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This review assess the state of the art of microplastics pollution in the western tropical and sub-tropical Atlantic Ocean. This type of pollution, just as its counterpart – larger marine debris, is often neglected by governments and the private sectors. Most of the study area approached here in bordered by Brazil, South America largest territory/coastline, and a strong contender in the world economy. Coalescing and discussing the information available on microplastics pollution at aquatic environments should alert authorities that this is a real problem to be urgently faced by regulators and other stakeholders. Formulating and implementing source-control and abatement measures for microplastics pollution should be regarded as an opportunity to lead southern hemisphere countries in the search of healthier marine environments.

Microplastics in Coastal and Marine Environments of the Western Tropical and Sub-Tropical Atlantic Ocean

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Short sentence (~20words): "Microplastics interact with marine biota of the Tropical Western Atlantic Ocean causing chemical and physical harm from the individual to the population levels."

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Abstract

Microplastic pollution is a global issue. It is present even in remote and pristine coastal and marine environments, likely causing impacts of unknown scale. Microplastics are primary- and secondary-sourced plastics with diameters of 5 mm or less that are either free in the water column or mixed in sandy and muddy sediments. Since the early 1970s, they have been reported to pollute marine environments; recently, concern has increased as soaring amounts of microplastics in the oceans were detected and because the development of unprecedented processes involving this pollutant at sea are being unveiled. Coastal and marine environments of the western tropical and sub-tropical Atlantic Ocean (WTAO) are contaminated with microplastics at different quantities and from a variety of types. The main environmental compartments (water, sediments and biota) are contaminated, but the consequences are still poorly understood. Rivers and all scales of fishery activities are identified as the most likely sources of this pollutant to coastal waters; however, based on the types of microplastics observed, other maritime operations are also possible sources. Ingestion by marine biota occurs in the vertebrate groups (fish, birds, and turtles) using these environments. In addition, the presence of microplastics in plankton samples from different habitats of estuaries and oceanic islands is confirmed. The connectivity among environmental compartments regarding microplastics pollution is a new research frontier in the region.

Keywords: South America, marine conservation, fisheries, Exclusive Economic Zone.

Introduction

Environmental plastic pollution is a widespread scientific and social concern because this pollutant has steadily invaded oceans across the globe and is now ubiquitous in habitats as small as bird's nests and in ecosystems as large as oceanic basins (1,2). Marine plastic pollution has a story as long as the first synthetic polymer because at that time, more than a hundred years ago, solid wastes generated by our society were thrown into the sea, which was then the cheapest disposal option for large cities. Its scientific recording, however, is much newer, dating from approximately 60 years ago (3).

A fraction of that pollution, microplastics (300 μm up to 5 mm in diameter), has been reported as reaching continental aquatic environments under severe pressure from human uses (4), as well as remote places of the globe (5). Coastal and open seas are frequently reported as polluted by microplastic debris (3,6,7 and citations therein). This pollutant has reached every marine environment, being reported as far as the deep ocean (8), including deep sea trenches (9), Arctic sea-ice (10) and environments within the Antarctic Circumpolar Current (11). During its spread in the marine environment, it invaded the biosphere and, through different pathways, reached many levels of the marine food chains (e.g., 3,7,12).

Microplastics have been found in the sea since the early 1970s, when they were first reported in the scientific literature (e.g., 3); however, it is likely that microplastic marine pollution occurred even before then. However, due to the recent booming of publications, it is a common mistake to assume that microplastics in marine environments is a new subject, especially when compared to larger (>5 mm) and very large items (in the scale of meters). The two main size fractions of plastics pollution at sea have actually followed different, but almost parallel, study paths (13). Seldom have these lines crossed (5). The microplastic pollution reporting timeline began with virgin plastic pellets (primary plastics) and evolved into the reporting of items from a myriad of other sources, as the decay of large items dominated the scene (secondary plastics).

Plastic pellets have a particular body of specific literature dealing with their sources, transport, development processes in the sea, contamination by persistent organic pollutants (POPs), ingestion by animals and possible sinks (e.g., 3,7). They have also been found to be associated with other co-pollutants, e.g., toxic metals (e.g., 14), and possibly pharmaceuticals. Certain plastic additives, such as TiO_2 nanoparticles (15), could also have harmful effects in the environment (16). Pellets are the most conspicuous form of microplastics at sea due to their differentiation in shape. In addition, in the class of primary microplastics at sea, there are microspheres that are used in cosmetics, which have been widely reported in North Atlantic waters under a number of sampling and environmental situations (17). Further along the size scale are nanoplastics, an emerging concern for science and society (18,19).

More than 200 papers on microplastics were published in peer-reviewed journals in the last few decades, including extensive critical reviews (e.g., 3,7). New, more focused review papers concentrated on specific environments, such as deep sea sediments, and analytical challenges (13,20). Texts for the general public have appeared with critical synthesis (21) and managed to reach a large audience. Books have aimed at summarizing and facilitating the theme and dissemination of important findings to the public beyond academia (22,23). The subject has finally managed to call the attention of authorities in developed countries, and now, public policies exist to characterize microplastic pollution in the oceans and to devise strategies to address its control and abatement. On the part of the European Union, for example, the monitoring of microplastics is an obligation of member states within the framework of the Marine Strategy Framework Directive (MSFD – indicator 10.1.3).

In general, freshwater environments have received less attention regarding microplastic pollution than the marine environment (4,5,24,25). However, attention might be turning towards reservoirs, rivers and other inland aquatic habitats (4) because they are frequently identified as a significant source of microplastics in coastal and marine environments. The contribution of river basins to marine pollution by microplastics in coastal areas and beyond to the open ocean has already been demonstrated (26), but it is still poorly documented. In South America, especially because of its densely populated and industrialized east coast where rivers run to the western tropical and sub-tropical Atlantic Ocean, plastic and microplastic pollution is a charted consequence (27) of poor river basin management (28). Although existing works show the contamination of river basins by large plastic items at different parts of the continent (27), much less is known about microplastics

(29). It can only be inferred that this size class of plastics follows the same patterns of the larger fraction and that microplastics enter the marine environment from river basins. The river basins of South America are particularly interesting due to their volume and world ecological significance.

There are worldwide reports of microplastic pollution in estuaries buried in tidal flats, on estuarine beaches (e.g., 30), within flooded mangrove forests (31,32) and along the main channel of estuaries (4) that ultimately connect with coastal waters. The main distribution pathway of this pollutant, that is, its transport as particulate matter within the water column, was investigated through its presence in plankton samples to establish spatio-temporal patterns of microplastic-related variables and ecological consequences (33). Therefore, pollution by microplastics in marine environments of the western tropical and sub-tropical Atlantic did not surprise the scientific community because it is adjacent to and downstream from heavily polluted estuaries and beaches (24,34).

Further out at sea, microplastics were reported in the open ocean (35,36), and consequently, they were also found around oceanic islands. Beaches on oceanic islands also have records of microplastic pollution (37). Model predictions on the accumulation of plastics in the South Atlantic Ocean, especially in its sub-tropical gyre, are also known in the scientific literature (36,38). *In situ* works have recently confirmed that in the Atlantic Ocean microplastics might actually follow the same trends predicted for larger items in all oceanic gyres (35).

As microplastics are widely available in the environment, it is not surprising that different animal groups (39,40) ingest them. Other forms of interaction with the biota, as a substrate for biofilm formation for instance, are also possible (41,42) and may include pathogens. Examples of these include *Arcobacter* spp. (43,44) and *Vibrio* spp. (42). Biofouling is independent of the size of the plastic item.

A number of works list the threats posed by microplastic pollution to the marine biota and even to human societies (e.g., 3,7,39). There is no reason to believe that these threats are not present in the western tropical and sub-tropical Atlantic Ocean (WTAO) because all of the environmental precursors are present. In this way, the present literature review focuses on a lesser known area of the world oceans with respect to microplastic pollution: the coastal and marine environments of the western tropical and sub-tropical

Atlantic. We aim to report on the present status of microplastic pollution and, after coalescing the information, to discuss the possible consequences of this threat.

Presence of microplastics in the tropical and sub-tropical coastal environments of the western tropical Atlantic Ocean

Estuaries as a gateway to the oceans

The Goiana river estuary (7°S) is a tropical estuary of the western Atlantic (45), where studies on the microplastic interactions with the biota (29,46–48) and environmental compartments (49,50) were developed (Figure 1). This estuary serves as a model environment to study the ecology of tropical estuaries from different points of view (e.g., fish and invertebrate ecology, marine pollution and fisheries). Microplastics were present in the tidal flats, where clams (*Anomalocardia brasiliana*) are intensely exploited by the local traditional community (45,49,50). The fishery community recognizes that plastic pollution is a real problem and a threat to biological resources in the area (51). Plastic pollution on beaches and in low estuaries (52,53), mangrove forests (24), tidal creeks and main channels (49,54) is known to serve as a potential source of secondary microplastics to these environments.

The presence of microplastics and their interaction (namely, ingestion) with the biota in the Goiana river estuary were reported when the stomach contents of catfish (*Cathorops spixii*, *Cathorops agassizii* and *Sciades herzbergii*), which are demersal species with estuarine resident habits, were found to be contaminated with microplastics (55). In this estuary, there are eight species of marine catfish with the genus *Cathorops* being of paramount ecological importance and representing the majority of the fish biomass in the system. Although of low market value, the local population appreciates these catfish. They are also part of the diet of a number of larger fish of social and commercial interest, such as the Centropomidae (56). The most representative catfish species are *Cathorops spixii* (density: 1340 individuals ha^{-1} and biomass: 14,203 g ha^{-1}), *Cathorops agassizii* (250 individuals ha^{-1} and 4226 g ha^{-1}), and *Sciades herzbergii* (9 individuals ha^{-1} and 270 g ha^{-1}) (56). The species of this family correspond to 53% of the local capture in number (1600 individuals ha^{-1}) and 63% in weight (19 kg ha^{-1}) (56). In Possatto et al. (55), 18, 33, and 18% of the examined *Cathorops spixii* (n = 60), *Cathorops agassizii* (n = 60) and *Sciades herzbergii* (n = 62) individuals, respectively, had plastic fragments in their stomach contents. These amounts are comparable to the percentage of fish found to be contaminated in other studies elsewhere (e.g. 57), The types of fragments varied and included both hard and soft plastics. The number of fragments found in the stomach contents of each individual contaminated ranged from 1 to 10 items. The contamination spreads across ontogenetic phases: juveniles, sub-adults and adults. These findings suggest that as soon as the fish are released from the father's mouth (these species have parental care behaviour) and have to feed by themselves, they are immediately exposed to microplastic pollution at the bottom of the main channel.

Microplastic contamination in the stomach contents of another group of demersal fish (*Stellifer brasiliensis* and *Stellifer stellifer*), which are two estuarine drums from the family Sciaenidae, was also reported at the Goiana river estuary (46). After the analysis of 569 individuals, ~8% showed microplastics in their stomach contents. The average number of items found in the stomach contents of the contaminated individuals was approximately 1. The authors found this contamination occurred year round along all of the reaches of the estuary, but the highest number of fragments ingested was observed in adults during the late rainy season in the middle estuary. Different ontogenetic phases presented microplastic contamination in their stomach contents. The interesting characteristic of this species microplastic ingestion process was that these drums exclusively ingested blue nylon threads, which are small fragments of the blue nylon ropes used in fisheries.

Mojarras (*Eugerres brasilianus*, *Eucinostomus melanopterus* and *Diapterus rhombeus*), which are fish from the Gerreidae family, also had stomach contents that were contaminated with microplastics (48). In three different size classes corresponding to juveniles, sub-adults and adults (n=425), the gut contents of 13.4% of individuals contained microplastic debris. Again, blue nylon fragments were prevalent among all types of microplastics available in the estuarine system (29,58). In a process similar to the one already observed for marine birds, in which satiation can be related to plastics ingestion (59), the condition index of the most contaminated group was significantly different from the sampled population. In this region, mojarras are a fish of high commercial interest, and contamination by any sort of pollutant or processes that might affect its populations (poor conditions, reproduction failures) can be a problem for the artisanal/commercial fisheries.

The water column of the Goiana river estuary was examined for the seasonal and spatial variations of microplastics (<5 mm) and their quantification relative to zooplankton (29,58). In the absence of obvious sources, these microplastics are mostly the result of the degradation of larger items accumulated in the flooded forest and other estuarine habitats. The total density (in 100 m^{-3}) of microplastics represented half of the total fish larvae density and was comparable to the fish egg density. Soft and hard plastics, threads and paint chips were found in the samples. About 15,000 microplastics (~26 items 100m^{-3}) were recorded from 216 plankton samples in an yearly sampling effort. From these, around 41 % were soft plastic, 30% paint chips, 28% hard plastic and 1.5% threads. Their origins are likely the river basin, sea and fisheries (including the lobster fleet). In some occasions, the amount of microplastics surpassed that of ichthyoplankton. The highest amount of microplastics was observed during the late rainy season, when the environment is under influence of the highest river flow, which induces the runoff of plastic fragments to the lower estuary. The density of microplastics in the water column will determine their bioavailability to planktivorous organisms and then to larger predators, possibly promoting the transfer of microplastic between trophic levels. These authors also reported having found fish larvae entangled in microplastics (nylon threads) by the caudal fin during their laboratory work with plankton samples from the Goiana estuary. The microplastic distribution in aquatic environments is influenced by the prevailing circulation patterns, winds and source proximity. Well-mixed environments, such as the river main channel, have a tendency to have an even distribution of microplastic density. However, in stratified estuaries, the salt wedge and its seasonal variations can be a factor in microplastic density differentiation (29,58).

All of the above works were conducted according to a strict sample design (60,61) that allowed the results to be statistically treated to identify spatial and temporal variations in ecological variables, including the ingestion of microplastics by fish. The adherence to sample designs that can positively identify spatio-temporal patterns in the distribution of ecological variables and pollutants, such as microplastics, is important for the suggestion of the most probable sources and the ingestion or entanglement risks. Nylon (polyamide) and polyethylene fibres were the most frequent types of microplastics found in the Goiana river estuary and could be linked to their most probable sources: nets and cables used in fisheries and other maritime operations. The near-absence of plastic pellets in these works suggests that the sources of microplastics for this environment are secondary, resulting from the fragmentation of larger items, either along the river basin or within the estuary. Marine sources are less likely, or have a weaker signal.

It was not possible to determine and quantify the real damage caused by microplastics to individuals (48), but researchers can identify possible threats at the population level (55). However, further refinement of the existing data and conceptual models (48) could reveal the resulting damage from microplastic ingestion by fish, as suggested by other studies that tested similar hypotheses for marine birds (e.g., (62,63). The works developed at the Goiana river estuary speculate on the preferential ingestion of blue fibres by demersal fish (46,48,55). It was hypothesized that the groups of fish studied actively ingest these fragments as a result of their widespread distribution and availability (29,58) and by choosing its form, and possibly its colour and smell, when confounded with their natural prey (Polychaetes) (48). It is possible that the ingestion of blue microplastics might actually be a preference because many other colours and shapes are available in the environment (49,50,29,58) but are seldom found in stomach contents.

This estuary is also important for other animal groups of conservation interest, such as sea turtles (51,64). The presence of four sea turtle species was confirmed: *Chelonia mydas*, *Caretta caretta*, *Eretmochelys imbricata* and *Dermochelys coriacea*. The presence of the three most easily distinguishable ontogenetic phases (hatchlings, juveniles and adults) confirms the importance of the estuary and adjacent areas for sea turtles feeding, gathering, nesting, growing and resting grounds. Although poaching is a cultural habit that is still practiced by many people, fishing (entanglement in gillnets) is the most important threat to sea turtles, and conservation measures to reduce the loss of fishing gear are necessary (65). This would be the basis of the design of desirable mitigation actions enhancing conservation efforts and benefiting marine diversity as a whole because better gear maintenance and proper discarding would decrease the sources of these microplastics to the estuarine environment.

Possatto et al. (55) identified potential threats at the population level (catfish), and Ramos et al. (48) identified threats at the individual level (mojarras). For marine birds of the Pacific, a greater incidence of plastics in animal diets can result in smaller prey and therefore health complications (62), indicating that for more than one marine animal group, prey and plastics can be correlated in a negative way. It is important to examine the role of microplastics and the size and composition of diet items because, as larger size fractions items, microplastic can cause false satiation and influence the types and size of prey and, consequently, energy yields (e.g. 48). Additionally, the capacity to predate, or not, preferred prey can be affected, and animals might be forced to access prey easier to catch due to inactivity, but less nutritious (3,7). These variations induced by the presence and accumulation of microplastics in the digestive tract might be just as important as seasonal fluctuations in prey availability because estuarine fish have little or no limitations of prey when healthy and capable of using all estuarine habitats. Species occupying broad niches, or generalists, might be more susceptible to microplastics ingestion because the shape, size, odour and colour of its prey are also diverse, increasing the risk of confusion during foraging. Physical damage caused by stomach replenishment is usually combined with abrasion of the inner digestive tract. Therefore, determining the microplastic presence and distribution patterns will indicate the predominance of primary (pellets) or post-production plastics (fragments) and possibly suggest sources and trends of bioavailability.

Detailed studies on microplastic characteristics might reveal the underlying mechanism of microplastic ingestion by marine fauna. As microplastics become more frequent and more abundant in animal diets, it would be interesting to examine the retention times in the animal's digestive tract, as well as environmental residence times, to determine the potential damage that each of the items can cause to the natural activities of individuals and populations. Pellets and secondary microplastics are known to be contaminated by a wide range of POPs and pharmaceuticals. When ingested, these items will further interact with the biota by desorbing the organic loads during "digestion". Although small, the animal's biomass to organic contaminant mass ratio might be large enough to cause damage, especially considering the number of microplastic items ingested during the animal's lifetime.

Beaches adjacent to the Goiana river estuary were also found to be contaminated with plastics (52,53) that can potentially degrade and generate microplastics, especially when large accumulations of wrack and river-borne vegetation occur (52). Wrack, associated with intense solar radiation, high organic matter contents and wave action, are environmental factors that may accelerate the chemical and physical decay of polymers and facilitate fragmentation and generation of microplastics. This combination of factors promotes increased residence times of plastics in the estuary and their exposure to harsh environmental conditions (burial in organic rich sediments, sun light, and sea salt). From these beaches, microplastics are exported to the sea through the outwards net flux of the river-estuary-sea ecocline, which, in this region, is dominated by wide intertidal plains of high ecological significance, as stepping stones to the coastal reefs and platform environments (53). Microplastics likely also flow through the estuarine ecocline, as particulate matter does when following the natural channel of energy and matter exportation from the continent to the sea.

Microplastics on sandy beaches and in the stomach contents of stranded animals

Urban beaches and beaches around highly populated areas are the other coastal environments of the western tropical and sub-tropical Atlantic where microplastics were found stranded (66) and where plastic pellets were reported buried in the sand (67–69). Microplastics and pellets were also reported to be present in the stomach contents of marine turtles (70,71) and marine birds stranded or accidentally captured by longline fishing fleets (66,72,73). Microplastics are seldom perceived as a threat to large vertebrates (turtles, mammals and birds) to whom larger items (>5 mm) seem to offer greater risk (23). The works developed in the western tropical Atlantic region show that the ingestion of microplastics is also an issue for any size of marine biota, as previously suggested in other parts of the world (74), and not necessarily only through the food web (12).

Plastic pellets may serve as carriers of toxic contaminants (75), including polycyclic aromatic hydrocarbons (PAHs). Considering that beach morphodynamics and pellet distribution varied along the shore and that contaminant sources may vary on different scales, it is expected that this variability is reflected in the concentration and composition of contaminants. This hypothesis was tested through the sampling of plastic pellets at 30 sites along the shore in Santos Bay (23° 57'S). The total PAH concentrations and the priority PAHs showed high variability, with no clear horizontal spatial pattern. Their composition differed among the sampling sites and the sources of contamination, as indicated by the isomer ratios, were also variable. The high small-scale spatial variability found here has implications for estimating the plastic pellet contamination on beaches because a sample from a single site is unlikely to be representative of an entire beach (67,68). When examining the same variables for pellets buried up to 1 m deep in the beach sand, the total PAHs varied, with the highest concentrations near the surface; meanwhile, the priority PAHs showed a different pattern. PAHs at greater depths did not reach the toxicity levels above the perceived effect levels. The types of PAHs differed along the sediment layers, and a mixture of sources can be suggested. These results provided the first information on the vertical distribution of PAHs in sandy beaches associated with plastic pellets and evidence of a potential environmental risk (67,68).

When investigating the use of the Paranaguá Estuary (25° 30' S) as a foraging habitat by juvenile green turtles (*Chelonia mydas*), plastic debris of various sizes, including a microplastic fraction, were also reported (70). Between June 2004 and July 2007, the carcasses of 80 juvenile green turtles (carapace length range: 29 to 73 cm) were found stranded (n = 71) or captured (n = 9) in fishing nets. The digestive tracts of 76 turtles contained food, which was quantified (ml) and identified (e.g., algae, seagrass, mangrove propagules, mangrove vegetation, shells). Anthropogenic debris was classified by material, colour and size, including items of <1 cm^2. As this was the smallest size reported by the authors, it is possible that microplastics (up to 0.25 cm^2) were also present. Anthropogenic debris was frequently ingested (69.7% of individuals) and was especially important in the late rainy season. Marine turtles are one of the most studied marine biota regarding plastics ingestion. However, microplastics are not often reported separately from larger items. Worth mentioning that ingestions rates are usually high in WTAO (71) and elsewhere (e.g. (65,76). This study highlights that important estuarine and coastal ecosystems, such as the Paranaguá Estuary and adjacent regions (no direct evidence of contamination by microplastics), which provide shelter, feeding grounds and resting areas for juvenile green turtles, are contaminated by microplastics and that their biota are exposed through ingestion

(70). Further south, <32°S, marine turtles were found to have ingested synthetic debris in marine and coastal environments as a consequence of the intensive and continuous release of these highly persistent materials (71). All green turtles found stranded and necropsied (*n*=34) had ingested plastic debris, including microplastics, namely, pellets. No correlation was found between the number or type of ingested items and the turtle's size and/or weight, suggesting a non-selective ingestion as detected before for loggerhead turtles. Most items were found in the intestine. The ingestion of debris by turtles is probably an increasing problem on the southern Brazilian coast (71). The interest in the effects of plastics ingestion by marine turtles in areas of the western Atlantic is growing (77,78); however, the detection of microplastic ingestion and its consequences for the animals remain a scientific challenge.

At the southern Brazilian coast, 40% of the seabirds (14 of 35) were found to have ingested plastic debris (71). Twelve Procellariiformes (66%), two Sphenisciformes (22%) and none of the 8 Charadriiformes were found to be contaminated, with Procellariiformes ingesting the majority of items. Seabirds feeding by diverse methods are contaminated, highlighting the plastic hazard to this biota (71). The Procellariiformes are the birds that are most affected by plastic pollution. Plastic fragments and pellets were the most frequent items found in the digestive tract of eight species of Procellariiformes that were incidentally caught by longline fisheries, as well as beached birds in southern Brazil (72). Plastic objects were found in 62% of the petrels and 12% of the albatrosses in a single study. The Great shearwater, Manx shearwater, Cory's shearwater and Antarctic fulmar were found to have greater quantities and frequencies of the occurrence of plastic. There was no significant difference in the number of plastics between the birds from loglines fisheries and beached birds. No correlation was found between the number of prey and number of plastics in the digestive tract of the birds analysed, but this does not discard the hypothesis that, in some cases, the presence of plastic in the digestive tract has a negative effect on the feeding efficiency of these birds (72). Another negative effect comes from the occurrence of polychlorinated biphenyls (PCBs) and organochlorine pesticides (OCPs) in the ingested plastics pellets and plastic fragments (73). Although transfer through the food chain may be the main source of exposure to POPs for seabirds, plastics could be an additional source for the organisms that ingest them, such as the Procellariiformes, which are the seabirds most affected by plastic pollution (72).

Marine turtles and sea birds are studied for microplastic contamination after stranding on beaches or being captured by fishery gears, but they may represent an important link between coastal and open sea environments, as they often transit between these two to close their annual cycles of feeding and reproduction. As these animal groups move from one habitat to the other, it is possible that they become contaminated in any one of them or, most likely, in either habitat used in their lifecycles.

The presence of microplastics in archipelagos and islands beaches of the western tropical Atlantic Ocean

Geographical isolation from the main continental sources is not an impediment for the introduction of microplastic pollution to marine environments (1,2). Prediction models (35) and early samplings (79,80) have established the presence of microplastic pollution in the western tropical Atlantic. Both archived samples and new sampling campaigns confirmed the hypothesis that microplastics were present in this oceanic basin. However, the seawater around oceanic islands, when found to be contaminated with microplastics (79,80), represent a special case of open ocean environments. Open ocean archipelagos are hotspots of biodiversity and bear high ecological and sometimes socio-economic importance (for example, fisheries and tourism). Although of reduced size and apparently insignificant in the oceanic basin scale, these islands of the tropical Atlantic (and probably every oceanic island around the world) have a strong influence in the local-scale distribution of pelagic microplastics. A density gradient can be perceived where the density decreases seawards (79), indicating that the aggregation of biomass that occurs in such environments also favours a detectable increase in microplastics. This process not only increases the risk posed to the biota that use this special oceanic environment but also makes microplastics available for deposition (and accumulation) in sedimentary environments associated with these islands, both subaereal and subaquatic. Differences in the density of microplastics from one island to another are not always easily explained, and they are likely not latitude related but are highly dependent on a combination of local, regional and wide scale processes (79,80).

Microplastics are present in the sediments of oceanic islands beaches (81). Although the deposition of microplastics on the beaches of oceanic islands is not always possible because it depends on the type of shore, remobilization to the adjacent waters is an expected process; when sandy beaches are present, there is an accumulation of this pollutant together with the sediments. The longer the residence time in an environment, the higher the microplastic accumulation, and microplastics found on beaches are in reality a sample of the types and sizes available in surrounding waters. To establish this relationship, coupled studies are necessary.

The connectivity of beaches on oceanic islands and their surrounding waters was recently studied (82). Previously, studies mostly focused on the presence of plastic particles on the sea surface *or* on sediments. However, in the western tropical Atlantic Ocean, sampling was conducted in three archipelagos (Fernando de Noronha, Abrolhos and Trindade Island) of different latitudes and distances from the continental sources of microplastics. Plastic particles were collected concomitantly on the sea surface, during near-shore neuston plankton tows (300 µm) (n=160), and on sandy beaches (n =60), where the strandline was scraped (top 2 cm). Microplastics were present in 68% of the plankton samples and 60% of the sand samples. Similar hard plastic fragments, which are secondary-sourced microplastics, were sampled in both habitats and predominated when compared to other types of particles collected in the same environments. These plastics have diverse colours, shapes, sizes and materials and seem to originate from both land and marine-based sources. Surface waters around the studied islands were the main source of the hard plastic fragments to the beaches. These hard plastics were likely sorted by the same hydrodynamic processes that select the sediments and therefore were susceptible to the sedimentary balance of the beach. They are likely in constant exchange with the surrounding waters from where they can recycle or be exported to re-join the bulk of microplastics that circle in this oceanic basin. This behaviour is probably part of a longer cycle that eventually defines the final sink of this category of microplastics around oceanic islands (82).

Future research needs in the region (WTAO)

The next challenges in tackling this problem will be to gather sufficient and high quality information to begin building realistic and scalable mechanistic models (based on fundamental ecological principles) of plastics' role in ecosystem functioning (Figure 2). This should enable us to predict a diverse range of responses to combined human pressures – microplastics and POPs, for instance – to be extrapolated even to where there is little or no historical records on which to rely. To fulfil this goal, the required studies must focus on ecosystem properties and the participation of this pollutant in biogeochemical cycles. Inventory-like studies focused on a single biological species might soon go outdated, since the prediction is that the great majority of marine biota actually interacts with some size fraction of plastics, and especially microplastics. However, even the best algorithms in the world will fail to guide our actions accurately if they are not based on a firm understanding of microplastic marine pollution and its fate. Thereby, field research will have to continue evolving through better sampling techniques and planning. Likewise, laboratory procedures and mathematical tools will have to evolve to extract the most information from samples. Most of the predicted effects of microplastic ingestion by marine fauna do not depend directly on polymer composition but rather on its shape and size. Microplastics have therefore become a fundamental variable in plankton research.

Connectivity among habitats and environments through the transport of microplastics by water or within the biological compartment are new subjects to be studied. Information on pelagic and sedimentary microplastics from other sites of high ecological, social and economic interest of the western tropical Atlantic, such as the Atol das Rocas archipelago, Abrolhos and Manuel Luis banks, are other frontiers to be exploited that will help the understanding of microplastic dispersion across the continental platform and, consequently, threats to the marine biota. The smallest fraction of microplastics related to the skin scrubbers and other cosmetics has not yet been studied in the waters of the western tropical Atlantic. In time, it will be important to surpass this size barrier and to conduce field investigations of these items, as well as the fibres from clothes washing processes. Further advances are also needed in determining the role of microplastics in exotic species transportation as biofouling. On the other hand, biofouling can change the density of microplastics and cause it to sink or to have a different fate (ingestion) from merely floating near the surface.

River basin conservation regarding macro and microplastic pollution should be an integral part of coastal and marine conservation (28). Thereby, other potential study sites regarding microplastic pollution and its contribution to marine loads are the Amazon river delta and other large rivers of South America. The Orinoco delta on the border with the Caribbean and the La Plata estuary at the southern limit of this province are other important sites that should receive attention regarding both macro and microplastic pollution due to their ecological, social and economic importance.

The formation of novel and testable hypotheses on microplastics in coastal and marine environments will most certainly lead to more precise predictions of its fates. As we have identified sources of microplastics to the world oceans, sinks must also be studied in detail. Prediction and study of both natural and human-driven processes that link terrestrial and marine and marine habitats and ecosystems through microplastic transfer may determine the ecological implications of future trajectories of human interferences on the oceans.

In addition, there are other challenges ahead. In light of recent research advances, microplastics can no longer be considered the smallest size fraction of plastics at sea: papers on nanoplastics (18,19) have also been published. These works indicate a "time-bomb" situation (A.A. Koelmans, pers. comm.), in which it is practically impossible to predict what the future of plastics at sea will be because the smaller and smaller sizes that are recognized have ecological effects. Nanoplastics are also likely to have adverse impacts, further to those observed for larger size categories (S.J.M. Blaber, pers. comm.).

Final remarks

The present economic scenario of the last decade for WTAO includes the perspective of a growing oil and gas exploitation at sea and an increase in the coastal-based petrochemical industry. Additionally, economic prosperity will increase the plastic consumption from different groups in society, including more expandable packaging items. Plastic pollution is now spreading to outer space and will probably reach the lithosphere, where it will remain buried in sediments for centuries, in a perverse and unpredictable decomposition experiment. Microplastics are a mark of the Anthropocene (83) onto marine environments.

Even small human communities can generate disproportional amounts of plastic wastes that threaten the adjacent aquatic environments. Microplastics are usually derived from larger items exposed to environmental conditions, so proper waste management is an important ecological issue that has effects on the economy. Isolated rural environments are under a similarly large threat of microplastic pollution as the result of its steady accumulation in every habitat of the marine ecosystems.

Owing to an expected increase in plastic consumption in South America, further investigations of marine plastics and especially microplastic pollution in this region are highlighted as a priorities for research. The construction of realistic models to understand the role of plastics in functioning ecosystems, in particular, is a research challenge. A number of knowledge gaps (such as the microplastic transport between environmental compartments) were identified to aid further investigations of this topic. While several reviews have already been published on marine microplastic pollution, it was important to provide a critical overview of microplastics research within WTAO.

The explosion in the number of papers on microplastics in the international literature is in large part due to the enforcement of the EU Marine Strategy Framework Directive (Descriptor 10), which triggered a number of laboratories to start working with plastics, microplastics and nanoplastics. As a result, the EU quickly developed a number of basic field and laboratory skills to cope with the demand. EU countries have also approached capacity building to fulfil the task of monitoring European seas regarding microplastic pollution, setting an example for other parts of the world. The potential implications of the information already gathered by researchers at WTAO in the hands of decision-makers can finally make an effective difference in the conservation of marine ecosystems, as intended by the regional governments. Considering its focus on tropical and subtropical waters, this review is likely to be of interest to researchers and policymakers.

Brazil, as the largest territory and coastline in South America and a strong contender in the world economy, borders most of the study area approached in this review. Governments and the private sector, despite the existence of regulations for waste disposal on land, often neglect microplastic marine pollution as larger marine debris. Coalescing and discussing the information available on microplastic pollution for all of the aquatic environments of South America should alert authorities that this is a real problem to be faced by regulators and other stakeholders. Based on the information already available, it should be possible to formulate and implement source-control and abatement measures for microplastic marine pollution. These actions must be regarded as an opportunity to lead the southern hemisphere countries in the challenge of promoting healthier marine environments.

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Figures caption

Figure 1**:** Location of the studied sites in the western tropical and subtropical Atlantic Ocean (WTAO) mentioned in the text.

Figure 2**:** Summary flowchart of the available information and future research needs for the western tropical and subtropical Atlantic Ocean (WTAO).

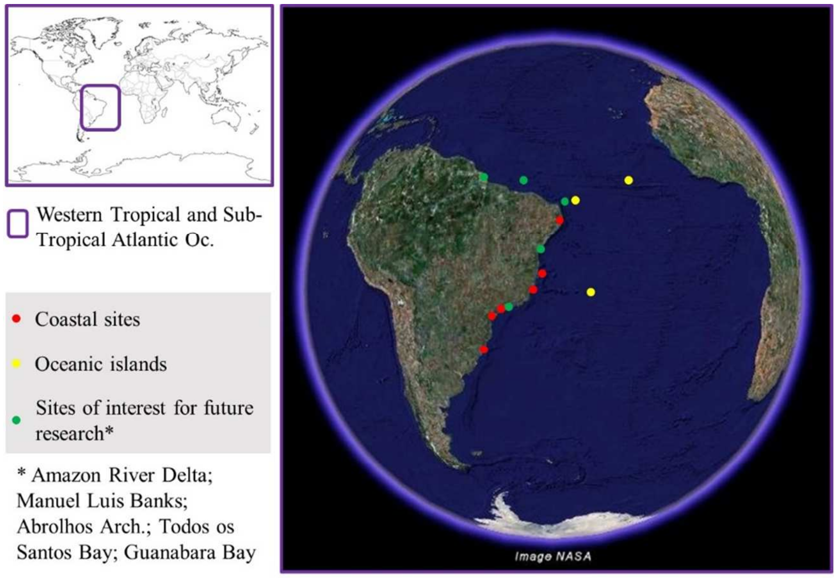
Western Tropical and Sub-Tropical Atlantic Oc.
Coastal sites
Oceanic islands
Sites of interest for future research*
* Amazon River Delta; Manuel Luis Banks; Abrolhos Arch.; Todos os Santos Bay; Guanabara Bay
Image NASA

Figure 1

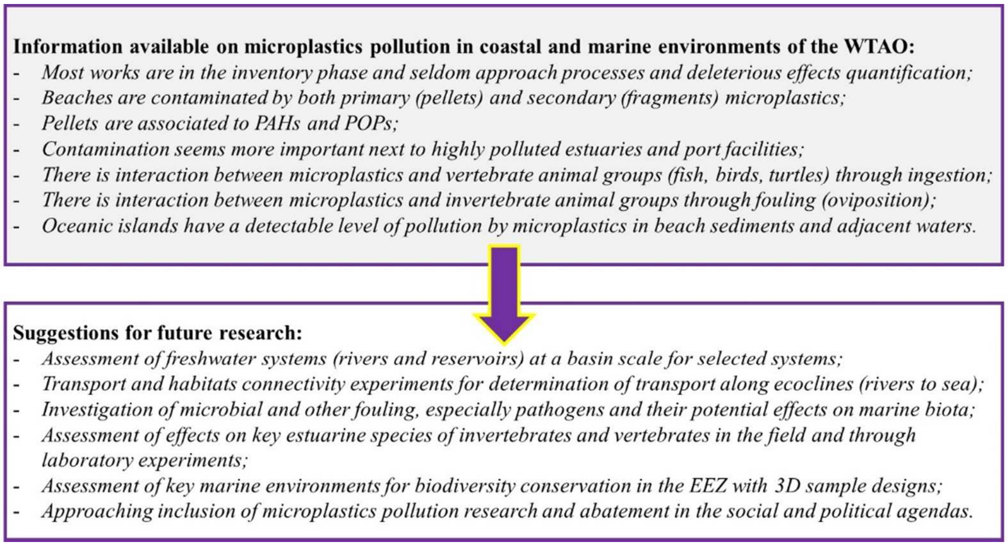
Information available on microplastics pollution in coastal and marine environments of the WTAO:
- Most works are in the inventory phase and seldom approach processes and deleterious effects quantification;
- Beaches are contaminated by both primary (pellets) and secondary (fragments) microplastics;
- Pellets are associated to PAHs and POPs;
- Contamination seems more important next to highly polluted estuaries and port facilities;
- There is interaction between microplastics and vertebrate animal groups (fish, birds, turtles) through ingestion;
- There is interaction between microplastics and invertebrate animal groups through fouling (oviposition);
- Oceanic islands have a detectable level of pollution by microplastics in beach sediments and adjacent waters.
Suggestions for future research:
- Assessment of freshwater systems (rivers and reservoirs) at a basin scale for selected systems;
- Transport and habitats connectivity experiments for determination of transport along ecoclines (rivers to sea);
- Investigation of microbial and other fouling, especially pathogens and their potential effects on marine biota;
- Assessment of effects on key estuarine species of invertebrates and vertebrates in the field and through laboratory experiments;
- Assessment of key marine environments for biodiversity conservation in the EEZ with 3D sample designs;
- Approaching inclusion of microplastics pollution research and abatement in the social and political agendas.

Figure 2