	algivore	benthic	GIT*	micro	trophic guild information retrieved from " Hwang et al. 2021" DOI:10.3390/app11199294	https://doi.org/10.1016/j.jhazmat.2022.130067
Shen et al.	2023		China	reservoir	mussel	*Unio douglasiae*	algivore	benthic	GIT*	micro	trophic guild information retrieved from " Su et al. 2018" DOI: 10.1021/acs.est.7b05798	https://doi.org/10.1016/j.jhazmat.2022.130067
Shen et al.	2023		China	reservoir	mussel	*Corbicula fluminea*	algivore	benthic	GIT*	micro		https://doi.org/10.1016/j.jhazmat.2022.130067
Shen et al.	2023		China	reservoir	mussel	*Anodonta woodiana elliptica*	filter	benthic	GIT*	micro	trophic guild information retrieved from " Chen et al. 2015" DOI:10.1080/07924259.2015.1047039	https://doi.org/10.1016/j.jhazmat.2022.130067
Thamsenanupap et al.	2022	Evidence of microplastics in the Chi River Basin, Thailand: Anthropogenic influence and potential threats to edible arthropods	Thailand	river	prawn	*Caridina* sp	algivore	benthic	whole	micro		https://doi.org/10.1016/j.limno.2022.126030
Thamsenanupap et al.	2022		Thailand	river	prawn	*Macrobrachium* sp.	omnivore	benthic	whole	micro		https://doi.org/10.1016/j.limno.2022.126030
Thamsenanupap et al.	2022		Thailand	river	insect	*Aethriamanta* spp.	carnivore	benthic	whole	micro		https://doi.org/10.1016/j.limno.2022.126030
Thamsenanupap et al.	2022		Thailand	river	insect	*Aciagrion* sp.	carnivore	benthic	whole	micro		https://doi.org/10.1016/j.limno.2022.126030
Thamsenanupap et al.	2022		Thailand	river	insect	*Sphaerodema molestum*	carnivore	benthic	whole	micro		https://doi.org/10.1016/j.limno.2022.126030
Winkler et al.	2022	Following the fate of microplastic in four abiotic	Italy	river	trichoptera	Hydropsychidae	filter	benthic	whole	micro		http://dx.doi.org/10.1016/j.scitotenv.2022.153638

		and biotic matrices along the Ticino River (North Italy)									
Yasaka et al.	2022	Bioaccumulation of Microplastics in Fish and Snails in the Nam Pong River, Khon Kaen, Thailand	Thailand	river	snail	*Filopaludina martensi*	omnivore	benthic	soft tissue	micro	10.14456/ea.2022.8
Yasaka et al.	2022		Thailand	river	snail	*Pomacea canaliculata*	omnivore	benthopelagic	soft tissue	micro	10.14456/ea.2022.9
Yücel & Kılıç	2022	Microplastic contamination in the freshwater crayfish *Pontastacus leptodactylus* (Eschscholtz, 1823)	Turkey	reservoir	crayfish	*Pontastacus leptodactylus*	omnivore	benthic	GIT*	micro	https://doi.org/10.1016/j.marpolbul.2022.114337

*Gills were also analyzed, but not included in our quantitative synthesis because of limited distinct studies for comparison

APPENDIX M – Linear mixed model results for fish

Table S5. Summary table from linear mixed model for plastic uptake by fish and categorical predictors. Significant values ($p < 0.05$) are highlighted in bold; GIT – gastrointestinal tract

	Value	**Std.Error**	**DF**	**t-value**	**p-value**
(Intercept)	0.568388	0.200914	387	2.829004	0.0049
reservoir	0.195439	0.21179	78	0.922797	0.359
river	-0.03898	0.110669	387	-0.35226	0.7248
stream	0.105759	0.151588	387	0.697673	0.4858
wetland	-0.42471	0.423821	78	-1.00211	0.3194
carnivore	0.017721	0.084561	387	0.209566	0.8341
detritivore	0.066569	0.096229	387	0.691775	0.4895
herbivore	0.073221	0.093287	387	0.7849	0.433
omnivore	0.066542	0.086951	387	0.765283	0.4446
planktivore	0.121684	0.100449	387	1.2114	0.2265
benthopelagic	-0.04706	0.071042	387	-0.6624	0.5081
demersal	-0.03009	0.075073	387	-0.40079	0.6888
pelagic	0.005494	0.076546	387	0.071771	0.9428
all organs	**1.010232**	**0.417548**	**78**	**2.419436**	**0.0179**
gills	-0.02635	0.144243	387	-0.18269	0.8551
GIT	0.047123	0.138886	387	0.339296	0.7346
liver	-0.22687	0.191991	387	-1.18167	0.2381
muscle	-0.09595	0.168271	387	-0.57019	0.5689
stomach	-0.20546	0.222675	78	-0.9227	0.359

APPENDIX N – Linear mixed model results for fish body length and weight

Table S5. Summary table from linear mixed model for plastic uptake by fish and body length and weight as predictors.

	Value	**Std.Error**	**DF**	**t-value**	**p**
(Intercept)	0.557935	0.062484	257	8.929238	<0.001
Body length (cm)	0.002211	0.001327	257	1.666385	0.0969
Body weight (g)	0.000164	2.38E-05	257	0.691102	0.4901

APPENDIX O – Linear mixed model results for invertebrates

Table S7. Summary table from linear mixed model for plastic uptake by invertebrates and categorical predictors. Significant values ($p < 0.05$) are highlighted in bold

	Value	Std.Error	DF	t-value	p
(Intercept)	0.174495	0.462163	59	0.377562	0.7071
reservoir	0.346517	0.27663	25	1.252639	0.2219
river	**0.523586**	**0.184706**	**25**	**2.834703**	**0.0089**
carnivore	0.018054	0.05208	59	0.346662	0.7301
detritivorous	0.0563453	0.089904	59	0.626729	0.5333
filter	-0.01556	0.098548	59	-0.15791	0.8751
herbivore	-0.00434	0.057693	59	-0.07521	0.9403
omnivore	0.038302	0.04566	59	0.838841	0.4049
benthic	0.23147	0.409808	59	0.565746	0.5737
benthopelagic	0.6089516	0.445836	59	1.365864	0.1772
pelagic	0.45809	0.5119	25	0.894881	0.3794
soft tissue	-0.23647	0.203952	25	-1.15945	0.2572
whole	**-0.63594**	**0.226876**	**25**	**-2.80302**	**0.0096**

APPENDIX P – Linear mixed model results for invertebrates body length and weight

Table S8. Summary table from linear mixed model for plastic uptake by invertebrates and body length and weight as predictors.

	Value	**Std.Error**	**DF**	**t-value**	**p**
(Intercept)	0.583719	0.148566	15	3.929012	0.0013
Body length (mm)	-0.00079	0.00223	6	-0.03553	0.9728
Body weight (mg)	0.000417	0.00040	6	1.027249	0.3439