Plastic Contamination in Brazilian Freshwater and Coastal Environments: A Source-to-Sea Transboundary Approach

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Contents

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Abstract Plastic debris is ubiquitous in aquatic environments. Freshwater and estuarine ecosystems are not different, and plastic contamination is abundant. Despite ecological and socioeconomic importance, previous reviews identified a low number of publications regarding these ecosystems. An organized review to provide a comprehensive qualitative overview of the plastic debris pollution in Brazil was conducted, considering the literature available ($n = 37$) on Brazilian freshwater and estuarine areas. Literature was reviewed analysing the potential sources, distribution and contamination patterns in different environmental compartments aiming at gathering information that will contribute to the understanding of the status of the plastic pollution in these Brazilian systems. Results indicate that research regarding freshwater systems is almost absent, whilst estuaries present studies considering all-sized plastics. Sources of plastic debris varied according to the environmental compartment. Composition and distribution are also dependent of the compartment investigated; however, there is a clear dominance of plastics. Regarding distribution, it is a clear knowledge gap, considering that most studies analysed describe the levels of pollution without concluding about pathways and trajectories. Interaction between plastic debris and biota was highlighted, including benthos, mammals, reptiles, molluscs, and fishes. The source-to-sea approach might be a key approach to comprehensively understand the plastic debris problems within the Brazilian coast.

Keywords Brazil, Plastic contamination, Source-to-sea, Transboundary

1 Introduction

The high global consumption and plastic versatility in a wide range of products, in several formats, types and ways combined with inadequate solid waste management, have become a constant problem in coastal environments [1–6]. Marine debris have affected a wide range of organisms, from planktonic, fishes, birds, turtles to big marine mammals as pinnipeds and cetaceans by ingestion or entanglement [3]. Solid waste management is very important, but to be efficient to combat marine debris, it is important to understand aspects such as sources, pathways and trajectories. Several system-entry sources are identified, including urban areas and associated drainage or shipping routes [5, 7, 8], and marine debris accumulation can be influenced by many factors, such as rainfall [9, 10], hydrological factors [11, 12], coastline geography [13] and estuary-specific circulation processes [2, 5, 12].

A good diagnostic about the marine debris situation is essential to solve the problem (not dependent to take action) preventing it in the source. For that, adopting the source-to-sea approach may be useful. However, what do we know about the different compartments along the source to sea continuum in Brazil? Within this transboundary continuum, two compartments, freshwater and estuarine environments, were considered understudied by previous studies, especially in Latin America [14]. But is it still a nowadays valid pattern? As rivers and coastal environments are key compartments for the adoption of a source-to-sea transboundary approach to deal with plastic pollution, it is crucial to understand what knowledge is available about these systems in Brazil.

Because of that, this chapter aims to show a literature review of the main sources of micro-, meso- and macroplastic debris, the composition and spatial distribution and the interaction between plastic debris and biota in freshwater and estuarine systems in Brazil.

2 Materials and Methods

Among the various methodological procedures that can accompany the mapping and evaluation of the academic production of a specific topic, Araújo [15] cites that the bibliometric analysis allows both the definition of the relevance of a research and also contributes to the analysis of a thematic-trend in an arrangement of scientific works. However, since they currently involve both quantitative and qualitative techniques, the work involving this methodology needs to make clear the procedures and steps adopted in understanding the form, structure or volume of scientific communication [16].

The stages adopted here were:

1. Selection of database for scientific literature (Scopus and Web of Science)
2. Definition of keywords (marine litter or marine debris; microplastic or microlitter or nanoplastic; estuarine or river or bay; and Brazil) following the main analytical categories for this research
3. Test to define the most appropriate keywords for the search of scientific literature through the relative percentage of the corresponding return value of each keyword
4. Combined search in selected databases
5. Organization of data in a reference management software (EndNote): *research corpus*
6. Reading of selected scientific literature for the composition of the final portfolio of systematic study.

Of the 713 scientific papers, a total of 643 papers were discarded by the following criteria: "Is the study area in Brazil?" and "The study covers: estuarine area, bay or river near estuary?". If both answers were "yes", the study remained in the analysis portfolio or because they are common among the databases. In this way, 70 papers were selected. However, only 37 papers were sent to the systematic analysis described below, because the others focused on adjacent areas to estuarine environments and they will be the target of a complimentary investigation regarding only such specific environments. It is worth mentioning that repositories of universities and even sites of important scientific events in the area also pointed out important readings in the area. However, this specific literature was not used in the systematic analysis itself, but as a complementary reading for the composition of the discussion of this chapter. The bibliometric analysis considered papers published from 2003 to 2019.

3 Results

3.1 Sources of Plastic Debris

Plastics have been acknowledged to have several sources in South America [17]. Land-based and sea-based activities are the most common sources. They include activities performed during urban waste disposal, along waterways and marine traffic, salmon and mussel farms, transport from rivers and streams and fishing and harbour activities [2, 5, 8]. Considering that source-to-sea approach is an ecological concept, which considers a continuum of environmental compartments, the following analysis regarding sources was conducted focusing on different ecosystems, disregarding the size of the plastics. In addition, wastewater treatment plants are a contemporary source of microbeads and microfibres released by industries of cosmetic/personal care products and textile industries, respectively [18].

3.1.1 Sources of Plastic Debris in Freshwater Systems

Very few studies have addressed the sources of plastic debris in Brazilian freshwater systems (Fig. 1). The contamination of freshwater fishes (*serrasalmid*) inhabiting the Xingu River, Amazon, revealed the origin of the microplastics ingested [19]. Fragments of polyethylene denounced the source associated with fishing gear lost or discarded in the river basin, whilst the polyamide, polyester and polyethylene terephthalate polymers pointed to sources from discarded trash, since they are commonly used to produce plastic bags, bottles, threads and clothes [19]. These observations support the same conclusion reported for the Pajeú River Basin, where the contamination of a freshwater fish (*Hoplosternum littorale*) revealed that urbanization close to water bodies is a potential source of microplastics to this freshwater environment [20].

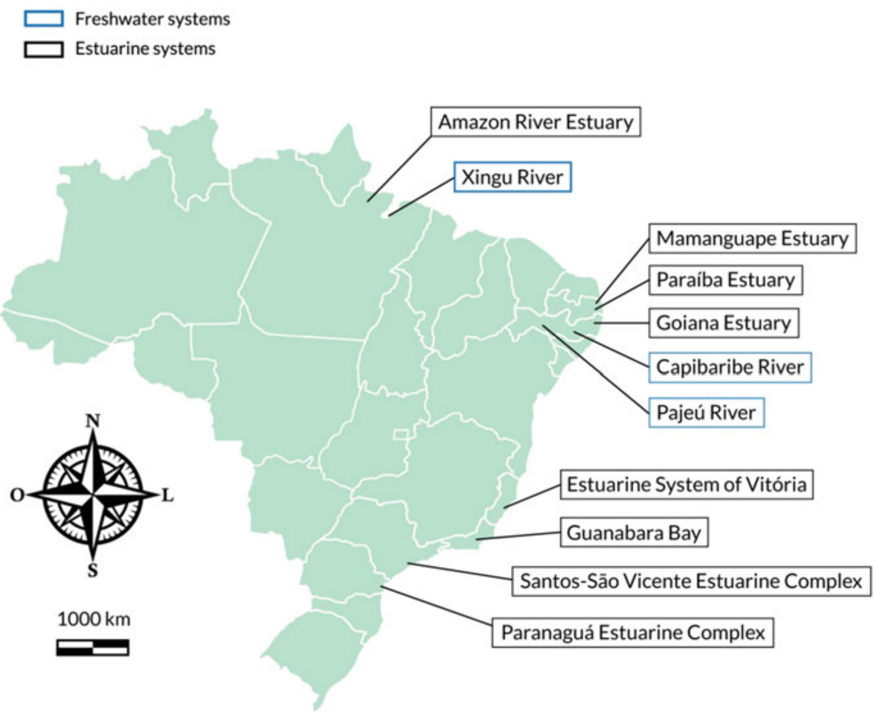

Fig. 1 Map of the Brazilian freshwater and estuarine systems already studied regarding marine debris. Source: André R. A. Lima & Guilherme V. B. Ferreira

3.1.2 Sources of Plastic Debris in Estuarine Systems

Plastics coming from the river basin, inappropriate disposal of communities along the margins and fishery activities (mussel pickers) are the main sources of macroplastics to the mangrove forest of the Goiana estuary (Fig. 1) [21]. Additionally, digging of sediments for mussels by fishers and dredging of the tidal plain are secondary sources of macroplastics to the main channel [21]. Moreover, polystyrene foam buoys, ropes and nets represented 22.3% of all marine debris in an estuarine beach located in the lower Goiana estuary. These items have as sources fishing related activities [10]. Unlabelled plastic bags, PET bottles, caps and soft packaging and rigid containers (33.6%) can have either local or non-local sources, whilst rubber, polyurethane foam and sewage-derived plastics (2%) are related to domestic sources, mainly the fishing villages along the margins of the lower estuary [10].

For the Goiana estuary (Fig. 1), the sources of microplastics were inferred according to their distribution patterns [3]. During the dry season, when the stratification of the water column is more pronounced, microplastics in the middle estuary have the lowest density, whilst in the upper and lower estuaries, the microplastics are abundant. This means that the middle estuary is a physical boundary for microplastics and, therefore, those found in the upper estuary have the river basin as the main source, whilst those found in the lower estuary are associated with coastal villages, harbours and local fishery activities [3]. For this same system, the colour and length of microfilaments ingested by the commercial fish *Cynoscion acoupa* (acoupa weakfish) were also used to infer about their sources [22]. Longer and little weathered filaments, especially white and black ones, were frequently ingested in the upper estuary, suggesting a riverine origin. Contrarily, smaller filaments with signs of weathering, especially red ones, were proportionally more ingested in the lower estuary, suggesting a coastal/oceanic source [22].

Fishing activities are also acknowledged as one of the most important sources of microfibres to the estuarine system of Vitória (SE) (Fig. 1), when fishing nets are unintentionally disposed or abandoned or even during ship loading and unloading [23].

Floating macroplastics entering Guanabara Bay have their main source in the continental runoff [24]. For this same system, the sources of microplastics are not only associated with local rivers and streams but also with fishing and harbour activities [25]. On the other hand, in Jurujuba Cove, a cove with three beaches located within Guanabara Bay, microplastics have their main origins associated with the flush of domestic effluents from a stream discharging into the cove and the fragmentation of blue gallon bottles used for mussel cultivation [26].

In the Santos-Sao Vicente Estuarine Complex (Fig. 1), the sources of plastic debris are acknowledged to be the regional garbage dumps located close to the mangrove, illegal dumping of domestic items, irregular settlements along the estuarine margins and lack of sanitation [27]. The deficiency in the basic sewage system and the deliberate disposal of debris into this estuarine complex are the main causes of macroplastic contamination resulting in a high percentage of domestic (55.41%) and multiple (42.71%) sources, although sources such as tourism, fishery and hospital are also important (1.88%) [28].

For the Paranaguá Estuarine Complex (Fig. 1), the majority (5,620) of the macroplastic items (46.6%) are from a non-identifiable source, followed by beach users (1,996; 16.6%), domestic (1,915; 15.9%), fisheries (1,364; 11.3%), ships and harbour (866; 7.2%) and sewage related items (287; 2.4%), which together represents 53.4% [2]. Another probable source of marine debris is associated with land-based rubbish dumps in the cities of Paranaguá, Antonina and Morretes [5]. This estuary urges attention from the government and citizens because the region is acknowledged as a World Heritage Site due to the presence of one of the last remnants of the Atlantic rainforest [5] (Fig. 2).

3.2 Composition and Spatial Distribution of Macroplastics

Plastics are known to represent the greater part of the items found in marine debris. In the Brazilian freshwater and estuarine systems, such pattern is also observed. Considering the source-to-sea approach and the connectivity between environmental

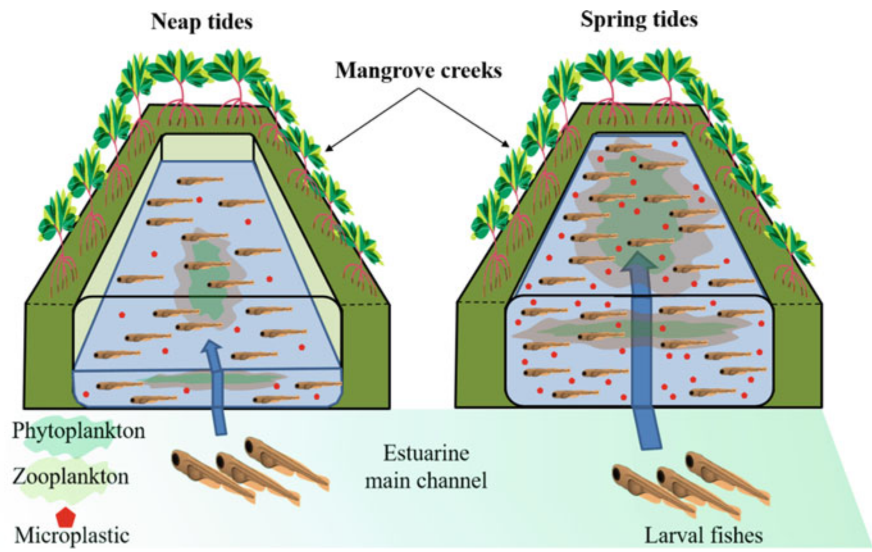

Fig. 2 Patterns of microplastic accumulation in mangrove creeks as ruled by moon phases and tidal cycles according to Lima et al. [31]. Source: André R. A. Lima & Guilherme V. B. Ferreira

compartments, it is expected that these environments work as a temporary sink to these items, being conducted to coastal waters and shorelines and, ultimately, going to the ocean water column and bottom (Fig. 3) [11].

3.2.1 Patterns of Macroplastic Contamination in Freshwater Systems

The only study reporting the composition and spatial distribution of plastic debris in freshwater systems was performed in the Setúbal floodplain lake (Paraná River) [29]. Although this is not a Brazilian system, this lake is located within a river that has its origin in the confluence of two important Brazilian rivers, the Grande and Paranaíba Rivers, which in turn extend through Argentina and Paraguay. There, an alarming plastic contamination was detected in shoreline sediments (Table 1). In total, 217 macroplastic items were collected (1.15 items m^2), among which were food wrappers, bags and disposable foam food containers, the most common type. These plastics were especially composed of polypropylene, polystyrene and polyethylene. Also, the present study was the only one to identify densities of mesoplastics, which showed an average density of 25 items m^2 [29]. Foam plastics (expanded polystyrene) and hard plastics (various polymers) were the most common categories. The highest abundance of macro- and mesoplastics at the downstream site is likely to be a result of the entrapment in a concrete breakwater.

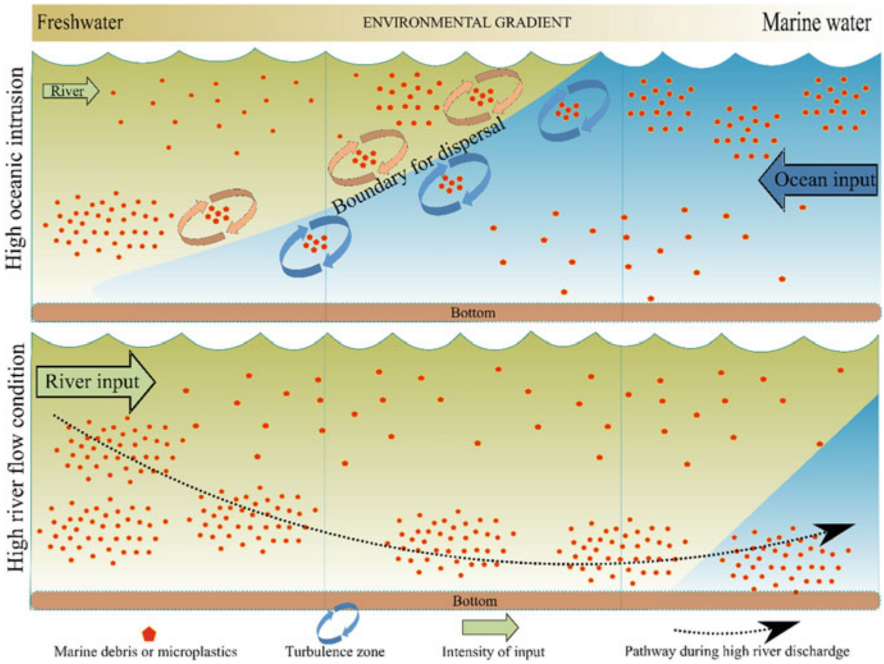

Fig. 3 Conceptual model for the transboundary movement of microplastics along an environmental gradient from freshwater to the ocean according to Krelling and Turra [2], Krelling et al. [11] and Lima et al. [3]. Source: André R. A. Lima & Guilherme V. B. Ferreira

3.2.2 Patterns of Macroplastic Contamination in the Water Column of Estuarine Systems

In Guanabara Bay (Fig. 1), one of the most impacted systems in the tropical western Atlantic, pollution has a positive relationship with the increased urbanization and industrialization [17]. The floating debris is among the major concerns regarding pollution due to the inefficient management of solid wastes by the municipalities of the Rio de Janeiro Macrometropolis [24]. Plastic bag fragments, styrofoam, food packages, clothes, flexible rods, pellets, cigarette butts, straws, cups and gillnets composed the debris in the bay between 2013 and 2015 [24]. Plastics accounted for 71–84% of all items.

Macroplastics were also frequently present in the Santos-Sao Vicente Estuarine Complex, representing 89.64% of the floating debris (2,339 items) observed over 17 months [28]. Ebb spring tide conditions were responsible for entrapping the debris upstream in the U-shaped system due to the confluence of the flows from both channels [28].

In the Paranaguá Estuarine Complex, the density of benthic marine debris (i.e. glass, foam, clothing, metal, plastic), and in particular plastic pieces of bags, wrappers and cups (92.4%), was significantly higher near urbanized locations and

Table 1 Materials and methods applied in surveys to evaluate the contamination of Brazilian freshwater and estuarine systems with macro, meso and microplastics

System	Size	Category	Type of plastics	No. and/or density	Sampling design	Sampler	Sample	References
Goiana Estuary	Macro	Buried plastics	Hard plastics	38 items (5,900 items 100 m^{-3})	30 cores along the mangrove forest, the top and fringe of the tidal plain/ Monthly sampling from March 2009 to May 2010	Cylindrical cores	Sediments	Costa et al. [21]
			Soft plastics					
			Nylon polyamide					
	Macro	Deposited debris	Hard plastics	6,944 items (10.8 items 100 m^{-2})	3 transects in a estuarine beach located inside the lower estuary/ Monthly sampling from April 2006 to March 2007	Hand collection	Surface sediments	Ivar do Sul and Costa [10]
			Soft plastics					
			Foam					
			Nylon					
			Rubber					
			Cloth					
			Wood					
			Metal					
			Paper					
	Micro	Floating plastics	Hard plastics	14,724 items (26.04 items 100 m^{-3})	3 bottom and 3 surface trawls in the upper, middle and lower estuary/ Monthly sampling from April 2012 to March 2013	Plankton net – 300 μm	Surface and bottom waters	Lima et al. [3, 32]
			Soft plastics					
			Threads					
			Paint chips					
	Macro	Floating plastics	Hard plastics	1,662 items (3.4 items 100 m^{-3})	12 mangrove creeks/April and May 2008	Trap net – 500 μm	Water column	Lima et al. [31]

(continued)

Table 1 (continued)

System	Size	Category	Type of plastics	No. and/or density	Sampling design	Sampler	Sample	References
			Soft plastics					
	Micro		Threads	2,710 items (1.4 items 100 m^{-3})				
			Paint chips					
Guanabara Bay	Macro	Floating litter	Plastic fragments	Not available	1 site in the upper bay and 4 sites at the bay entrance/Review from 2013 to 2015	Hand collection	Surface water	Bernardino and Franz [24]
			Styrofoam					
			Food packages					
			Clothes					
			Flexible rods					
			Pellets					
			Cigarette butts					
			Straw					
			Cups					
			Gillnets					
	Micro	Floating plastics	Fragment	1,640 items 100 m^{-3}	3 hauls per each 3 stations in the Jurujuba Cove/Rainy and dry seasons	Plankton net – 150 μm	Water column	Castro et al. [26]
			Sheet					
			Fibres					
			Pellets					
	Micro	Buried plastics	Fibres	8,766 items (1,200 to 130,000 items 100 m^{-2})	34 sites along 17 sandy beaches/cold-dry and warm-rainy seasons	Non informed	Sediments	De Carvalho and Baptista Neto [25]
			Fragments					
			Styrofoam					

			Pellets					
	Micro	Floating plastics	Film	6,300 items 100 m^{-3}	3 sites in the bay/March and September 2016	Plankton net–64 μm and 200 μm	Surface water	Figueiredo and Vianna [34]
			Fragments					
			Fibres					
	Micro	Floating plastics	Fragments	710 items 100 m^{-3}	3 stations in the western portion of the Bay/Summer of 2016	Plankton net – 300 μm	Surface water	Olivatto et al. [33]
			Fibres					
			Styrofoam					
			Rubber					
			Film					
			Granule					
Vitória Bay	Micro	Buried plastics	Fibres	247 items (0 to 38 items $sample^{-1}$)	20 sites along the main channel	Van Veen Grab Sampler	Sediments	Baptista Neto et al. [23]
			Plastic fragments					
Setúbal lake	Macro	Buried Plastics	Food wrappers	11,500 items 100 m^{-2}	2 transects	Hand collection	Sediments	Blettler et al. [29]
			Bags					
			Foam					
	Meso	Buried plastics	Foam	2,500 items 100 m^{-2}		Stainless steel shovel		
			Hard plastic					
	Micro	Buried plastics	Hard plastic	70,400 items 100 m^{-2}				
			Fibres					
Santos-São Vincente Estu-arine Complex	Macro	Deposited debris	Plastic bags	2,129 (133 items m^{-2})	2 surveys in 4 upstream and 4 down-stream sites along the swamp/August 2006	Hand collection	Surface sediments	Cordeiro and Costa [27]
			Food wrappers					
	Macro	Floating litter	Plastic fragments	2,339 items (121.56 to 173.33		Visual censuses	Surface water	Fernandino et al. [28]

(continued)

Table 1 (continued)

System	Size	Category	Type of plastics	No. and/or density	Sampling design	Sampler	Sample	References
			Cloth	items campaign^{-1})	6 stations along the main channel/ Monthly sampling between July 2010 and January 2012			
			Glass					
			Metal					
			Paper					
			Rubber					
			Wood					
Paranaguá Estuarine Complex	Macro	Deposited debris	Plastic fragments	12,048 items	4 transects along 9 estuarine beaches located in the internal, median and external sectors of the outer estuary/ Periods of high riverine discharges, frontal systems and regular weather conditions between 2015 and 2016	Hand collection	Surface sediments	Krelling and Turra [2]
			Styrofoam					
			Wood					
			Rubber					
			Glass					
			Metal					
			Cloth					
			Cigarette butts					
			Paper					

port areas in the upper and middle sectors, reaching 23.37 items ha^{-1} on average, but no seasonal trends were observed [5].

3.2.3 Patterns of Macroplastic Contamination in Mangrove Areas

Mangrove forests act as a retainer of macroplastics for long periods until they reach the margin of the river, when tidal action flushes the plastics away [30]. In the mangrove forest and the tidal plain of the Goiana estuary, 38 weathered macroplastic fragments were found, with hard polypropylene plastics, soft packaging (cellophane) and nylon polyamide being the most common items, totalling 59 items m^3 [21]. The accumulation of plastics occurred during the dry season, and the mangrove forest was the most contaminated area [21]. Another survey recorded 2,710 macroplastic items (>5–181 mm) in the water column of 12 mangrove creeks, representing 62% of the total plastic debris found [31]. The total density of macroplastics in these creeks is comparable to the density of larvae of the commercial taxa *Cynoscion acoupa* (~1.4 items or larvae 100 m^{-3}). During the full moon, when the spring tide flooded the mangrove forest and flushed more efficiently the mangrove soil, macroplastics presented the highest density, representing the probable pathway of plastic debris from the mangrove forest to the main channel [31].

Among the solid wastes accumulated along mangrove swamps in the Santos-Sao Vicente Estuarine Complex (Fig. 1), 62.81% are composed of macroplastics [27]. In total, 2,129 items (1.33 items m^2) weighing 207.5 kg (129.66 g m^2) were collected (Table 1). The upstream sites are the most contaminated, with plastic bags and food wrappers being the most abundant items [27].

3.2.4 Patterns of Macroplastic Contamination on Estuarine Beaches

A total of 6,944 marine debris were collected in an estuarine beach located within the lower part of the Goiana estuary, with an average density of 10.8 items 100 m^{-2} [10]. Plastics represented >95% of all items. Hard and soft polyethylene plastics were the most frequent, followed by polystyrene foam. A greater amount of marine debris is deposited during the rainy season, when river runoff increases and may carry debris from the upstream area seawards [10].

In total, 12,048 marine debris were collected in nine beaches located along a gradient (i.e. internal, median and external) in the lower portion of the Paranaguá Estuarine Complex (Fig. 1) [2]. Plastics, especially fragments, dominated the items (74.8%), followed by styrofoam (8.7%). The higher abundance and most types of marine debris were observed during periods of high riverine discharge along the entire gradient, with a high dominance of domestic, sewage and fisheries related items (Fig. 3). An intermediate abundance of debris was observed during periods of intense southerly winds associated with frontal systems. Under this condition, the external sector had the lowest abundance of items when compared with the other environmental conditions [2].

This means that rather than bringing ocean-generated items to the coast, the frontal systems act as a generator of longshore drifts that is likely clearing the external sector transporting marine debris offshore. On the other hand, marine debris had the lowest abundance and less variety of types during regular weather conditions (absence of high river discharge and frontal systems). Under such conditions, the internal and median sectors had the lowest abundance of both factors, and domestic and sewage related items had a homogeneous distribution along the gradient. The number of items during a higher river discharge overpassed the amount observed during regular weather conditions, mainly in the external sector. Such result indicates that land-generated items from the innermost parts are transported into the system through river discharge [2].

A simplified hydrodynamic model of dispersion, ground-truthing estimates and regressive vectors revealed that marine debris along the Paranaguá Estuarine Complex gradient are exported after a residence period of 5 days from the inner estuary to the open ocean, which in turn acts as a sinking zone [11]. Once marine debris is exported to the outer estuary, there is no movement upstream anymore (Fig. 3). Therefore, the inner estuary is a ground for generation and release of marine debris, and a transboundary approach must be used to manage marine debris in the land-sea transition zone [11].

3.3 Composition and Spatial Distribution of Microplastics

3.3.1 Patterns of Microplastic Contamination in Freshwater Systems

In freshwater systems, only one study was performed in the Setúbal floodplain lake (Paraná River) regarding microplastics. Microplastics were mainly composed of hard plastics and fibres, totalling 104 items m^{-2}. The highest abundance of microplastics was observed at the upstream site, in contrast to the pattern observed for macro- and mesoplastics in the same area [29].

3.3.2 Patterns of Microplastic Contamination in the Water Column of Estuarine Systems

The distribution patterns of microplastics were assessed in the Goiana estuary, a marine protected area of the type extractive reserve [3]. In total, 14,724 microplastics, representing an average density of 26.04 items 100 m^3, were collected within 12 months (Table 1). Microplastics are found during the entire seasonal cycle and share the same habitats with zooplankton. Their high abundance is comparable to fish eggs and half of fish larvae density in the main channel.

The density of microplastics can overpass the abundance of ichthyoplankton during specific seasons, areas and position in the water column [32]. According to these studies, microplastics are retained within the estuary during the dry season, when the stratification of the water column functions as a physical boundary that does not allow microplastics to cross the middle estuary seaward and even upstream (Fig. 3). This suggests that microplastics from the upper estuary are associated with the river basin and that they have a marine or local origin in the lower estuary. On the other hand, during the end of the rainy season, when precipitation increases and the river runoff is high, microplastics are flushed from the upper estuary to the lower estuary, together with zooplankton (Fig. 3) [3]. During this season, microplastics (<5 mm) and fish larvae have the same density in the lower estuary (~14 items or larvae 100 m^3). Such comparable density increases the chances of microplastic ingestion by organisms that feed on zooplankton [32]. Therefore, the river basin is an important source of microplastics, and the estuary is a route for the exportation of continental microplastics to the open ocean [3, 32].

Mangrove creeks of this same estuary are also contaminated with microplastics, totalling 1,662 items collected within 2 months in 12 creeks [31]. The average density of microplastics is comparable to that of the fourth most abundant fish larvae *Gobionellus oceanicus* (~3.4 items or larvae 100 m^3) inhabiting the creeks. The tidal regimes ruled by changes in the moon phases influence the changes in the composition and abundance of microplastics. This means that during spring tides, the flooding of the creeks is greater and more microplastics are accumulated, whilst the opposite occurs during neap tides (Fig. 2 costa). However, the main concern of the study is that most larvae (80.22%) are in later developmental stages and, thus, are susceptible to ingest microplastics with <2 mm (42.2%).

All surface water samples of the western part of Guanabara Bay are contaminated with microplastics, whose concentration ranged from 1.40 to 21.3 items m^{-3}, with polyethylene and polypropylene being the most abundant polymers (Table 1) [33]. This scenario is consistent with those of highly densely populated coastal regions with the lack of solid waste management, characterizing the bay as one of the most contaminated systems worldwide [33].

A diverse array of small-sized microplastics (<1 mm), especially of blue colour (60%) and composed of polyethylene (72%), were found in surface waters of Jurujuba Cove (Guanabara Bay) [26]. The average density of microplastics was 16.4 items m^3, with higher densities observed on the São Francisco beach during both the rainy and dry seasons. The main concern for the region is that most microplastics are in the dimensions that most MP can be filtered by mussels and the mussel farming in the region may be producing contaminated products for human consumption, since microplastics can carry pathogens or toxic compounds [26].

Another study in the same bay detected that the plankton net with 64 μm mesh collected more microplastics (4.8 items m^3), when compared to the net with 200 μm (1.3 items m^3) [34]. A variety of types, colours and sizes were observed, but blue hard microplastics with a size of 200–300 μm width were the most frequent. Polyethylene and polypropylene were the most common polymers. Comparing the abundance of microplastics and copepods, a prey frequently ingested by fish larvae and chaetognaths, demonstrated that although most microplastics are in the same size ranges of the copepods, they are too diluted to represent risk of ingestion [34].

3.3.3 Patterns of Microplastic Contamination in Estuarine Sediments

Benthic sediments of the estuarine system of Vitória Bay (Fig. 1) were reported to be contaminated by synthetic microfibres (77%) and microfragments (23%) [23]. In total, 247 microplastics were found in 20 samples along the entire main channel, with the lower and uppermost regions being the most contaminated (Table 1). Most microplastics exhibited a plastic-associated microbial community formed by bacteria, fungal filaments and spores, known as plastisphere. This raised questions such as the function of microplastics as microbial vectors, pathogens and transfer of foreign species to non-native habitats [23].

Beach sediments within Guanabara Bay are polluted with small plastic fragments (8,766 particles), including fibres, fragments, styrofoam and pellets [25]. Microplastics are the most abundant category (56%), varying from 740 items m^2 during the cold-dry season in the inner bay to 1,300 items m^2 during the warm-rainy season in the outer bay, being probably the result of the flush of microplastics seawards when rainfall increases [25].

3.4 Interaction Between Plastic Debris and Biota in Freshwater and Estuarine Ecosystems

Several types of interactions between the fauna inhabiting estuaries and marine debris are known very well. They include entanglement [35], ingestion [36], gut blockage [37], transportation of exotic species [38] and even dispersion of pathogenic bacteria (*Escherichia coli* and *Vibrio* spp.) to areas without sewage pollution [39].

3.4.1 Interaction Between Plastic Debris and Benthos of Freshwater Systems

A study performed in the Capibaribe River (Fig. 1) detected that the presence of plastic bags caused changes in the macrobenthic community [40]. Most differences were observed between macrobenthos collected under a plastic bag and macrobenthos collected distant from a plastic bag. Deposit feeders are attracted under plastic bags, since light penetration is limited and microalgae sink and become abundant in the sediment or even because the coverture might serve as a protection against seabird predation. On the other hand, suspension feeders such as the dominant Polychaeta *Streblospio* sp. are excluded due to the feeding limitations imposed by the plastic coverture [40].

3.4.2 Ingestion of Plastic Debris by Mammals, Reptiles and Molluscs in Estuarine Systems

Most studies regarding interaction between plastic debris and estuarine fauna focused on the fates and effects of plastic ingestion. At estuaries (the Mamanguape River Estuary) and coasts (Rio Grande do Norte and Bahia States) of northeast Brazil (Fig. 1), four Antillean manatees (*Trichechus manatus manatus*) were confirmed to have ingested plastic debris [37]. Two were found dead due to ingestion of large amounts of plastic bags and raschel knit fabric or gut blockage. The other two specimens were found debilitated. During rehabilitation, small amounts of plastic debris were eliminated along with faeces [37].

Microplastic contamination has also been confirmed in the commercial mussel *Perna perna* [41, 42] (Table 2). Approximately 75% of the mussels collected in the lower portion of the Santos estuary were contaminated with microplastics with no spatial distribution patterns [41]. At Guanabara Bay, all natural and farmed mussels analysed were highly contaminated with blue and transparent fibres, ranging between 16.6 and 31.2 items per individuals [42]. Such high contamination rates raised questions about human health. Depuration procedures can significantly decrease the quantity of microplastics in mussels, but the quantity that remains in the tissues is still high and may not be adequate for consumption [42].

A high amount of plastic debris was detected in the gut contents of green turtles (*Chelonia mydas*) ($n = 80$) inhabiting the Paranaguá Estuarine Complex [36]. In total, 69.7% of the turtles ingested plastic debris, totalling 3,737 items. From these, three stranded animals died due to debris ingestion. Plastic bags, hard plastics, nylon, polystyrene and rubber were the most frequent ingested debris. Debris ingestion was especially higher during the late rainy season, when the seagrass *Halodule wrightii* was not available for consumption, although debris could have been ingested a long period before and not excreted [36].

3.4.3 Ingestion of Plastic Debris by Fishes in Estuarine Systems

In the lower part of the Amazon River estuary (Fig. 1), 13.8% out of 189 fish specimens representing 46 species captured as bycatch by the shrimp fishery ingested 228 microplastics (polyamide, rayon and polyethylene) [43]. Pellets represented the most frequent item (97.4%), followed by sheets, fragments and threads. The number of microplastics ingested showed a positive correlation with the fish length, but no relationship with the trophic level was detected [43]. However, the main concern of this study is that most species are of commercial importance, which raises human health concerns, since pellets can adsorb chemical pollutants (Fig. 4) [44].

Fishes inhabiting rivers and estuaries are also prone to ingest microplastics, and this seems to have a direct relationship with the degree of anthropogenic activities in the river basin, along estuarine margins and adjacent areas [22, 45]. In the lower

Table 2 Density of meso and microplastics ingested by different taxa inhabiting Brazilian freshwater and estuarine systems

Systems	Trophic category	Species	Size of plastics		References
			Micro (items ind.$^{-1}$)	Meso (items ind.$^{-1}$)	
Xingu River	PIS	*Pristobrycon* cf. *scapularis*	0.21	0.35	Andrade et al. [19]
	PIS	*Pristobrycon eigenmanni*	–	0.33	
	PIS	*Pygocentrus nattereri*	–	0.75	
	PIS	*Serrasalmus manueli*	–	0.14	
	PIS	*Serrasalmus rhombeus*	–	0.33	
	HEB	*Metynnis guaporensis*	–	0.27	
	HEB	*Myloplus rubripinnis*	0.13	0.2	
	HEB	*Myloplus schomburgkii*	0.16	0.16	
	OMN	*Acnodon normani*	–	0.25	
	OMN	*Myloplus rhomboidalis*	–	2	
	OMN	*Ossubtus xinguense*	0.58	1.63	
	OMN	*Tometes ancylorhynchus*	–	0.6	
	OMN	*Tometes kranponhah*	0.14	0.19	
Pajeú River	INS	*Hoplosternum littorale*	3.6	–	Silva-Cavalcanti et al. [20]
Amazon River Estuary	PIS/ZOB	*Bagre bagre*	12.8	–	Pegado et al. [43]
	PIS/ZOB	*Bagre marinus*	7.8	–	
	PIS	*Caranx hippos*	30.7	–	
	ZOB	*Selene vomer*	2	–	
	PIS	*Lutjanus analis*	1	–	
	PIS/ZOB	*Lutjanus synagris*	1	–	
	ZOB	*Narcine brasiliensis*	3	–	
	OMN	*Polydactylus oligodon*	3	–	

(continued)

Table 2 (continued)

Systems	Trophic category	Species	Size of plastics: Micro (items ind.$^{-1}$)	Meso (items ind.$^{-1}$)	References
	PIS	*Cynoscion leiarchus*	2	–	
	PIS/ZOB	*Cynoscion microlepidotus*	1.3	–	
	PIS/ZOB	*Cynoscion virescens*	3	–	
	PIS/ZOB	*Macrodon ancylodon*	2	–	
	OPT	*Sphyrna tiburo*	9	–	
	PIS	*Trichiurus lepturus*	2	–	
Goiana River Estuary	PIS	*Cynoscion acoupa*	0.5 to 13	–	Ferreira et al. [22]
	PIS/ZOB	*Centropomus undecimalis*	0.3 to 9	–	Ferreira et al. [52]
	PIS/ZOB	*Centropomus mexicanus*	0.5 to 7	–	
	ZOP/ZOB	*Pomadasys ramosus*	0.2 to 2.3	–	Silva et al. [50]
	ZOP/ZOB	*Haemulopsis corvinaeformis*	0.3 to 1.4	–	
	ZOB	*Cathorops spixii*	0.15 to 1	–	Possatto et al. [6]
	ZOB	*Cathorops agassizii*	0.4 to 0.9	–	
	ZOB	*Sciades herzbergii*	0.15 to 0.6	–	
	ZOB	*Stellifer brasiliensis*	0.03 to 0.12	–	Dantas et al. [51]
	ZOB	*Stellifer Stellifer*	0.02 to 0.2	–	
	ZOB	*Eugerres brasilianus*	0.16 to 0.78	–	Ramos et al. [49]
	ZOB	*Eucinostomus melanopterus*	0.05 to 0.16	–	
	ZOB	*Diapterus rhombeus*	0.18 to 0.28	–	
Paraíba and Mamanguape estuarine Systems	ZOP	*Opisthonema oglinum*	0.33	–	Vendel et al. [48]
	ZOP	*Rhinosardinia bahiensis*	0.35	–	
	OPT	*Anchoa januaria*	0.13	–	

(continued)

Table 2 (continued)

Systems	Trophic category	Species	Size of plastics Micro (items ind.$^{-1}$)	Meso (items ind.$^{-1}$)	References
	PIS/ ZOP	*Lycengraulis grossidens*	0.17	–	
	OPT	*Atherinella brasiliensis*	0.03	–	
	INS	*Poecilia vivipara*	0.11	–	
	OMN	*Hyporhamphus unifasciatus*	0.15	–	
	PIS	*Oligoplites saurus*	0.17	–	
	ZOB	*Diapterus auratus*	0.97	–	
	ZOB	*Diapterus rhombeus*	0.06	–	
	ZOB	*Eucinostomus argenteus*	0.02	–	
	ZOB	*Eugerres brasilianus*	0.06	–	
	ZOB	*Achirus lineatus*	0.5	–	
	ZOB	*Symphurus tessellatus*	0.25	–	
	ZOB	*Sphoeroides testudineus*	0.09	–	
Santos Estuary	PLK	*Perna perna*	Non-informed	–	Santana et al. [41]
Guanabara Bay	PLK	*Perna perna*	16.6 to 31.2	–	Birnstiel et al. [42]

Trophic categories: *PIS* piscivorous, *HEB* herbivore, *OMN* omnivore, *INS* insectivorous, *PLK* planktivorous, *ZOB* zoobenthivorous, *ZOP* zooplanktivorous, *OPT* opportunist

Xingu River Basin (Fig. 1), 26.7% out of 172 specimens belonging to 16 serrasalmid species were contaminated with plastic fragments [19]. Approximately, 80% of the species were contaminated. Polyethylene, polyvinyl chloride, polyamide, polypropylene and polyethylene terephthalate were the most common polymers. Mesoplastics accounted for most contamination, when compared with microplastics (Table 2). Although the frequency of occurrence and the mass of the plastics did not differ among species or guilds, omnivorous fishes had the highest rates of contamination (25–100%), followed by piscivorous (14.3–75%) and herbivorous (13.3–27.3%) [19].

The diet of the Brazilian silverside *Atherinella brasiliensis*, for example, presented highest microplastic occurrences in the severely impacted Paraíba River estuary and the lowest in the less impacted Mamanguape estuary [4]. Other authors

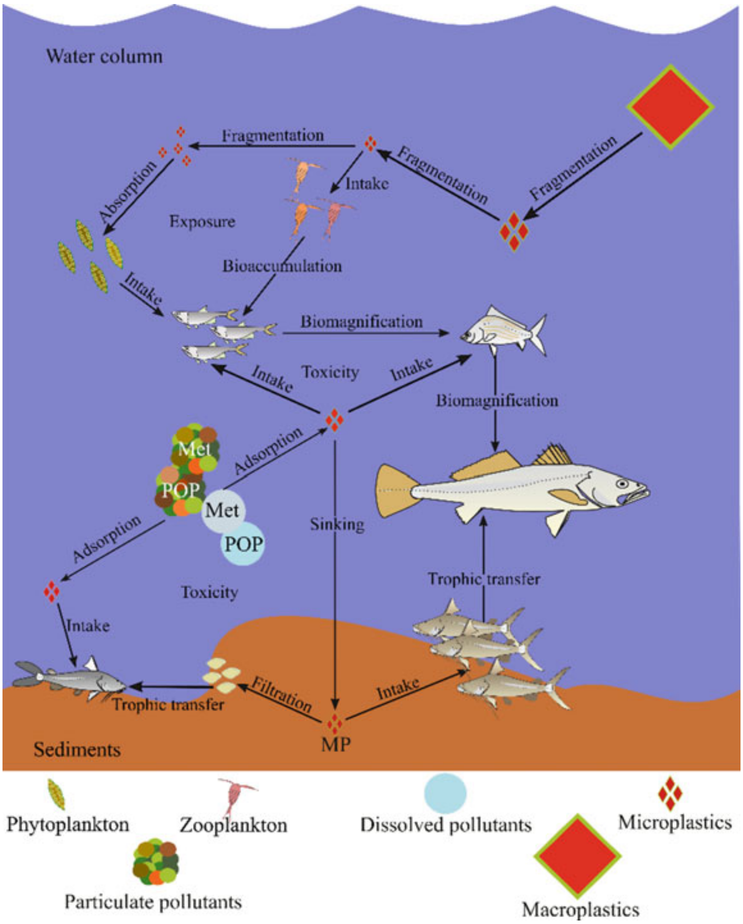

Fig. 4 Some possibilities for the pathways and contamination patterns of plastic debris in the marine environment. Source: André R. A. Lima & Guilherme V. B. Ferreira

[46] proposed another important approach when analysing the diet of *C. acoupa*. For the authors, the ingestion of microplastics is enhanced when the spatio-temporal distribution of the species coincides with periods of high availability of microplastics in the main channel or even in the adjacent coastal area. That contamination varies with the dietary ontogenetic shifts along the life cycle [46]. Another current study asserted that the ingestion of microplastics can have an impact on the health of the individual by diminishing the fish's body condition factor, as revealed in the Guri sea catfish *Genidens genidens* in the Laguna estuarine system [47]. In fact, several conclusions have been generated in recent years and might help to propose managerial action to protect and conserve estuarine resources.

Approximately 9% of the 2,233 fishes inhabiting the Paraíba and Mamanguape estuarine systems ingested microplastics, regardless of length classes, functional guilds and trophic guilds [48]. Fibres were the most frequently ingested type (90%), reaching a maximum of 4 items per individual (Table 2). The widespread contamination on both systems is revealed by the occurrence of microplastics in fish guts along most sampling sites [48].

In the Goiana estuary, at least 11 fish species were evaluated regarding microplastic ingestion (Table 2). There, juveniles, subadults and adults of fishes of commercial and ecological importance were contaminated with microfilaments, especially the blue ones. For the Ariidae catfishes, contamination was recorded in 33% of *Cathorops agassizii* (0.4–0.9 items ind.$^{-1}$), 18% of *C. spixii* (0.15–1 items ind.$^{-1}$) and 18% of *Sciades herzbergii* (0.15–0.6 items ind.$^{-1}$) [6]. The Gerreidae mojarras were also contaminated, being 16% of *Eugerres brasilianus* (0.16–0.78 items ind.$^{-1}$), 9 % of *Eucinostomus melanopterus* (0.05–0.16 items ind.$^{-1}$) and 11% of *Diapterus rhombeus* (0.18–0.28 items ind.$^{-1}$) [49]. For the Haemulidae grunts *Haemulopsis corvinaeformis* and *Pomadasys ramosus*, ingestion of microfilaments varied between 0.3–1.4 items ind.$^{-1}$ and 0.2–2.3 items ind.$^{-1}$, respectively, for the combination of the factors, such as habitats, seasons and ontogenetic phases [50]. In addition, all ontogenetic phases of the Sciaenidae drums were contaminated with blue microfilaments, being 9.2% of *Stellifer stellifer* (0.02–0.2 items ind.$^{-1}$) and 6.9% of *Stellifer brasiliensis* (0.16–0.78 items ind.$^{-1}$) [51]. These contamination rates showed a relationship with the patterns of use of estuarine resources, including habitats and food items.

Regarding *Cynoscion acoupa*, a top predator of commercial importance in the region, microfilaments were more frequently ingested than any natural food item [46]. Among the sampled specimens, only 34% ingested natural prey, whereas 64% of juveniles, 50% of subadults and 100% of adults were contaminated with microfilaments (0.5–13 items ind.$^{-1}$) (Table 2). Moreover, ingestion of microfilaments was detected in all ontogenetic phases of the commercially exploited snooks *Centropomus undecimalis* (0.3–9 items ind.$^{-1}$) and *C. mexicanus* (0.5–7 items ind.$^{-1}$) [52]. More than 50% of the individuals of both species are contaminated. The lower estuary and the coastal zone were the most contaminated sites. The contamination is enhanced with the onset of the piscivory in the adult phase, when peaks of fish ingestion coincide with the peaks of microplastic ingestion [52]. The adult phases of the acoupa weakfish and snooks seem to be more susceptible to contamination through direct ingestion and trophic transfer when they shift their feeding mode to piscivory [22, 52]. Such conclusion is emphasized by the fact that 50% of the fishes ingested by these species were also contaminated, evidencing the likelihood of trophic transfer between prey and predator.

Such behaviour is also reported for the other species assessed in the Goiana estuary, where the contamination with microfilaments was higher in latter phases, when diet and foraging became more complex [49–51]. Additionally, for most species, the highest ingestion rates were observed during the late rainy season in the middle, lower estuaries and coastal zone. This time coincided with the highest availability of microplastics, when river runoff increases and flush plastics seaward [3]. However, to the best of our knowledge, there are few studies addressing the relationship between ontogenetic dietary shifts and microplastic contamination

[22, 46, 49]. These studies asserted that the ecological units are not the species, but their different ontogenetic phases. Ferreira et al. [52] emphasized that the different phases of a species can have multiple and complex uses of essential habitats throughout the year and these behaviours are closely related to microplastic contamination. This means that although fishes may have a great spatial range, the different ontogenetic phases of most species inhabit specific estuarine habitats at least for an entire season (i.e. significant peaks of abundance); and it might coincide with peaks of microplastic availability, when peaks of contamination are commonly recorded [50, 52]. Thus, patterns of estuarine use by fishes can be a good tool to improve management and conservation planning regarding the environmental contamination with plastics.

The contamination of 83% of *H. littorale* specimens was also evaluated in the Pajeú River Basin [20]. Most fragments were microplastics (88.6%), with fibres being the most common type (46.6%). In total, 176 plastics were found in the stomachs of the species, with an average of 3.6 items per fish (Table 2). Microplastics were negatively correlated with food diversity, but positively related to urbanized areas [20].

4 Discussion

4.1 Contributions, Lessons Learned and Knowledge Gaps Regarding Plastic Pollution in Brazilian Riverine and Coastal Environments

The connectivity among river basins, coastal zones and open ocean ruled by environmental gradients is widely discussed in the scientific literature through the so-called source-to-sea continuum or transboundary approach [11, 53, 54]. Such well-established gradient needs to face the intense societal and economic use and occupation. River basins and coastal zones withstand high population density, agricultural/industrial expansion and the improper disposal of wastes and sewages. This significantly alters water quantities and quality, upsetting environmental processes, especially by the contamination of water bodies [17]. The last path for these contaminants is, therefore, the sea.

Among environmental problems, pollution from plastic wastes is a noticeable problem of global concern and acknowledged as one of the world's most pressing environmental issues (Fig. 5). Plastic has reached epidemic proportions with an estimated 100 million tonnes now found in the oceans, being ~90% from land-based sources [55].

Fig. 5 Impacts caused by inappropriate disposal practices. Plastic (**a**) bags in a river margin; (**b**) disposed in a mangrove area; (**c**) along a beach, (**d**) disposed at land, (**e**) interacting with a sea bird, (**f**) in the gut of a dead bird, (**g**, **h**) debris removal along beaches. Source: Wikimages under Creative Commons or Public Domain

4.2 Conventions and Regulations Regarding Plastic Pollution in Brazilian Riverine and Coastal Environments

In May 2019, during the Basel Conference in Geneva, approximately 180 governments pointed plastics as hazardous wastes due to their toxic composition, capacity of adsorbing other pollutants as well as their capacity of fragmentation, which leads to a more dangerous scenario. The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (the Basel Convention) is thus an international treaty designed to reduce the movements of hazardous waste between nations [56]. The Convention aims to protect humans and the environment against the effects resulting from the generation, transboundary movements and management of hazardous wastes [56].

Marine plastic debris have a clear transboundary nature, emphasizing that this problem has a global scale connected by international impacts [53]. Thus, national measures alone cannot be able to control the problems of marine debris. It urges for international cooperation. The international legislative instruments regarding marine debris are categorized into "hard law" and "soft law" [56]. Hard law agreements are international, intergovernmental and regional conventions describing "legally binding contracts with compulsory requirements or legal operations to the parties" [56]. Examples of hard law agreements are the UN Convention on the Law of the Sea, the Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal and the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter [53]. Soft law agreements describe "nonbinding arrangements between parties" [56]. They include resolutions adopted by conferences, intergovernmental and international organizations, regional strategic action plans, declarations, guidelines and codes of conduct [56].

Despite its importance, the above-mentioned international legislation has not been taken entirely into account by the Brazilian government. Recently, an agreement to limit the global volume of plastic waste was signed by 187 countries – from Norway to Nicaragua. Brazil, as well as the United States and Argentina, opposed to the initiative defined at a meeting in Geneva, Switzerland. The decision was adopted at the end of a 2-week State party conference of three international conventions – Basel, Stockholm and Rotterdam – regarding dangerous products. This allowed the introduction of more effective amendments to the Basel and Stockholm Conventions, known as the Ban Amendment, to better control international traffic and the environmental impact of plastic waste by making it illegal to export hazardous waste from industrialized to least developed countries, even if it is for recycling. The initiative proposed by the UN aims to reduce, starting in 2020, the amount of plastic wastes which are difficult to recycle and sent to poorer nations. It means that countries that export plastic will need the consent of importing countries when it concerns contaminated, mixed or nonrecyclable plastic garbage.

Another relevant aspect regarding especially poorer countries is the lack of basic sanitation. It is acknowledged as the worst issue regarding developing countries in South America [57, 58], and generally the effluents from urban settlements, industries and agriculture are not treated before being discharged [57, 58]. Furthermore, the uncontrolled disposal of sewage and solid wastes is widespread along river basins, estuarine courses, coastal zones and marine waters [59]. It is such a complex situation that during the last 20 years the sanitation project of Rio de Janeiro costed R $ 10 billion (US$2.5 billion), without success. The Plan for the Municipal Environmental Sanitation was created in 2011 and encompasses 15 municipalities of Rio de Janeiro. The plan has the potential to reduce the pollution of the bay with solid wastes and wastewaters; however, all debris produced by the surrounding municipalities keep reaching the estuary. Therefore, the efficiency of these programs is still uncertain and must include social awareness [24].

Also, recycling has gained more attention since 2010, when the National Policy for Solid Wastes (Law 12,305/10) was approved [55]. Therefore, the selective collection and transportation of solid waste have been institutionalized in few municipalities in accordance with Brazilian laws. This law is an instrument of economic and social development to facilitate the collection and return of solid wastes to the corporate sector. However, the difficulties of mobilising citizens for the separation of recyclable materials and the improper surveillance to obligate companies that produce solid wastes to perform proper disposal practices according to legislation are still a concern.

The recent implementation of the law added to the lack of monitoring and surveillance has resulted in the functioning of informal and precarious material recovery facilities. Furthermore, pickers are not contracted or paid for in accordance with legal provisions; incentives under federal law have not been established between municipalities and pickers' cooperatives and associations. Local governments often omit their duties regarding urban solid waste recovery [55]. Approximately 1.835 million tonnes per day of solid waste were collected throughout the country in 2008. Almost 58.3% of the waste collected was sent to sanitary landfills, 19.4% to controlled landfills and 19.8% to dumping sites. Among these, 32% of the collected wastes were recyclable materials, corresponding to 58,527 tonnes per day. However, the recycling of solid wastes was only 13% in 2008.

Other authors recommended some actions aiming at prevention and reduction of marine plastic debris that needs to be addressed by countries in a worldwide perspective [56]. Development of a new international marine plastic debris treaty of the scale and scope of the Montreal Protocol and strengthening and interlinking existing conventions on plastic waste emissions and on marine conservation are urgent tasks needing attention. Some recommendations are urgent and include the ban of disposable plastic food packaging, tableware items and shopping plastic bags or their replacement with biodegradable plastics and/or promotion of reusable packaging systems and ban of microplastics in cosmetics, personal care products and detergents [54]. In addition, development of techniques to reduce the amount of microfibres released by synthetic fabrics during washing, usage of alternative biodegradable materials, or establishment of deposits, return, and restoration systems and introduction of legislation for the dismantling and recycling of fibre-reinforced plastic boats are necessary [53, 56].

Considering the Brazilian territory, it is worth mentioning that the Brazilian government established a voluntary commitment to develop a national strategy to combat marine litter, in the context of the UN Ocean Conference. Within this commitment, there is a goal to develop the first National Plan to Combat Marine Litter. Launched in March 2019, it is still being implemented, and its results might be evaluated in the future to determine its efficiency. It is essential that future efforts within this framework take into account the source-to-sea approach, focusing on environments such as riverine and estuarine compartments.

4.3 *Problems Still Needing Attention and Recommendations*

Understanding the fate and effects of microplastics in the Brazilian aquatic system is still difficult, since the available studies do not provide a complete picture of the problem. It is notable that few studies have addressed plastic pollution in freshwater and estuarine systems, whilst more beaches are studied. However, semi-enclosed systems, such as rivers and estuaries, have a great capacity of retention and, thus, higher plastic densities when compared to open systems such as the marine environment, where plastics become somewhat "diluted". Despite this, freshwater systems have so far been neglected when compared to marine systems with regard to plastic pollution, which leads to several knowledge gaps and impairs the estimation of river plastic emissions to the world's oceans [60].

Some authors [2, 3] asserted that when the river flow enlarges due to increased rainfall, micro- and macroplastics are flushed seawards. These findings confirm that river basins are the main sources of microplastics transported to the coastal seas [31]. Since Brazil encompasses a variety of aquatic systems experiencing similar problems of pollution, efforts to understand the patterns of microplastic contamination in different settings of a source-to-sea continuum must be prioritized [58, 61].

In Guanabara Bay, for example, the habit of debris disposal in streams or its margins is dated since the seventeenth century [24]. 1847 saw the initiation of the collection of debris from beaches and the implementation of basic sanitation criteria to reduce pollution within the bay. In 1994, the Depollution Program of Guanabara Bay was established aiming to recover the ecosystem and water quality by the construction of sanitation systems. In 2004, the project *eco-barriers* was implemented by the State government to entrap the floating debris flushed by the streams discharging into the bay. In 2005, the project was suspended, but returned 10 years later, when the International Olympic Committee required a better quality of the bay to the State Secretary of the Environment before the beginning of the Olympic Games in 2016.

According to one of the studies [24], some measures for the management of solid wastes need to be urgently addressed by every municipality to follow the Brazilian legislation. They include (a) stimulation, monitoring, inspection and mandatory management of solid wastes in companies; (b) implementation of selective solidarity collection in schools and public bodies; (c) elaboration of public policies for the recognition and valuation of waste pickers; (d) implementation of eco-points and containers for the collection of solid debris; (e) preparation of a waste recycling program and expansion of existing recycling programs; (f) collection of technological waste; (g) environmental education program; (h) implementation and improvements in landfills and hazardous waste landfills.

Furthermore, international alternatives and technologies are available to prevent and mitigate plastic pollution [53, 62]. The technologies for the collection and removal of waterborne debris before it reaches the open sea have been divided into three categories by the Environmental Protection Agency: storm drain inlets, in-line and end-of-pipe debris capture systems and open-water debris capture systems. Moreover, some alternatives have been developed to reduce plastic production and control the management of the generated plastic waste. For example, to prevent the derelict of fishing gears there are useful alternatives to manage plastic pollution, such as fishing gears identification to improve the lost equipments; provision of adequate, affordable, and accessible onshore port reception/collection facilities; and tackling illegal, unreported, and unregulated fishing. In addition, the use of water-soluble polymers, oxidegradable and biodegradable polymers and cellulose acetate can minimize the impacts of plastics in the marine environment. Furthermore, raising public awareness regarding plastic pollution, including training of professionals, education and campaigns in order to positively influence citizens about the problems of plastic pollution, is of great importance and might be provided by national and local authorities for the management of coastal debris [62, 63]. Evaluating the potential economic impacts of plastic debris might also be an important tool to influence positively decision-makers to prevent the input of debris, i.e. beaches and tourist areas [1]. Impacts might be significant; however they are not estimated.

Another approach to understand plastic pollution is the introduction of citizen science projects. These projects involve volunteer participation of citizens, schoolchildren and their teachers who contribute by acquiring information, data and samples to scientific studies [64, 65]. Citizen science encompasses local, national and international scales, with focus on the distribution and composition of marine debris, especially in the intertidal zone, and involves clear protocols, training of volunteers, in situ supervision by professionals and revision of samples and data [64]. In Brazil studies using citizen science are poorly available, but should be a useful alternative to increase the available information on marine debris sources, distribution and ecological impacts [64, 65].

It is possible that other initiatives might not be addressed in the present chapter, e.g. due to several aspects such as methodological limitations and literature available in formats which are not accessible through indexed basis. Considering that, the present chapter shows a systematic review, which is not intended to be a definitive review, but it is a starting point to identify contributions, lessons learned and knowledge gaps regarding plastic pollution in Brazilian riverine and coastal environments. On top of that, it is the first attempt to clearly identify problems still needing attention and recommendations for Brazilian riverine and estuarine environments.

5 Conclusion

The present chapter identified studies developed in Brazilian freshwater and estuarine systems. The literature review indicates a clear knowledge gap especially regarding freshwater systems. The studies focus on different sized debris, including micro-, meso- and macroplastic, and most possess a characteristic of inventory, only indicating the occurrence of plastic debris and suggesting the causes of such scenario. Fewer studies discussed the process by which these items reached the aquatic environments, the pathways and trajectories of the items or environmental factors influencing it.

The main sources of the plastics found in these Brazilian environments varied according to the environmental compartment studied and the size of the items. Most of the items found in freshwater systems were attributed to fisheries, urbanization and improper disposal. In estuarine environments, macroplastics were attributed to a myriad of sources, indicating the complexity of studying debris within this system. The examples of potential sources are runoff and local rivers, beach users, domestic litter, sewage, fisheries, harbours, dredging activities, dumping, improper disposal and the lack of sanitation. The microplastics found in estuaries were mostly associated with fisheries and harbouring activities (e.g. pellets). The relationship between sources and sinks within such environment is a clear knowledge gap, and it is essential to adopt the source-to-sea approach when investigating these areas.

Regarding the composition and spatial distribution of plastic debris, a lack of information is observed regarding freshwater systems. In the only study analysed, macroplastics were commonly composed of plastic bags and food wrapping, and the distribution is affected by physical barriers, such as breakwater, which seems to be determinant in the distribution of this kind of debris by increasing its accumulation. Microplastics are composed of hard plastics and microfibres, especially in the upper part of riverine systems. Stratification along the freshwater system, according to the proximity of the river source, seems to be a relevant factor for the debris distribution.

In the estuarine compartment, macroplastics appeared in the water column and in the bottom. Plastics are dominant, varying from 71% to 92.4%, and the most common items were plastic bags and fragments, food wrapping, cups and other varied items. The proximity to the source (urban areas, harbours, etc.) seems to be a determinant factor for the quality of items of macroplastics within estuarine systems. Microplastics in the estuarine environment were observed in both water column and bottom sediments, especially in the format of pellets, microfragments and microfibres. Especially the presence of polyethylene and polypropylene was noted. There is evidence that physical barriers influence microplastic distribution, especially the floating ones, such as breakwaters and the intermediate sectors of the estuaries, where more accumulation seems to occur. In addition, rainfall and tides seem to be a key environmental process to be investigated regarding microplastic distribution in the Brazilian systems.

In mangrove areas, plastics were investigated especially in the water column. 62% of the samples were plastics, also dominated by plastic bags, wrappings and plastic fragments.

Most debris found in estuarine beaches are plastics (83.5–95%); the most significant sources are domestic waste, sewage and fisheries. Rainfalls and riverine inputs are determinant factors for increasing the amount of plastics, and this compartment might be a temporary fate. Studies regarding mangroves and other intertidal areas, such as estuarine beaches, clearly lack in the literature about the Brazilian coastal areas.

The less studied environment is freshwater systems, and impacts were only observed for benthic species, accounting for a single study identified through this review. On the other hand, in estuarine environments, several studies describe the impacts of plastics on several species, including manatees, green turtles, mussels (*Perna perna*) and several fish species (serrasalmid, *H. litoralle*, *A. brasiliensis*, acoupa, snooks and others). Studies indicate that the level of contamination for fishes in the Brazilian estuaries might be associated with a relationship between microplastic availability and ontogeny phases. It is also suggested that seasons and fish location within the estuarine gradient may influence it as well. Depending on these factors, the studies identified different proportions of interaction of the species with plastic debris, i.e. ingestion rates by fish individuals varied from 6.9% to 100% of the samples. Quantities also varied ranging from 0.13 to 13 items per individual. Microfilaments, microfibres, pellets, nylon, fragments, pieces of plastic bags, rubber, sheets and threads are the most common items.

It is possible to conclude that there is a clear need to develop studies to understand the processes behind such levels of contamination, sources and fates of plastic debris within the different environments along the coastal environmental continuum. Consequently, the source-to-sea approach, which is not only an intellectual framework, but also an ecological continuum, might be a key approach to a comprehensive understanding of the plastic debris problems within the Brazilian coast.

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