Research, Society and Development, v. 11, n. 12, e164111234457, 2022
(CC BY 4.0) | ISSN 2525-3409 | DOI: http://dx.doi.org/10.33448/rsd-v11i12.34457

Abiotic factors associated with microplastic pollution in surface water of a tropical estuary

Fatores abióticos associados à poluição por microplásticos em águas superficiais de um estuário tropical

Factores abióticos asociados a la contaminación por microplásticos en las aguas superficiales de un estuario tropical

Received: 08/23/2022 | Reviewed: 09/06/2022 | Accept: 09/01/2022 | Published: 09/10/2022

Ana Karolyna Maia De Oliveira
ORCID: https://orcid.org/0000-0002-4823-2463
Paraiba State University, Brazil
E-mail: ana_karolyna39@hotmail.com
Bianca Oliveira Paiva
ORCID: https://orcid.org/0000-0001-9603-1124
Paraiba State University, Brazil
E-mail: bianca_paiva12@hotmail.com
Nyedja Fialho Morais Barbosa
ORCID: https://orcid.org/0000-0003-1813-320X
Paraiba State University, Brazil
E-mail: nyedja@servidor.uepb.edu.br
Ana Lúcia Vendel
ORCID: https://orcid.org/0000-0002-5631-2674
Paraiba State University, Brazil
E-mail: analuciavendel@servidor.uepb.edu.br

Abstract
The aquatic environment has suffered anthropic impacts through inadequate dumping from domestic, agricultural and industrial sources. Such waste products become fragmented into microplastics (MPs) which accumulate in these ecosystems and cause impact. This study offers the first evaluation of contamination of the surface water by MPs in the Paraíba River estuary, Paraíba State, northeast Brazil. Monthly surface water samples were performed with a phytoplankton net from March 2019 to February 2020, between Restinga Island and the Cabedelo Harbor, downstream of the estuary. About the abiotic factors tested, tide height and precipitation were inversely proportional to MPs abundance at the water surface. While water transparency, wind speed and direction and volume of filtered water did not affect it significantly. A total of 443 MPs were obtained in 1116.26 m3 of filtered water, with a mean abundance of 1.96 ± 1.44 MP/m3, ranging from 0.33 (September) to 4.76 (January). The results reveal an important incidence of MPs pollution downstream in this system. The predominance of MPs fibers (51%) and fragments (48%) result from the slow, natural breakdown of solid waste, confirming the lack of the proper discarding to trash in the João Pessoa metropolitan region. These findings underscore the need for the implementation of simple mitigating measures, such as basic sanitation to reduce local pollution as well as effective routine assessments from the anthropic impact and from water quality control measures in this and many other Brazilian estuaries.
Keywords: Anthropogenic impact; Paraíba River estuary; Tide; Rainfall.

Resumo
O ambiente aquático tem sofrido impactos antrópicos por meio de despejos inadequados de fontes domésticas, agrícolas e industriais. Os resíduos se fragmentam em microplásticos (MPs) que se acumulam nesses ecossistemas e causam tal grande impacto. Este estudo oferece a primeira avaliação da contaminação das águas superficiais por MPs no estuário do Rio Paraíba, Paraíba, Brasil. Amostras mensais de águas superficiais foram realizadas com rede de fitoplâncton entre março/2019 e fevereiro/2020, entre a Ilha da Restinga e o Porto de Cabedelo, à jusante neste estuário. Sobre os fatores abióticos testados, a altura da maré e a precipitação foram inversamente proporcionais à abundância de MPs na superfície da água. Enquanto transparência da água, velocidade e direção do vento e volume de água filtrada não afetaram significativamente tal abundância. Um total de 443 MPs foi obtido em 1116.26 m3 de água filtrada, com abundância média de 1,96 ± 1,44 MP/m3, variando de 0,33 (setembro) a 4,76 (janeiro). Os resultados revelam uma importante incidência de poluição por MPs à jusante neste sistema. O predomínio de fibras (51%) e fragmentos (48%) de MP reflete a decomposição lenta e natural dos resíduos sólidos indevidamente lançados no sistema, confirmando a falta de descarte adequado para o lixo na região metropolitana de João Pessoa. Este estudo

reforça a necessidade de se implementar medidas mitigatórias simples, como saneamento básico, para reduzir a poluição local, bem como efetivas e rotineiras avaliações do impacto antrópico voltadas ao controle da qualidade da água neste importante estuário paraibano.
Palavras-chave: Impacto antrópico; Estuário do Rio Paraíba; Maré; Chuva.

Resumen
El medio acuático ha sufrido impactos antrópicos a través de vertidos inadecuados de fuentes domésticas, agrícolas e industriales. Los desechos se fragmentan en microplásticos (MPs) que se acumulan en estos ecosistemas y causan un impacto tan grande. Este estudio proporciona la primera evaluación de la contaminación del agua superficial por MPs en el estuario del río Paraíba, Paraíba, Brasil. Se realizaron muestreos mensuales de agua superficial con red de fitoplancton entre marzo/2019 y febrero/2020, aguas abajo en este estuario. En los factores abióticos probados, la altura de las mareas y la precipitación fueron inversamente proporcionales a la abundancia de MP en la superficie del agua. Mientras que la transparencia del agua, la velocidad y dirección del viento y el volumen de agua filtrada no afectaron significativamente dicha abundancia. Se obtuvieron un total de 443 MPs en 1116.26 m3 de agua filtrada, con una abundancia media de 1,96 ± 1,44 MP/m3, variando de 0,33 (septiembre) a 4,76 (enero). Los resultados revelan una importante incidencia de contaminación por MP aguas abajo en este sistema. El predominio de fibras (51%) y fragmentos (48%) de PM refleja la descomposición lenta y natural de los residuos sólidos, lo que confirma la falta de eliminación adecuada de basura en la región metropolitana de João Pessoa. Este estudio refuerza la necesidad de implementar medidas de mitigación simples, como saneamiento básico, para reducir la contaminación local, así como evaluaciones de impacto antrópico efectivas y de rutina destinadas a controlar la calidad del agua en este importante estuario de Paraíba.
Palabras clave: Impacto antropogénico; Estuario del Río Paraíba; Marea; Lluvia.

1. Introduction

The contamination of aquatic ecosystems by synthetic polymers, particularly microplastics (MPs), has become a growing global problem (Ivleva et al., 2017). This material has characteristics, such as lightness, durability, strength and a low cost, that makes it a key factor in the fields of health, civil construction, energy and technology (Derraik, 2002; Ivleva et al., 2017). Indeed, there has been an exponential increase in the demand for plastics after World War II, with global production reaching 368 million tons/year in 2019, with at least 10% of this total has been discarded in the marine environment annually (Plastics Europe, 2020). This causes a considerable impact and remains accessible for ingestion by organisms of all guilds and trophic levels (Ferreira et al., 2018) in the aquatic environment. Other authors argue that between 4 to 12 million tons of plastics to enter the marine environment every year (Jambeck et al., 2015), 1.15 to 2.41 million tons of which are transported by rivers (Lebreton et al., 2017), which results in intense anthropogenic pressure on both ecosystems. Many plastic pollutants that impact the marine environment come from mainland sources, such as the outflow of rivers, transport by the wind, even as domestic, agricultural, and industrial effluents (Ryan et al., 2009), making the accumulation of plastics in oceans an environmental risk throughout the world, which not only causes esthetic problems, but also threatens the economy of coastal regions and, especially, the marine biota (Thompson et al., 2009).

Plastic waste enters the environment by accidental loss and improper dumping, where it undergoes physical fragmentation (Lusher et al., 2017) through photochemical degradation and mechanical abrasion (Thompson et al., 2004; Andrady, 2011). The term microplastic (MP) refers to all plastic particles between 0.1 µm and 5.0 mm in size (Thompson et al., 2004; Arthur et al., 2009). The ubiquitous presence of MPs in oceans has attracted the attention of environmentalists due to its potential toxicity to marine life (Jambeck et al., 2015).

The contamination of aquatic ecosystems by MPs occur in both freshwater bodies and oceans throughout the world (Barnes et al., 2009) and are found from the coast to ocean gyres (Cole et al., 2011). However, dispersed by winds, turbulence generated by ship traffic and oceanic currents, MPs are concentrated not only near the polluting sources but transported long distances to remote areas far from human activities (Ivar do Sul & Costa, 2014).

Estuaries have complex dynamics due to the influence of marine conditions and physical processes, such as changes in tide flow, circulation within the estuary and estuarine physiography (Mangas et al., 2013). This variation in physiographic and environmental variables contributes to the considerable primary production found in these ecosystems, which serve as places for the shelter, feeding, and reproduction of numerous aquatic species (Elliott et al., 2007; Santana et al., 2015). MPs in estuaries originate from multiple sources. According to Ivar do Sul & Costa (2013) and Ferreira et al. (2018), the main sources of MPs in these coastal environments are urbanization and fishing activities from both the river basin and adjacent marine regions. Domestic sewage discharged into the aquatic environment without treatment is among the diverse sources and has an abundance of polyester fibers resulting from the washing of clothes, which is a well-documented and impactful source of MPs (Browne et al., 2011). The high incidence of MPs has been reported in numerous marine environments, occurring in sediments (Claessens et al., 2011), on beaches (Martinelli Filho & Monteiro, 2019), on islands (Ivar do Sul & Costa, 2013), on surface waters (Schönlau et al., 2020) and in fishes (Vendel et al., 2017). Thus, the organisms that inhabit aquatic environments are exposed to the ingestion of MPs, which pose chemical and physical risks (Wright et al., 2013) and can cause endocrine and reproductive disorders (Shen et al., 2019; Zhang et al., 2021) as well as obstruction of the digestive tract (Wright et al., 2013). Moreover, MPs can serve as vectors for the transference of additives and persistent organic pollutants (POPs), which are bioaccumulated and biomagnified in organisms (Oehlmann et al., 2009; Rochman et al., 2013). The interaction between marine organisms and MPs, especially in coastal waters, is also the cause of concern regarding the potential risk to human health (Cole et al., 2013; Zhang et al., 2021) through the food chain (Wright et al., 2013). Humans receive MPs not only through ingestion, but also through dermal pathways and inhalation (Senathirajah et al., 2021), these authors estimate that each person ingests, on average, 0.1 to 5.0 g of microplastics per week throughout the world. The transfer of plastic material through tissue has been confirmed (Fabra et al., 2021) and several commercial species consumed by the human population have been the focus of studies on the ingestion of MPs (Cole et al., 2013; Miranda & De Carvalho-Souza, 2016; Zhang et al., 2021).

The present study is the first investigation of MPs in the Paraíba River basin. The aim was to identify and quantify the downstream occurrence of this pollutant to alert local administrators regarding the impact of pollution by MPs in surface waters of this important Brazilian estuary.

2. Material and Methods

Study área

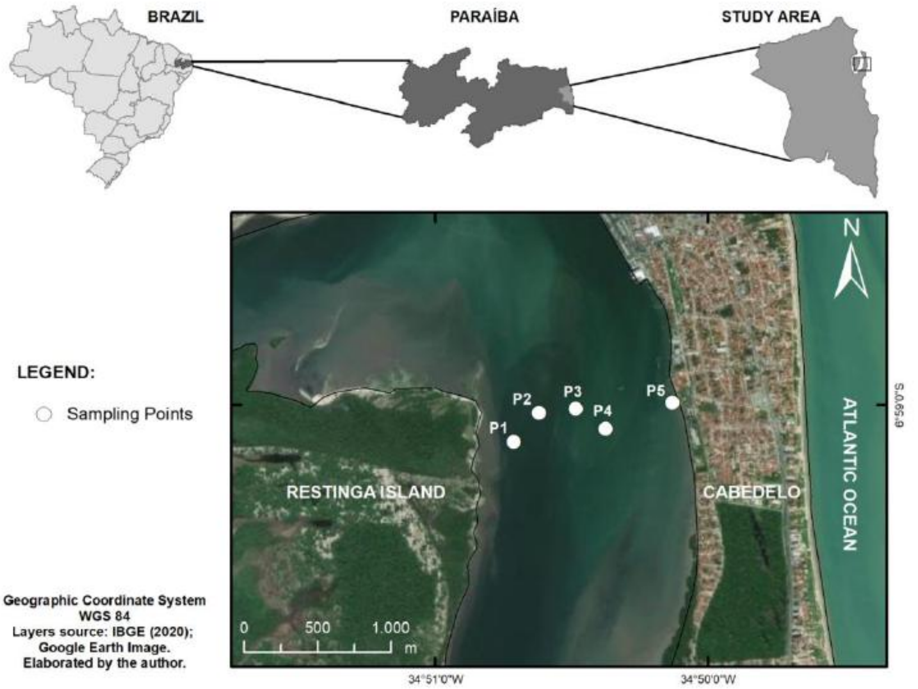
This study was developed in the Paraíba River estuary in the Paraíba State, northeast Brazil. The drainage basin of this river covers approximately 380 km and passes through 37 municipalities (Nishida et al., 2008). The estuary has an area of 3012 ha (Guedes, 2002) and the climate is equatorial (Köppen classification: As) with a dry summer (Álvares et al., 2013). The lowest precipitation occurs in November (dry season) and the rainy season extends from February to August (Alves et al., 2016).

The Paraíba River estuary has mangrove areas around the main channel and diverse smaller channels as well as remnants of the Atlantic Forest (Dolbeth et al., 2016). The characteristic fauna and flora of the estuarine environment have considerable biological importance and are also exploited by the population for consumption and sales. Thus, the estuary has both ecological importance and socioeconomic relevance for the local population as an area for artisanal fishing as well as tourism and harbor activities (Ferreira et al., 2017; Pessoa et al., 2019). This environment is situated in a metropolitan region with more than one million residents (IBGE, 2010) as well as large sugarcane plantations and shrimp farms (Dolbeth et al., 2016; Teixeira et al., 2020), sewage inputs from the cities of João Pessoa, Cabedelo and Lucena (70.8%, 51.1% and 29.7%, respectively) (IBGE, 2010) and impacts from dredging activities and shipping traffic related to the Cabedelo Harbor downstream. Thus, the estuary suffers anthropogenic impacts on a continuous basis, which is a direct, constant source of MPs in these waters.

Data sampling

Sampling of the surface water was conducted for one year between March 2019 and February 2020. Five samples were collected from five points each month, totaling five monthly pseudo replicates in the transect between the city limits of Cabedelo and Restinga Island (distance of 1.4 km) (Fig. 1). Samples were collected in the morning using a 20-µm phytoplankton net coupled to a Hydro Bios® flowmeter (model 438 110) to record water flow during the six-minute drag sampling performed at each point using a boat with an outboard motor, with 100 m between sampling points.

Figure 1. Sampling points between Cabedelo and Restinga Island in Paraíba River estuary, northeast Brazil. Source: QGIS 2.18.20 software - Lyon (2018).



Source: Authors (2022).

After the standardized sampling water, the material retained in the net was transferred to duly washed and identified glass flasks. The material was sent immediately to the laboratory.

At each sampling point, the following abiotic factors were determined: water temperature (ºC) with a thermometer, salinity using a refractometer and water transparency (m) using a Secchi disc. Rainfall data were obtained from the Real-Time Climate Monitoring Program of the Northeast Region (PROCLIMA, 2020). Estimates of wind speed and direction were obtained from the US National Weather Service (GFS/NCEP/US, 2020).

Laboratory analyses

Each water sample was filtered through a 15-µm filter and the content was stored in clean glass flasks labeled with the sampling point for subsequent analysis. Sorting was performed monthly through active searches with the aid of a stereomicroscope for the quantification and characterization of MPs. Plastic particles from the samples were quantified and classified based on color and type.

All due care was taken to avoid airborne contamination during the sorting in the lab to ensure the reliability of the quantification of the MPs in the 60 water samples, following the Airborne Contamination Control Protocol described by Paiva et al. (2022). To verify and control airborne contamination, blanks were used during the sorting of the samples, which consisted of three Petri dishes washed three times with water filtered through a 15-µm filter, dried and analyzed under a stereomicroscope to ensure the complete absence of airborne contamination by MPs. These three dishes were then placed alongside the stereomicroscope with distilled water filtered through a 15-µm filter to measure possible contamination by MPs from the interior of the lab during the sorting of the sample, which was performed in the least possible time. Blanks averages from three Petri dishes were decreased from MP number in this study.

Data analysis

The volume of filtered water was calculated as:

$$V = A \times R \times C \times 1000 \text{ in } m^3,$$

in which **A** is the area of the opening of the phytoplankton net (m^2), **R** is the number (final - initial) of rotations of the flowmeter and **C** is the measurement factor after the calibration of the equipment in meters per rotation (0.3) furnished by the manufacturer. This formula provided the abundance of MPs per cubic meter of filtered surface water.

To explain the abundance of MPs, a multiple linear regression model was run with the independent variables water transparency, wind speed, wind direction and tide height. The one way ANOVA was used to investigate significant differences in the abundance of MPs between months with a Tukey test a posteriori. The t-test was used to compare mean MPs abundance values at the five sampling points between high and low tides. The presupposition of normality was confirmed using the Shapiro-Wilk test ($p > 0.05$).

Two-way ANOVA was applied to the MPs values of each sample to investigate spatiotemporal differences between means. Spatial variation was investigated among the sampling points (five treatments with three repetitions each) distributed between Restinga Island and Cabedelo Harbor. Temporal variation was investigated during the 12-month period. Tukey's test was used for *a posteriori* comparison of means. The statistical analyses were performed using the RStudio 4.1.2 and BioEstat 5.0 softwares.

3. Results

Abundance and characterization of MPs

Sixty surface water samples were analyzed from the Paraíba River estuary over a 12-month period, with the occurrence of MPs in 100% of the samples. However, it was not possible to perform an adequate standardized quantification in September because the sample had a high quantity of oil related to an oil spill, which hindered sorting in this month, leading to a relatively low MPs count.

About the MPs abundance 13 blanks were decreased from 443 MPs in all 60 samples analyzed, i.e., a total of 430 microplastics were quantified in 1116.26 m^3 of filtered water, corresponding to 1.96 ± 1.44 items/m^3 as monthly average abundance.

About the color, blue MPs predominated, corresponding to 329 (74%) of the MPs found, followed by 45 transparent MPs (10%), 37 black MPs (9%) and 32 (7%) of other colors (Fig. 2a). About the type, among the total MPs found in the surface water of the estuary, 227 (51%) were fibers, 210 (48%) were fragments and six (1%) were filaments (Fig. 2b).

Figure 2. Classification of MPs according to color (**A**) and type (**B**) in surface waters from Paraíba River estuary, northeast Brazil.

Source: Authors (2022).

Abiotic factors

The multiple linear regression analysis revealed that water transparency, wind speed and wind direction were not significantly associated with the abundance of MPs ($p > 0.05$) (Table 1). Thus, these abiotic factors do not determine the distribution of MPs in the surface water of the estuary.

Table 1. ANOVA of abiotic factors and microplastics abundance in surface water from Paraíba River estuary, northeast Brazil.

Source of variation	DF	SS	MS	F-value	P-value
Regression	4	907.2859	226.8215	0.4726	0.7567
Residual	7	3359.6308	479.9413	0.7201	0.6060
Total	11	4266.9167	-	-	-

Source: Authors (2022).

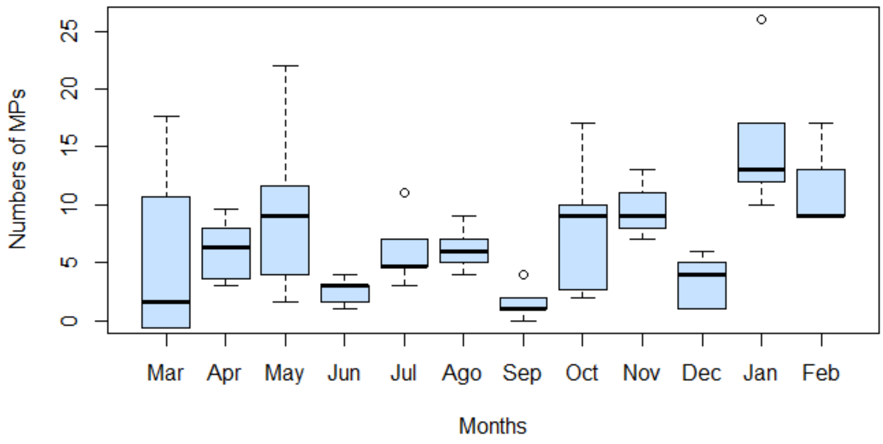
In terms of the monthly abundance of MPs, the total number of MPs recorded subtracted from the average number of MPs found in the blank of each sample was considered, so the total and average of corrected MPs reflect their volume and abundance detailed in Table 2. Through monthly boxplots, it was possible to verify that January stands out from the other months due to the higher median value, conversely, September has a lower median value compared to the other months (Figure 3).

Table 2. Abundance of microplastics per month in surface water from Paraíba River estuary, northeast Brazil.

Month	MPs in samples	Total corrected	Average corrected	Vol (m^3)	Total MP/m^3
Mar	37	28.67	5.73 ± 8.14	13.64	2.10
Apr	33	30.67	6.13 ± 2.82	19.17	1.60
May	49	48.33	9.67 ± 7.95	18.36	2.63
Jun	13	12.67	2.53 ± 1.19	20.38	0.62
Jul	31	30.33	6.07 ± 3.10	19.34	1.57
Aug	31	31.00	6.20 ± 1.92	22.99	1.35
Set	8	8.00	1.60 ± 1.52	23.99	0.33
Oct	41	40.67	8.13 ± 6.13	20.39	1.99
Nov	48	48.00	9.60 ± 2.41	10.65	4.51
Dec	17	17.00	3.40 ± 2.30	17.37	0.98
Jan	78	78.00	15.60 ± 6.35	16.40	4.76
Feb	57	57.00	11.40 ± 3.20	20.56	2.77

Source: Authors (2022).

Figure 3. Occurrence of microplastics by month in surface waters from Paraíba River estuary, northeast Brazil.



Source: Authors (2022).

According to the ANOVA results it was possible to verify there was an evident and significant difference in the average monthly MPs abundance (Table 3).

Table 3. One-way ANOVA of microplastics average monthly abundance in surface water from Paraíba River estuary, northeast Brazil.

Source of variation	DF	SS	MS	F-value	P-value
Treatment	11	870.265	79.115	3.7041	<0.001*
Residuals	48	1025.232	21.359	-	-
Total	59	1895.497	100.474	-	-

Source: Authors (2022).

As the one-way ANOVA was significant, a Tukey *post-hoc* test revealed significant pairwise differences between January that was statistically different from June, September and December (Table 4).

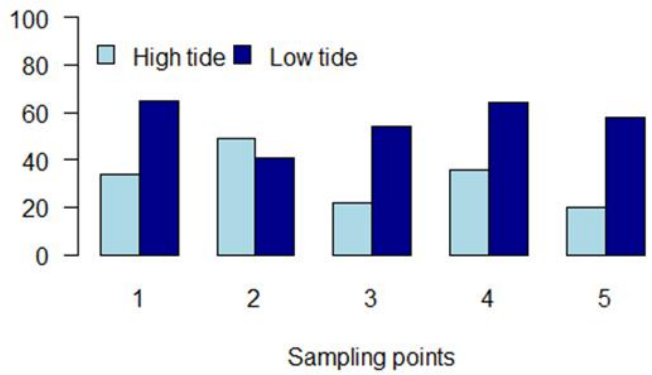
Table 4. Tukey's multiple comparisons for the average abundance of microplastics in the surface water from Paraíba River estuary, northeast Brazil.

Pairs with significant difference	Q	p-value
Jan and Jun	6.3218	<0.01
Jan and Sep	6.7736	<0.01
Jan and Dez	5.9028	<0.01

Source: Authors (2022).

The t-test revealed no significant difference in mean MPs between the dry and rainy periods ($t = 0.189$; $p > 0.05$). In contrast, a significant difference in abundance was found when considering tide height at the five sampling points, with a greater abundance at low tide compared to high tide ($t = - 2.9468$; $p = 0.042$) (Figure 4).

Figure 4. Abundance of microplastics in surface water during high and low tides at sampling points in Paraíba River estuary, northeast Brazil.



Source: Authors (2022).

4. Discussion

Microplastic influence

Numerous factors regulate the distribution patterns of microplastics in coastal ecosystems, such as the density and size of the solid waste, winds, ocean currents, geography of the coast and urbanization, leading to variable degrees of accumulation (Barnes et al., 2009; Kukulka et al., 2012). Moreover, the complex circulation dynamics of estuarine water due to tidal currents and River outflow can cause the resuspension of MPs in sediments and the water column, contributing to their accumulation in surface waters, as reported by Sadri & Thompson (2014) and Zhao et al. (2015). These dynamics certainly contributed to the spatiotemporal variation in the incidence of MPs in the downstream surface water of the Paraíba River estuary demonstrated in the present study.

The present results demonstrate worrisome contamination in this estuarine ecosystem, considering the accumulation of these pollutants and their impact on the food web in the form of direct and indirect ingestion by fishes (Wright et al., 2013;

Prata et al., 2020). Alves et al. (2016) proved that *Atherinella brasiliensis*, which is a common resident of this estuary, accidentally ingests MPs, confusing the particles for oligochaetes. Analyzing the fish assemblage of the Paraíba River estuary, Vendel et al. (2017) demonstrated the ingestion of 1.06 ± 0.30 items/fish, independently of size, functional group or trophic guild. Güven et al. (2017) reported the ingestion of 2.36 items/fish, with trophic level independent of the concentration of MPs. Amorim et al. (2020) reported the ingestion of 1.31 ± 0.52 items/fish. This reflects the importance of the ecosystem, the quality of which certainly exerts an impact on the life cycles of the diverse organisms that use the estuary.

The predominance of blue fibers (51%) is likely related to the contamination of the estuary by domestic sewage (Browne et al., 2011) and fishing gear (Cole et al., 2011), which are sources of colored fibers derived mainly from the washing of clothes and the degradation of nets and ropes used in fishing activities (Zhao et al., 2015). However, fragments (48%) were also found and the degradation and fragmentation of larger plastic waste could have contributed to the presence of this type of MPs (Cole et al., 2011; Eerkes-Medrano et al., 2015). The predominance of fibers has been described in many previous studies (Thompson et al., 2004; Desforges et al., 2014; Martinelli Filho & Monteiro, 2019; Schönlau et al., 2020; Napper et al., 2021). Attributing the high abundance of MPs to fishing activities is also common in studies that investigate MPs in the aquatic environment (Cardozo et al., 2018; Zhu et al., 2018; Zhang et al., 2021).

With the increasing demand for marine sources adjacent to the coast, there are concerns regarding food security and human health due to the consumption of this relatively low-cost protein. Ferreira et al. (2018) report that fishes of higher trophic levels are the main targets of fishing operations and are also the most susceptible to contamination through the bio transference of MPs from prey to predator. This can generate higher levels of contamination among top predators, which are consumed more by humans. Thus, humans are often exposed to MPs from the most diverse origins, as particles are widely distributed and they can be ingested or inhaled through foods, the air and beverages, including treated water.

Ferraz et al. (2020) quantified 105.8 MPs/L in water from eight residences along the Sinos River, Rio Grande do Sul State, southern Brazil, which was only a little less than one-third of the mean concentration of MPs found in the water from the river (330.2 items/L). Pivokonsky et al. (2018) found a mean abundance of MPs ranging from 338 ± 76 to 628 ± 28 items/L in treated water from three treatment stations, receiving different types of water bodies located in urban areas of the Czech Republic. It is not yet known whether or how these particles can pass through epithelial barriers and affect human health. However, these data cannot be ignored, as they indicate an important source of contamination for humans. Novel solutions for mitigating such contamination in water bodies have been proposed, such as the creation of a "liquid magnet" consisting of magnetized iron oxide and vegetable oil that attracts MPs from the water through magnetism (Olsen, 2021a) and a filtering system that retains MPs particles at water treatment stations, considerably diminishing the concentration of MPs in drinking water (Olsen, 2021b), such innovations are imminent and very welcome.

Since the background air contamination is difficult to avoid, to use procedural blanks is essential to quantify, the fibers coming from air contamination, so that we need enough blank samples to reliably measure this expected variance (Fries et al., 2013). Regarding this, in March, first month of screening, the MPs in the samples blanks was greater, but as soon as possible, this must be totally resolved and that is exactly what happened here. This confirms the importance of considering the analysis and the correction to the number of MPs according to the blank. Such an approach increases the fidelity in the abundance of MPs, in any compartment where the research is carried out, be in the abiotic or biological samples (Paiva et al., 2022).

The mean abundance of MPs in the downstream waters of the Paraíba River estuary was high, but the lack of data on contamination by MPs impedes a more precise regional comparison regarding temporal and spatial levels. However, comparing the abundance of MPs with values reported in other studies using the same sampling method (plankton net), such as in the estuary of the Goiana River in Pernambuco State, northeast Brazil (0.26 items/m^3) (Lima et al., 2014), the English

Channel (0.27 items/m^3) (Cole et al., 2014) and the Bohai Sea, China (0.33 ± 0.36 items/m^3) (Zhang et al., 2017), the abundance in the present study was higher than that found for the Tamar Estuary in England (0.028 itens/m^3) (Sadri & Thompson, 2014) and lower than that found in Guanabara Bay, Rio de Janeiro State, southeast Brazil (4.8 items/m^3) (Figueiredo & Vianna, 2018) and on the coast of Weihai, China (5.9 ± 3.5 items/m^3) (Zhang et al., 2021).

Anyway particles were found in all samples, confirming the high incidence of MPs in the surface waters of the estuary. The highest abundance was found in January, with low incidence of rainfall in the region (Dolbeth et al., 2016). High median values of MPs were observed from October onwards, especially in January, and could be associated with the post-rainy season period, whose solid waste input is notably higher downstream in the estuary. Summer and the arrival of the vacation period also represent a period of greater flow of people and, consequently, greater release of domestic sewage. In contrast, the significantly low abundance of MPs in September could possibly be associated with the oil spill that occurred on the northeast coast of Brazil in the middle of 2019 and recorded in the Paraíba State at the beginning of September, which coincided with the sampling period in the estuary. This oil hindered the clear viewing of MPs in the five samples and contributed to the low number of particles recorded in the month. According to Araújo et al. (2021) and Câmara et al. (2021), approximately 100 tons of crude oil spread over more than 3000 km, polluting 132 beaches in nine Brazilian states. More than a year after this incident, its causes are under confidential investigation and remain unknown; despite hypotheses about the origin of the oil, there has been no definite cause yet declared (Câmara et al., 2021). Oil spills occur on a daily basis and months are required for seawater to return to its original condition and the adsorption of crude oil to MPs has also been demonstrated experimentally (Yap & Tan, 2021).

Influence of abiotic factors

Winds can contribute to the concentration and distribution of MPs in estuaries (Vermeiren et al., 2016). With the increase in speed, the tension of winds results in a mixture of plastic debris floating on the surface and distributed vertically in the water column. Concentrations of microplastics on the sea surface are reported to be smaller under conditions of strong winds (Kukulka et al., 2012). In periods of rainfall and at high tide, concentrations of MPs can increase due to the fact that the rain increases the transport of debris from rivers into the estuary and the particles can be returned to the estuary with the incoming tide (Sadri & Thompson, 2014; Figueiredo & Vianna, 2018). In the present study, however, the highest record of MPs occurred at low tide, which is similar to findings described by Rowley et al. (2020) and Chinfak et al. (2021). This suggests that the rivers carry significant concentrations of particles into the estuary (Chinfak et al., 2021) and the concentrations are lower at high tide due to the input of seawater, which has fewer urban contaminants (Sutton et al., 2016). No significant association was found between the other abiotic factors investigated and the distribution of MPs in the surface water of the estuary.

The considerable incidence of MPs may be influenced by the rivers that flow into the Paraíba River estuary, which suffer from the impacts of urbanization throughout the entire year. Rivers are widely reported to be the main means of the transport of MPs from the mainland to coastal seas (Eerkes-Medrano et al., 2015; Lebreton et al., 2017; Martinelli Filho & Monteiro, 2019), transporting 70 to 80% of the plastic debris found in the marine environment (Carvalho et al., 2021). The tributaries of the Paraíba River carry domestic and industrial debris (Guedes, 2002) to the mouth of the river. This estuarine region is also impacted by domestic sewage as well as materials used on sugarcane plantations and shrimp farms (Marcelino et al., 2005; Dolbeth et al., 2016; Teixeira et al., 2020).

As the present results demonstrate high contamination of the water of the Paraíba River estuary, more in-depth studies are needed along the drainage basin, as broader samples in terms of time and space contribute to the assessment of the water quality of the environment being studied (Zhao et al., 2015). It is important to prioritize the continual assessment of water quality with a standardized volume of filtered water and mesh size, which will consequently furnish a good comparative parameter to assist in the management and control of the contamination of the estuary. The present investigation is the first on the occurrence of microplastics in surface waters of the Paraíba River estuary, making an important contribution to raise awareness regarding local contamination and encourage conscious management to ensure water quality in this estuary.

5. Conclusion

The analysis of the occurrence and distribution of microplastics in surface waters of the Paraíba River estuary revealed a considerable incidence of pollution by these particles. The contamination found in the samples was considered elevated, with the incidence of MPs inversely proportional to local precipitation and tide height. This first investigation on surface estuarine waters underscores the need for the urgent implementation of mitigating measures to reduce local pollution in this ecosystem.

In addition to implementing measures to reduce the release of solid waste into the environment, regular monitoring of the site is necessary, as well as expanding this assessment protocol to the sediment, the water column and even in the ingestion of PM by fish species, especially estuary residents. Furthermore, future assessment studies should include a larger area to confirm the effectiveness of actions focused on the control of water quality, especially in urbanized estuaries.

Acknowledgments

The authors thank Patricia Keytth Lins Rocha, Jicaury Roberta Pereira da Silva and Summeya Jedha Leão França for helping in field sampling and technical support.

References

Alvares, C. A., Stape J. L., Sentelhas, P. C., Moraes Gonçalves, J. L., & Sparovek, G. (2013). Koppen's climate classification map for Brazil. *Meteorologische Zeitschrif,* 22(6):711-728. http://dx.doi.org/10.1127/0941-2948/2013/0507

Alves, V. E., Patrício, J., Dolbeth, M., Pessanha, A., Palma, A. R. T., Dantas, E. W., & Vendel, A. L. (2016). Do different degrees of human activity affect the diet of brazilian silverside *Atherinella brasiliensis*? *Journal Fish Biology,* 89(2):1239-1257. https://doi.org/10.1111/jfb.13023

Amorim, A. L. A., Ramos, J. A. A., Nogueira Júnior, M. (2020). Ingestion of microplastic by ontogenetic phases of *Stellifer brasiliensis* (Perciformes, Sciaenidae) from the surf zone of tropical beaches. *Marine Pollution Bulletin,* 158:111214. https://doi.org/10.1016/j.marpolbul.2020.111214

Andrady, A. L. 2011. Microplastics in the marine environment. *Marine Pollution Bulletin,* 62:1596-1605. https://doi.org/10.1016/j.marpolbul.2011.05.030

Araújo, K. C., Barreto, M.C., Siqueira, A.S., Freitas, A.C.P., Oliveira, L.G., Bastos, M.E.P.A., Rocha, L.A., & Fragoso, W.D. (2021). Oil spill in northeastern Brazil: application of fluorescence spectroscopy and PARAFAC in the analysis of oil-related compounds. C*hemosphere*. 267:129-154. http://dx.doi.org/10.1016/j.chemosphere.2020.129154

Arthur, C., Baker, J., & Bamford, H. (2009). Proceedings of the international research workshop on the occurrence, effects, and fate of microplastic marine debris. September 9-11, 2008. NOAA Technical Memorandum NOS-OR & R-30. https://repository.library.noaa.gov/view/noaa/2509

Barnes, D. K. A., Galdani, F., Thompson, R.C., & Barlaz, M. (2009). Accumulation and fragmentation of plastic debris in global environments. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 364:1985-1998. https://doi.org/10.1098/rstb.2008.0205

Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., & Thompson, R. (2011). Accumulation of Microplastic on Shorelines Woldwide: Sources and Sinks. *Environmental Science & Technology.* https://doi.org/10.1021/es201811s

Câmara, S.F., Pinto, F.R., Da Silva, F.R., Soares, M.O., De Paula, T.M. (2021). Socioeconomic vulnerability of communities on the Brazilian coast to the largest oil spill (2019-2020) in tropical oceans. *Ocean & Coastal Management,* 202:105-506. https://doi.org/10.1016/j.ocecoaman.2020.105506

Cardozo, A.L.P., Farias, E.G.G., Rodrigues-Filho, J.L., Monteiro, I.B., Scandolo, T.M., & Dantas, D.V. (2018). Feeding ecology and ingestion of plastic fragments by Priacanthus arenatus: What's the fisheries contribution to the problem? *Marine Pollution Bulletin*, 130:19-27. https://doi.org/10.1016/j.marpolbul.2018.03.010

Carvalho, A.R., Garcia, F., Riem-Galliano, L., Tudesque, L., Albignac, M., Halle, A.T., & Cucherousset, J. (2021). Urbanization and hydrological conditions drive the spatial and temporal variability of microplastic pollution in the Garonne River. *Science of The Total Environment,* 769:144-479. https://doi.org/10.1016/j.scitotenv.2020.144479

Chinfak, N., Sompongchaiyakul, P., Charoenpong, C., Shi, H., Yeemin, T., & Zhang, J. (2021). Abundance, composition, and fate of microplastics in water, sediment, and shellfish in the Tapi-Phumduang River system and Bandon Bay, Thailand. *Science of The Total Environment*, 781:146-700. https://doi.org/10.1016/j.scitotenv.2021.146700

Claessens, M., De Meester, S., Landuyt, L.V., De Clerck, K., & Janssen, C.R. (2011). Occurrence and distribution of microplastics in marine sediments along the Belgian coast. *Marine Pollution Bulletin,* 62:2199-2204. https://doi.org/10.1016/j.marpolbul.2011.06.030

Cole, M., Lindeque, P., Fileman, E., Halsband, C., Goodhead, R., Moger, J., & Galloway, T. S. (2013). Microplastic ingestion by zooplankton. *Royal Society B: Biological Sciences,* 47:6646-6655. https://doi.org/10.1021/es400663f

Cole, M., Lindeque, P., Halsband, C., & Galloway, T.S. (2011). Microplastics as contaminants in the marine environment: a review. *Marine pollution bulletin*, 62:2588-2597. http://dx.doi.org/10.1016/j.marpolbul.2011.09.025

Cole, M., Webb, H., Lindeque, P. K., Fileman, E. S., Halsband, C., & Galloway, T.S. (2014). Isolation of microplastics in biota-rich seawater samples and marine organisms. *Scientific Reports*, https://doi.org/10.1038/srep04528

Derraik, J. G. B. (2002). The pollution of the marine environment by plastic debris: a review. *Marine Pollution Bulletin,* 44:842-52. https://doi.org/10.1016/S0025-326X(02)00220-5

Desforges, J.P.W., Galbraith, M., Dangerfield, N., & Ross, P.S. (2014). Widespread distribution of microplastics in subsurface seawater in the NE Pacific Ocean. *Marine Pollution Bulletin,* 79:94-99. https://doi.org/10.1016/j.marpolbul.2013.12.035

Dolbeth, M., Vendel, A.L., Pessanha, A., & Patrício, J. (2016). Functional diversity of fish communities in two tropical estuaries subjected to anthropogenic disturbance. *Marine Pollution Bulletin*, 112:244-254. https://doi.org/10.1016/j.marpolbul.2016.08.011

Eerkes-Medrano, D., Thompson, R.C., & Aldridge, D.C. (2015). Microplastics in freshwater systems: a review of the emerging threats, identification of knowledge gaps and prioritization of research needs. *Water Research*, 75:63-82. http://dx.doi.org/10.1016/j.watres.2015.02.012

Elliott, M., Whitfield, A.K., Potter, I.C., Blaber, S.J.M., Cyrus, D.P., Nordlie, F.G., & Harrison, T.D. (2007). The guild approach to categorizing estuarine fish assemblages: a global review. *Fish and Fisheries*, 8:241-268. https://doi.org/10.1111/J.1467-2679.2007.00253.X

Fabra, M., Williams, L., Watts, J.E.M., Hale, M.S., Couceiro, F., & Preston, J. (2021). The plastic Trojan horse: Biofilms increase microplastic uptake in marine filter feeders impacting microbial transfer and organism health. *Science of The Total Environment*, 797:149-217, https://doi.org/10.1016/j.scitotenv.2021.149217

Ferraz, M., Bauer, A.L., Valiati, V.H., & Schulz, U.H. (2020). Microplastic Concentrations in Raw and Drinking Water in the Sinos River, Southern Brazil. *Water*, https://doi.org/10.3390/w12113115

Ferreira, G.V.B., Barletta, M., Lima, A.R.A., Morley, S.A., Justino, A.K.S., & Costa, M.F. (2018). High intake rates of microplastics in a Western Atlantic predatory fish, and insights of a direct fishery effect. *Environmental Pollution*, 236:706-717. https://doi.org/10.1016/j.envpol.2018.01.095

Ferreira, P.V.C., Amorim, A.L.A., Pessoa, W.V.N., & Ramos, J.A.A. (2017). Influência das fases da lua na abundância de Larimus breviceps na zona de arrebentação da praia de Miramar-PB. *Principia*, 36:107-115.

Figueiredo, G. M., & Vianna, T. M. P. (2018). Suspended microplastics in a highly polluted bay: Abundance, size, and availability for mesozooplankton. *Marine Pollution Bulletin*, 135:256-265. https://doi.org/10.1016/j.marpolbul.2018.07.020

Fries, E‡., Dekiff, J. H., Willmeyer, J., Nuelle, M-T., Ebertc, M., & Remy, D. (2013). Identification of polymer types and additives in marine microplastic particles using pyrolysis-GC/MS and scanning electron microscopy†. *Environmental Science Processes & Impacts*, 15, 1949–1956. https://doi.org/10.1039/C3EM00214D

Guedes, L. S. (2002). Monitoramento geoambiental do estuário do rio Paraíba do norte-PB por meio da cartografia temática digital e de produtos de sensoriamento remote. [Master's thesis, University Federal do Rio Grande do Norte]. Campus Repository. https://repositorio.ufrn.br/jspui/handle/123456789/18745

Güven, O., Gökdağ, K., Jovanović, B., & Kıdeyş, A. E. (2017). Microplastic litter composition of the Turkish territorial waters of the Mediterranean Sea, and its occurrence in the gastrointestinal tract of fish. *Environmental Pollution*, 223:286-294. https://doi.org/10.1016/j.envpol.2017.01.025

IBGE- Instituto Brasileiro de Geografia e Estatística. (2021). Censo demográfico 2010. https://cidades.ibge.gov.br/

Ivar do Sul, J. A., & Costa, M. F. (2013). Plastic pollution risks in an estuarine conservation unit. *Journal of Coastal Research*, 65:48-53.

Ivar do Sul, J. A., & Costa, M. F. (2014). The present and future of microplastic pollution in the marine environment. *Environmental Pollution,* 185:352-64. https://doi.org/10.1016/j.envpol.2013.10.036

Ivleva, N.P., Wiesheu, A.C., & Niessner, R. (2017). Microplastic in Aquatic Ecosystems. *Angewandte Chemie International Edition*, 56(7):1720-1739. https://doi.org/10.1002/anie.201606957

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., & Law, K.L. (2015). Plastic waste inputs from land into the ocean. *Science*, 347:768-771. https://doi.org/10.1126/science.1260352

Kukulka, T., Proskurowski, G., Morét-Ferguson, S., Meyer, D.W., & Law, K.L. (2012). The effect of wind mixing on the vertical distribution of buoyant plastic debris, *Geophysical Research Letters*, 39:L07601. http://dx.doi.org/10.1029/2012GL051116

Lebreton, L.C.M., Zwet, J.V.D., Damsteeg, J.W., Slat, B., Andrady, A., & Reisser, J. (2017). River plastic emissions to the world's oceans. *Nature Communications*, 8:15611. https://doi.org/10.1038/ncomms15611

Lima, A.R.A., Costa, M.F., & Barletta, M. (2014). Distribution patterns of microplastics within the plankton of a tropical estuary. *Environmental Research,* 132:146-155. https://doi.org/10.1016/j.envres.2014.03.031

Lusher, A.L., Welden, N.A., Sobral, P., & Cole, M. (2017). Sampling, isolating and identifying microplastics ingested by fish and invertebrates. *Analytical Methods* 9:1346. https://doi.org/10.1039/C6AY02415G

Mangas, A.P., Da Silva, A.C., Ferreira, S.C.G., Palheta, G.D.A., & De Melo, N.F.A.C. (2013). Ictioplâncton da baía do Guajará e do estuário do rio Pará, ilha do Marajó, Pará, Brasil. *Boletim Técnico Científico do Cepnor*, 13:43-54. http://dx.doi.org/.10.17080/1676-5664/btcc.v13n1p43-54

Marcelino, R.L., Sassi, R., Cordeiro, T.A., & Costa, C.F. (2005). Uma abordagem socioeconômica e sócio-ambiental dos pescadores artesanais e outros usuários ribeirinhos do estuário do rio Paraíba do Norte, Estado da Paraíba. *Tropical Oceanography*, 33:179-192. http://dx.doi.org/10.5914/tropocean.v33i2.5061

Martinelli Filho, J. E., & Monteiro, R. C. P. (2019). Widespread microplastics distribution at an Amazon macrotidal sandy beach. *Marine Pollution Bulletin*, 145:219-223. https://doi.org/10.1016/j.marpolbul.2019.05.049

Miranda, D. A., & De Carvalho-Souza, G. F. (2016). Are we eating plastic-ingesting fish? *Marine Pollution Bulletin*, 103: 109-114. https://doi.org/10.1016/j.marpolbul.2015.12.035

Napper, I.E., Baroth, A., Barrett, A.C., Bhola, S., Chowdhury, G.W., Davies, B.F.R., Duncan, E.M. Kumar, S., Nelms, S.E., Niloy, M.N.H., Nishat, B., Maddalene, T., Thompson, R.C., & Koldewey, H. (2021). The abundance and characteristics of microplastics in surface water in the transboundary Ganges River. *Environmental Pollution,* 274:116348. https://doi.org/10.1016/j.envpol.2020.116348

Nishida, A.K., Nordi, N., & Alves, R.R.N. (2008). Aspectos socioeconômicos dos catadores de moluscos do litoral paraibano, Nordeste do Brasil. *Revista de Biologia e Ciências da Terra.*

Oehlmann, J., Schulte-Oehlmann, U., Kloas, W., Jagnytsch, O., Lutz, I., Kusk, K.O., Wollenberger, L., Santos, E.M., Paull, G.C., Van Look, K.J.W., & Tyler, C.R. (2009). Critical analysis of the biological impacts of plasticizers on wildlife. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 364:2047-2062. https://doi.org/10.1098/rstb.2008.0242

Olsen, N. (2021a, 1 de setembro). Estudante irlandês cria "imã" que atrai microplásticos. Ciclo vivo. https://ciclovivo.com.br/inovacao/inspiracao/estudante-irlandes-cria-ima-que-atrai-microplasticos/?noamp=mobile

Olsen, N. (2021b). Brasileiro ganha prêmio internacional por sistema que filtra microplásticos. Ciclo vivo. https://ciclovivo.com.br/inovacao/inspiracao/brasileiro-ganha-premio-internacional-por-sistema-que-filtra-microplasticos/

Paiva, B.O., De Souza, A.K.M., Soares, P.L., Palma, A.R.T., & Vendel, A.L. (2022). Control of Airborne Contamination in Laboratory Analyses of Microplastics. *Brazilian Archives of Biology and Technology*, 65. https://doi.org/10.1590/1678-4324-2022210399

Pessoa, W.V.N., Ramos, J.A.A., & Oliveira, P.G.V. (2019). Composition, density and biomass of fish community from the surf zone as a function of the lunar cycle at Miramar Beach in Cabedelo, Paraíba. *Neotropical Ichthyology*, 17(2):e170042. https://doi.org/10.1590/1982-0224-20170042

Pivokonsky, M., Cermakova, L., Novotna, K., Peer, P., Cajthaml, T., & Janda, V. (2018). Occurrence of microplastics in raw and treated drinking water. *Science of The Total Environment,* 643:1644-1651. https://doi.org/10.1016/j.scitotenv.2018.08.102

Plastics Europe. (2020). Association of Plastics Manufactures. Plastics - the Facts 2020: An analysis of European plastics production, demand and waste data. https://www.plasticseurope.org/en/resources/publications/4312-plastics-facts-2020

Prata, J.C., Castro, J.L., Da Costa, J.P., Duarte, A.C., Rocha-Santos, T., & Cerqueira, M. (2020). The importance of contamination control in airborne fibers and microplastic sampling: Experiences from indoor and outdoor air sampling in Aveiro, Portugal. *Marine Pollution Bulletin,* 159:111-522. https://doi.org/10.1016/j.marpolbul.2020.111522

Rochman, C.M., Hoh, E., Kurobe, T., & The, S.J. (2013). Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. *Scientific reports,* 3(1):1-7. https://doi.org/10.1038/srep03263

Rowley, K.H., Cucknell, A.C., Smith, B.D., Clark, P.F., & Morritt, D. (2020). London's river of plastic: High levels of microplastics in the Thames water column. *Science of The Total Environment*, 740(20):140018. https://doi.org/10.1016/j.scitotenv.2020.140018

Ryan, P. G., Moore, C. J., Franeker, A. A. V., & Moloney, C. L. (2009). Monitoring the abundance of plastic debris in the marine environment. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 364:1999-2012. https://doi.org/10.1098/rstb.2008.0207

Sadri, S. S., & Thompson, R. C. (2014). On the quantity and composition of floating plastic debris entering and leaving the Tamar Estuary, Southwest England. *Marine Pollution Bulletin,* 81:55-60. https://doi.org/10.1016/j.marpolbul.2014.02.020

Santana, L.M.B.M., Costa, L.V., & Abessa, D.M.S. (2015). A Contaminação antrópica e seus efeitos em três estuários do litoral do Ceará, Nordeste do Brasil – Revisão. *Arquivos de Ciências do Mar,* 48(2):93-115. http://www.periodicos.ufc.br/arquivosdecienciadomar/article/view/5853

Schönlau, C., Karlsson, T.M., Rotander, A., Nilsson, H., Engwall, M., Bavel, B.V., & Kärrman, A. (2020). Microplastics in sea-surface waters surrounding Sweden sampled by manta trawl and in-situ pump. *Marine Pollution Bulletin*, 153:111-019. https://doi.org/10.1016/j.marpolbul.2020.111019

Senathirajah, K., Attwood, S., Bhagwat, G., Carbery, M., Wilson, S., & Palanisami, T. (2021). Estimation of the mass of microplastics ingested – A pivotal first step towards human health risk assessment. *Journal of Hazardous Materials,* 404:124-004. https://doi.org/10.1016/j.jhazmat.2020.124004

Shen, M., Zhang, Y., Zhu Y., Song, B., Zeng, G., Hu, D., Wen, X., & Ren, X. (2019). Recent advances in toxicological research of nanoplastics in the environment: a review. *Environmental Pollution*, 252:511-521. https://doi.org/10.1016/j.envpol.2019.05.102

Sutton, R., Mason, S.A., Stanek, S.K., Willis-Norton, E., Wren, I.F., & Box, C. (2016). Microplastic contamination in the San Francisco Bay, California, USA. *Marine Pollution Bulletin*, 109:230-235. https://doi.org/10.1016/j.marpolbul.2016.05.077

Teixeira, Z., Vital, S.R.O., Vendel, A.L., Mendonça, J.D.L., & Patrício, J. (2020). Introducing fuzzy set theory to evaluate risk of misclassification of land cover maps to land mapping applications: Testing on coastal watersheds. *Ocean & Coastal Management*, 184:0964-5691. https://doi.org/10.1016/j.ocecoaman.2019.104903

Thompson, R.C., Moore, C.J., Vom Saal, F.S., & Swan, S.H. (2009). Plastics, the environment and human health: current consensus and future trends. *Philosophical Transactions of The Royal Society Biological Sciences*, 1:1-14. https://doi.org/10.1098/rstb.2009.0053

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., Mcgonigle, D., & Russel, A.E. (2004). Lost at sea: where is all the plastic? *Science*, 304:838. https://doi.org/10.1126/science.1094559

Vendel, A.L., Bessa, F., Alves, V.E.N., Amorim, A.L.A., Patrício, J., & Palma, A.R.T. (2017). Widespread microplastic ingestion by fish assemblages in tropical estuaries subjected to anthropogenic pressures. *Marine Pollution Bulletin*, 117:448-55. https://doi.org/10.1016/j.marpolbul.2017.01.081

Vermeiren, P., Muñoz, C.C., & Ikejima, K. (2016). Sources and sinks of plastic debris in estuaries: A conceptual model integrating biological, physical and chemical distribution mechanisms. *Marine Pollution Bulletin,* 113:7-16. https://doi.org/10.1016/j.marpolbul.2016.10.002

Wang, J., Tan, Z., Peng, J., Qiu, O., & Li, M. (2016). The behaviors of microplastics in the marine environment. *Marine Environmental Research*, 113:7-17. https://doi.org/10.1016/j.marenvres.2015.10.014

Wright, S.L., Thompson, R.C., & Galloway, T.S. (2013). The physical impacts of microplastics on marine organisms: A review. *Environmental Pollution*, 178:483-492. https://doi.org/10.1016/j.envpol.2013.02.031

Yap, K. Y., & Tan, M. C. (2021). Oil adsorption onto different types of microplastic in synthetic seawater. *Environmental Technology & Innovation*, 24:101-994. https://doi.org/10.1016/j.eti.2021.101994

Zhang, W., Zhang, S., Wang, J., Wang, Y., Mu, J., Wang, P., Lin, X., & Ma, D. (2017). Microplastic pollution in the surface waters of the Bohai Sea, China. *Environmental Pollution,* 231:541-548. https://doi.org/10.1016/j.envpol.2017.08.058

Zhang, X., Li, S., Liu, Y., Yu, K., Zhang, H., Yu, H., & Jiang, J. (2021). Neglected microplastics pollution in the nearshore surface waters derived from coastal fishery activities in Weihai, China. *Science of The Total Environment*, 769: 144-484. https://doi.org/10.1016/j.scitotenv.2020.144484

Zhao, S., Zhu, L., & Li, D. (2015). Microplastic in three urban estuaries, China. *Environmental Pollution*, 206:597-604. https://doi.org/10.1016/j.envpol.2015.08.027

Zhu, L., Bai, H., Chen, B., Sun, X., Qu, K., & Xia, B. (2018). Microplastic pollution in North Yellow Sea, China: Observations on occurrence, distribution and identification. *Science of The Total Environment*, 636:20-29. https://doi.org/10.1016/j.scitotenv.2018.04.182