

Research article

Comprehensive risk assessment of microplastics in tidal channel sediments in amazonian mangroves (northern Brazil)

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ABSTRACT

Pollution by microplastics (MPs) in mangroves is a growing concern, given its potential ecological and human health impacts. The characteristics of microplastic pollution and a risk assessment of MPs in the Amazon region's coastal sediments are still insufficient, and information about MP pollution in the benthic component of the mangrove ecosystem is lacking. We analyzed MP concentrations in the surface sediment of 9 stations in three tidal channels along the Ajuruteua Peninsula connected to the Caeté River estuary, aiming to assess the hazard level on the environment based on the Pollution Load Index (PLI). Raman and Fourier transform infrared spectroscopy determined the MP's chemical composition. The results showed that the abundance of sediment MPs ranged from 100 to 1200 items kg⁻¹, with an average of 433 ± 261.6 items kg⁻¹. The MPs were mainly composed of transparent and blue fragments and fibers, ranging in size from 100 to 5000 µm. Six types of polymers were identified, including alkyd varnish (AV), resin dispersion (RD), chlorinated polyethylene (CPE), polyethylene-polypropylene (PE-PP), low-density polyethylene (LDPE), and hostaperm blue (HB). Hydrodynamic processes within estuaries and tidal channels play a crucial role in explaining the concentrations found, as circulation determines the pattern of sediment deposition and the particles adhered to it. PLI risk assessment showed that all sampling sites were at hazard level I: a low level of contamination in the mangrove sediments. However, a more comprehensive and systematic monitoring campaign is needed to expand our knowledge about pollution and contamination by MPs in Amazon mangrove areas.

1. Introduction

Microplastics (MPs) are defined as plastic particles with a size equal to or less than 5 mm (Prata et al., 2019; Sarkar et al., 2023) and are produced through primary sources (intentionally and deliberately manufactured as microscale particles) or secondary sources (resulting from the fragmentation of larger plastic debris) (Cole et al., 2011; Prata et al., 2019). Both types of MP are recognized for persisting at high levels in aquatic and marine ecosystems (Conkle et al., 2018). Primary MPs are found in personal care products (Bashir et al., 2021), biomedical products (Hwang et al., 2020) or in plastic resin for commercial use (du Bois

et al., 2021), industrial applications, as well as for air blasting and textiles (Conley et al., 2019). This material is discharged into rivers and estuaries or directly into the sea through the discharge of wastewater (Kay et al., 2018; Talvitie et al., 2017). Secondary MPs, on the other hand, originate from the fragmentation of plastic packaging and the wear and tear of fishing tackle as a result of prolonged exposure to ultraviolet (UV) light, wave action, physical abrasion by sediments, and biological degradation (Ashjar et al., 2023; Govender et al., 2020; Leads et al., 2023).

MPs are recognized, along with several new pollutants, as emerging contaminants (Anderson et al., 2018; Yin et al., 2019), and are becoming

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a growing concern worldwide due to their widespread occurrence and their adverse environmental and biological effects (Yu et al., 2023). This occurrence extends over long distances due to the action of currents and winds that facilitate the transport of MPs from terrestrial areas to their final sinks (Haque and Fan, 2023). As these particles migrate over long periods and distances, their surface tends to adsorb numerous contaminants and fouling biota, such as algae and/or invertebrate species, increasing their surface area and weight and decreasing their buoyancy. (Almeida et al., 2023). Furthermore, once MPs reach freshwater zones, they have a higher probability of sinking due to the lower water density than saltwater (Haque and Fan, 2023). This, combined with the hydrodynamics of the environment and the physical characteristics of MPs, such as density, size, and shape (Owowunu et al., 2023), results in the sinking of these particles and their subsequent accumulation in sediments (Haque and Fan, 2023). In this way, marine sediments become sinks for MPs. The presence of MPs in different compartments of marine ecosystems, including the water column (Dai et al., 2018), aquatic organisms (Nunes et al., 2023), and sediment (Zhang et al., 2022) has been widely discussed. This discussion reflects recognition of the global implications of MPs' presence on the environment and human health.

The mangrove ecosystem is one of these coastal estuarine environments that play a fundamental role as a habitat and food source for a great diversity of terrestrial and marine organisms, playing a key role in retaining sediments and solid waste suspended in the water column (Deng et al., 2020; Maghsodian et al., 2021). Mangrove areas are very important for sequestering and storing large quantities of carbon, making a major contribution to mitigating climate change and providing organic inputs for adjacent aquatic systems, including the ocean (Alongi, 2014; Eid et al., 2020). Mangroves are also considered to be natural filters that mitigate pollution in coastal areas (Maghsodian et al., 2021), as they act as a barrier preventing river pollutants from entering the ocean (Li et al., 2019; Martín et al., 2022). This includes pollution by macro- and microplastics (Yin et al., 2019) from urban or industrial environments that dump their waste through sewage and wastewater directly into the bodies of water that link the terrestrial and marine environments (Celis-Hernández et al., 2021).

Mangroves have a high potential for accumulating contaminants, such as plastics, and this is one of the main reasons for the intensification of studies on pollution or contamination by MPs in mangroves around the world (Garcés-Ordóñez et al., 2019; Huang et al., 2020; R. Li et al., 2020; Naidoo et al., 2020). Research indicates that rivers are the main route for MPs to enter the ocean, with more than 1000 rivers responsible for 80% of global annual plastic emissions. Once in coastal environments, MPs can be transported by tides and currents and accumulate in sediments or be ingested by aquatic organisms (Lima et al., 2023; Meijer et al., 2021; Peng et al., 2017). Over the last nine years, research into the presence and characterization of MPs in mangrove areas has been intensified (Mendes et al., 2023). Several studies across Asia covering countries such as Indonesia (Cordova et al., 2021; Cordova et al., 2023), Singapore (Mohamed Nor and Obbard, 2014), India (Daniel et al., 2020; Maharana et al., 2020; Radhakrishnan et al., 2021; Ranjani et al., 2021), Iran (Maghsodian et al., 2021), Malaysia (Pariatamby et al., 2020; Tan and Mohd Zanuri, 2023), Bangladesh (Sarker et al., 2022), and especially China (Deng et al., 2020; Dou et al., 2021; Hu et al., 2022; Huang et al., 2020; Jiao et al., 2022; J. Li et al., 2020; R. Li et al., 2020; Pan et al., 2021; Peng et al., 2017; Yu et al., 2023, 2022; Zhang et al., 2020, 2017; Zhou et al., 2020; Zuo et al., 2020) investigate the presence of MPs in mangrove sediments. In the latter country, China, we observed a variation in the average abundance of MPs, ranging from 42.9 ± 26.8 items/kg to 3000 particles/kg (Mendes et al., 2023).

Mangroves along the coasts of countries such as Brazil, Mexico, Colombia, Peru, Jamaica, and the United States face significant challenges related to MP contamination (Aguirre-Sanchez et al., 2022; Celis-Hernández et al., 2021; Garcés-Ordóñez et al., 2019; Helcoski et al., 2020; Paes et al., 2022; Rose and Webber, 2019; Zamprogno et al., 2021). Urbanization, industrial activities, and inadequate waste

management contribute to introducing MPs into this ecosystem (Bratovic et al., 2022). In Todos os Santos Bay, Brazil, MPs were found in all mangrove sediment samples, averaging $10,782 \pm 7671$ items/kg and exceeding any other global MP pollution value reported for mangrove sediments (Paes et al., 2022). On the Brazilian Amazon coast, for example, research has been published on MP pollution in fish (Andrade et al., 2019; Pegado et al., 2018; Pegado et al., 2021), mussels (Rodrigues et al., 2024), in oysters (Pantoja et al., 2024), in water samples from the continental shelf (Queiroz et al., 2022), beach sediment (Martinelli Filho and Monteiro, 2019) and river sediment and water (Gerolin et al., 2020; Rico et al., 2023).

Contamination by MPs has become a relevant cause for concern, both due to its environmental impacts and the health of organisms, especially fish, which constitute the basis of food for Amazonian populations. The Amazon region is particularly important as it is home to the planet's greatest diversity of freshwater fish (de Souza et al., 2023). However, the effects of chemical compounds in plastic waste on the health of populations that consume these contaminated fish are still unknown (de Souza et al., 2023). On the other hand, the population increase in coastal urban areas has contributed to a more significant release of pollutants into bodies of water and adjacent mangrove areas (de Souza et al., 2023; Pantoja et al., 2024). On the Amazon coast, several fishing communities depend on capturing organisms for artisanal, commercial, and subsistence purposes (de Jesus et al., 2024; de Souza et al., 2023). However, these resources become more susceptible to contamination by MPs due to the distribution and/or accumulation of large quantities adsorbed in the bottom sediments from turbidity currents (Pohl et al., 2020). Some studies have investigated the role of turbidity currents in the transport of MPs and their influence on the differential deposition of particles, such as fragments and fibers. The results indicate that currents can potentially distribute significant amounts of MPs in seafloor sediments (Pohl et al., 2020). In another study, the results indicated that mangroves played a role in intercepting MPs, influenced not only by tides but also by human activities, such as aquaculture and disorderly occupation (Zhang et al., 2022).

The ability of MPs to concentrate on their surface other organic pollutants and heavy metals, as well as their resistance to degradation, means that the accumulation of MPs in sediments represents a threat to marine and human life (Yuan et al., 2022) since the ingestion of MPs has been observed in a series of commercial interest animals consumed by the human population as a source of protein, including fish, crustaceans, and mollusks. Thus, the aim of this study was i) to investigate the abundance and spatial distribution of MPs in the sediments of tidal channels in mangrove areas on the Ajuruteua Peninsula, on the coast of the state of Pará, northern Brazil, ii) to investigate whether hydrodynamic processes influence the distribution of MPs in the sediment, and iii) to carry out a risk assessment of pollution by MPs in the sediments of Amazonian mangroves. The results of this study provide a basis for a better understanding of the state and risk of MP pollution. They will also help support measures to prevent and mitigate negative impacts, helping to develop public policies and strategies to conserve mangroves and all the associated terrestrial and aquatic biodiversity and the food security of traditional communities living on the Brazilian Amazon coast.

2. Materials and methods

2.1. Study area

The study area is located on the Brazilian equatorial continental margin, 300 km southeast of the mouth of the Amazon River and 200 km east of Belém, the capital of the state of Pará. The estuaries in this region are generally extensive, entering more than 100 km towards the mainland, and include coastal plains that can be up to 30 km wide (Souza-Filho et al., 2009). The focal area of this study is the Ajuruteua Peninsula, specifically three tidal channels that cut across the peninsula (SE-NW) at differing distances from the mainland (Fig. 1), which is part

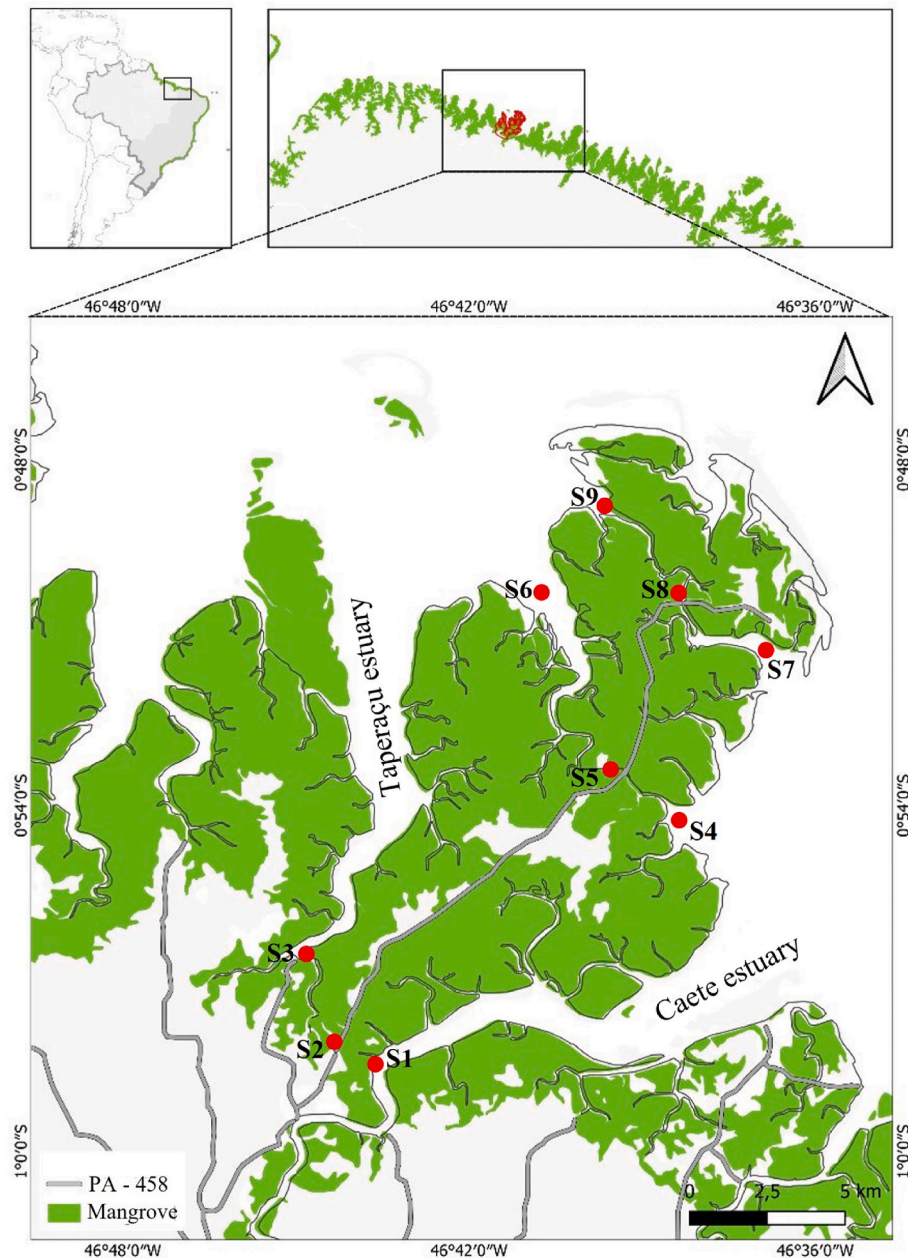


Fig. 1. Study area and location of the nine sediment sampling stations in the mangrove tidal channels on the Ajuruteua Peninsula (S1–S3, Furo do Taici; S4–S6, Furo do Meio and S7–S9, Furo Grande), Bragança-Pará, Brazil.

of the Caeté-Taperaçu Marine Extractive Reserve (MER), where renewable natural resources are traditionally extracted by local human populations (Magalhães et al., 2009). The Ajuruteua Peninsula is approximately 8 km in width and 25 km in length and is predominantly mangrove forest (Souza Filho, 2005). These forests mainly comprise *Rhizophora mangle* L., *Avicennia germinans* (L.), and *Laguncularia racemosa* (L.) C.F. Gaertn. are subject to differing salinity, frequency of flooding, and tidal range (Virgulino et al., 2020). The mangrove area on the peninsula is delimited by the Caeté River estuary to the east and the Taperaçu to the west (Gomes et al., 2013).

2.2. Sampling procedures

A total of 27 sediment samples were collected at nine sampling stations located in three tidal channels that cross the mangroves along the Ajuruteua Peninsula (Fig. 1). Stations S1, S2 and S3 are located in the

channel locally known as Furo do Taici, the innermost part of the peninsula and closest to the mainland, whose waters are influenced by continental drainage, the Caeté river and environmental impacts from the municipalities it passes through, with the most significant impacts coming from the city of Bragança, where much of the region's small-scale fishing activity takes place. Stations S4, S5, and S6 represent the tidal channel in the middle zone of the peninsula, locally known as Furo do Meio, where anthropogenic influence is lower. The other stations (S7, S8, and S9) represent the tidal channel in the outermost zone with the highest salinity, known as Furo Grande. They are located further away from the mainland and closer to the beach, with the most significant marine influence and flux of people due to fishing and tourism (Fig. 1). Both tidal channels (Furo do Taici, Furo do Meio, and Furo Grande) also connect the Caeté estuary to the east with the Taperaçu estuary to the west of the peninsula. This hydrodynamic connection is important for the flow of water and sediment between the estuaries, which have

distinct hydrodynamic characteristics and anthropogenic influences.

At each station, approximately 500 g of sediment were collected. Sampling was undertaken by collecting three replicates using a Van Veen grab (0.25 m² of sampling surface) from a boat. The 1500 g of sediment collected at each station was stored in aluminum containers and packed in thermal boxes for transport to the Mangrove Ecology Laboratory at the Federal University of Pará - Bragança Campus for storage and subsequent analysis.

2.3. Extraction of MPs

The MPs were extracted using the density separation method (Peng et al., 2017). First, 300 g of wet sediment from each sample was placed in aluminum containers to dry in an oven at 50 °C until it reached a constant weight (equivalent to 72 h). A 10 g aliquot was taken from each sample and transferred to a clean glass beaker filled with ultrapure water (UPW) (Paes et al., 2022; Wu et al., 2020). Then, 50 mL of 30% hydrogen peroxide (H₂O₂) was added to degrade the organic matter present in the sediment throughout 24 h (Paes et al., 2022). The samples were subjected to 300 ml of a solution (filtered) saturated with sodium chloride (NaCl) and stirred with a glass rod for 2 min, leaving them to settle.

Complete sedimentation of the material present in the NaCl solution occurs after 24 h and, from then on, the supernatant, which should contain the plastic particles if they are present in the sample, was filtered using a vacuum pump through a filter funnel with a glass fiber filter; GF/F, 47 mm Ø. The filter paper was then carefully removed from the funnel with metal tweezers and placed in a Petri dish covered with aluminum foil so that the material could be dried at room temperature and analyzed under a stereomicroscope.

2.4. Quantification and identification of MPs

After drying the filters, the particles were observed and photographed using a stereomicroscope (1 to 8x). The MPs were visually quantified, identified, and measured according to their physical characteristics (Hidalgo-Ruz et al., 2012; Peng et al., 2017). The MPs were quantified by their abundance (items kg⁻¹ of dry sediment) and classified into form, color, and size categories, which were measured using a simple micrometric eyepiece. In addition, the polymers were identified using Fourier transform infrared spectroscopy (FTIR) and a Raman spectrometer.

2.5. Quality assurance (QA) and quality control (QC)

To guarantee the accuracy of the experimental results, only glass and/or aluminum material was used, and no plastic material was used at any time during the field or laboratory procedures (Mendes et al., 2023). The materials were washed three times with UPW, and all open containers were covered or sealed with aluminum foil after use. During the procedures, the operator wore 100% cotton clothing. The chemical reagents used in the experiment were analytically pure, with impurities removed by filtration before use. Each step of the laboratory experiment was carried out in an exhaust hood and in the presence of only one person to avoid the presence and interference of dust and/or other impurities in the experimental results.

2.6. MPs risk assessment

In the present study, we used the Pollution Load Index (PLI) to assess the pollution level in the entire aquatic system (Tomlinson et al., 1980). The PLI has become a standardized and widely used method for detecting and assessing potential pollution levels in different locations and organisms (Chen et al., 2022; Pan et al., 2021; Ye et al., 2023). This index effectively assesses the risk of MP in diverse environments, including estuaries, bays, and mangrove areas (J. Li et al., 2020; Pan

et al., 2021). To assess the PLI in the study area, we used the abundance of MPs, applying the equations below:

$$PLI_{Si} = \sqrt{\frac{C_{Si}}{C_0}} \quad (1)$$

$$PLI_{Local} = \sqrt[n]{PLI_{S1} \cdot PLI_{S2} \cdot \dots \cdot PLI_{Sn}} \quad (2)$$

$$PLI_{Ajuruteua \text{ peninsula}} = \sqrt[3]{PLI_{Taici} \cdot PLI_{Meio} \cdot PLI_{Grande}} \quad (3)$$

Where: PLI_{Si} is the index at a sampling station, determined by the square root of the ratio between C_{Si} , which represents the abundance of MP obtained by averaging the values of the three replicates at a sampling station, and C_0 , which is the lowest value of MP abundance among all the replicates, and which in this study is defined as 100 items kg⁻¹ (Chen et al., 2022; G. Wang et al., 2021). PLI_{Local} is the value for a local tidal channel, defined by the n th root of the product of the PLI_{Si} values at the sampling stations in that tidal channel, where n represents the number of sampling stations (e.g., S1, S2, S3) in the tidal channel ($n = 3$). The risk value for the entire study area is obtained via the n th root of the product of the local MP indices, where n represents the number of local tidal channels sampled ($n = 3$).

2.7. Statistical analysis

The abundance of MPs is expressed in items per kg of dry weight (items kg⁻¹), and all data are presented as mean ± standard deviation (mean ± SD). Residual plots were used to check the assumptions of normality and homoscedasticity using the Shapiro-Wilk and Levene tests, respectively. For data that showed normality, analysis of variance (one-way ANOVA) was used, followed by Tukey's *post hoc* test. Variations in the concentration of MPs between the sampling stations along the peninsula were evaluated according to their distance from the mainland (Furo do Taici, Furo do Meio, and Furo Grande), with a significance level of 0.05. All the analyses were carried out using the Statistica 7.0 statistical package (Statsoft, n.d).

3. Results and discussion

3.1. Abundance and distribution of MPs

All sampling stations contained MPs. Fig. 2 illustrates the average abundance of MPs at the nine sampling stations. The abundance of MPs ranged from 100 to 1200 items kg⁻¹. These values are lower than the abundance of MPs found in Todos os Santos Bay, on the northeast coast of Bahia, Brazil, where values ranged from 555 to 31,087 items kg⁻¹ (Paes et al., 2022), and which are higher than those described in most studies carried out in other mangrove areas and estuaries worldwide (Fig. SI). In large Amazonian rivers, high levels of MPs were observed in sediments (417–8178 items kg⁻¹), where the highest concentrations were from the Negro River, in areas close to the city of Manaus, which, combined with hydrodynamic conditions suitable for sediment accumulation, contributes greatly to the increase in MPs in different Amazonian ecosystems (Gerolin et al., 2020).

Our findings show MP values with higher concentrations (1200 items kg⁻¹) at station S7 in the Furo Grande, located closer to the sea. This station is a busy port for landing fish and shellfish, especially mangrove crabs (*Ucides cordatus*) (Monteiro et al., 2014). The second highest values were recorded in the innermost part of the Ajuruteua Peninsula, at station S1 with 800 items kg⁻¹, where the influence of the continental drainage of the city of Bragança and fishing activity is more intense. Finally, the middle portion of the peninsula had lower MP values, 500 items kg⁻¹ at Station S6 (Fig. 2). Differences in the abundance of MPs among the sampling stations were significant (ANOVA, $F = 5.63$; $df = 2$ and 24 ; $p = 0.0099$), and the difference between the Furo Grande and

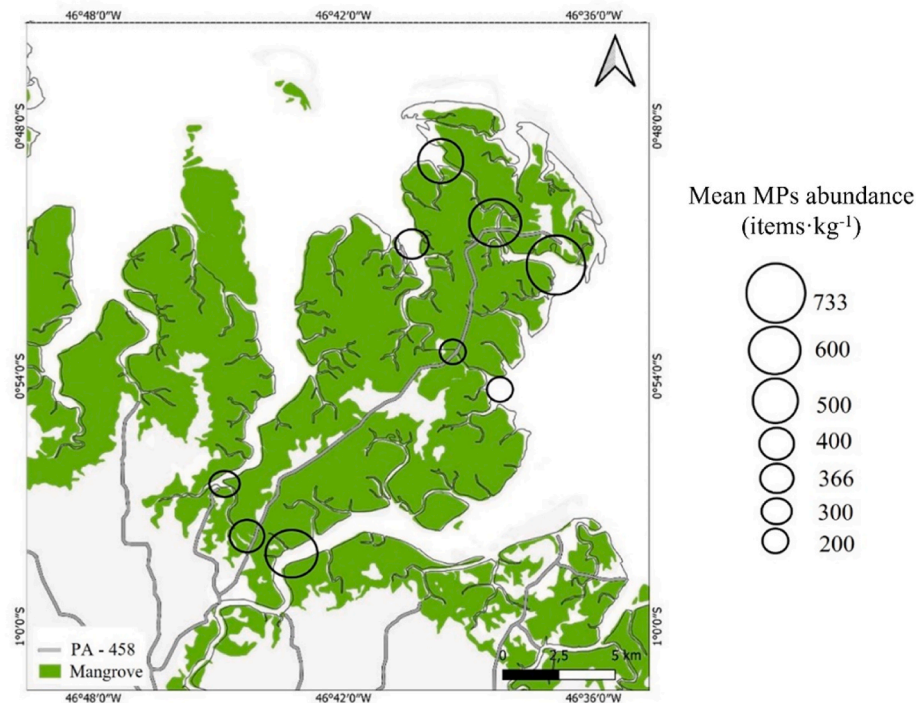


Fig. 2. Map of the Ajuruteua Peninsula showing the average abundance of MPs (items kg^{-1}) for each sampling station (S1–S3, Taici; S4–S6, Meio and S7–S9, Grande). The diameter of the circles represents the abundance of MPs.

Furo do Meio stations was significant (Tukey, $p < 0.01$). This may be because the area furthest from the mainland, from Furo Grande to Ajuruteua Beach, is more influenced by urbanization, increased fishing, commercial activity, and tourism at Furo Grande and Ajuruteua Beach, as well as urbanization in the nearby villages of Pescadores and Bonifácio. Intensification of anthropogenic activities associated with different ecosystems has been considered the main reason for the spatial distribution of MPs in marine and river sediments (Mohamed Nor and Obbard, 2014).

MPs in sediments highlight the connection between anthropogenic activities and environmental contamination (Gerolin et al., 2020). According to previous studies, diverse urban activities are one of the main sources of MP deposited on riverbeds (Hurley et al., 2018), and fishing is considered one of the most relevant additional sources of MP contamination in coastal ecosystems (Di and Wang, 2018; Ferreira et al., 2018). In Brazil, the state of Pará is one of the main fish producers, which gives it a significant role in the fishing industry in economic terms (Isaac et al., 2008). However, concerning the generation of plastic waste, such as nets and ropes, fishing can represent an important source of MPs (Montarolo et al., 2018). Overall, the results obtained in this study indicate that the presence of MPs in the sediments of the tidal channels of mangrove swamps on the Brazilian Amazon coast is influenced by anthropogenic activities. Previous research has suggested that the MPs found in coastal regions originate predominantly from domestic, industrial, and fishing activities and are introduced by freshwater, marine, and terrestrial sources (Kim et al., 2015; Zhang et al., 2017).

Studies investigating the presence of MPs in sediment samples from coastal environments (Alves and Figueiredo, 2019; Ashjar et al., 2023; Firdaus et al., 2020; Kannankai et al., 2022; Liu et al., 2020; Radhakrishnan et al., 2021; Rodrigues et al., 2022; Ye et al., 2023) generally, these are particularly vulnerable to the accumulation of MP due to their location and the pollution sources that affect them, even in lower abundances compared to studies carried out in Brazil (Fig. SI).

3.2. Morphological characteristics of MPs

3.2.1. Form of MPs

The MPs detected in this study were categorized into four main forms: fragment, fiber, film, and spherule/pellet (Fig. 3), which also shows the average values of the different forms of MP found in the replicates at each station. Fragments and fibers together account for 92.3% of the total number of particles found, 49.6% (average of 1944) and 42.7% (average of 1670), respectively (Fig. 3). This result corroborates other studies carried out on sediments from estuarine and urban areas and other aquatic environments, where between 59 and 80% of the particles sampled are fragments (Bayo et al., 2019; Gray et al., 2018), respectively. Fragments indicate that MP pollution in coastal environments may come from the fragmentation of large plastic waste (Hale et al., 2020; Hale et al., 2022). On the other hand, the considerable contribution of fibers is similar to the results from sediment analyses in other coastal areas, such as in a highly eutrophic tropical estuary in Brazil (81%; Alves and Figueiredo, 2019), Changjiang estuary in China (93%; Peng et al., 2017), a continental shelf in the southern East China Sea (45.8%; Li et al., 2022), Amazon rivers in Brazil (100%; Gerolin et al., 2020), Yangtze estuary in China (94%; Wu et al., 2020), Jinjiang estuary, Fujian in China (68.58%; Deng et al., 2020) and an Amazon macrotidal beach in Brazil (95%; Martinelli Filho and Monteiro, 2019). Similar trends have also been recorded for fragments, fibers, and films in urban and semi-natural estuarine areas, except for the spherule/pellet form (Bayo et al., 2019). The study implies that macro- or mesoplastic fragmentation likely contributes to the main MP particles in mangrove tidal channel sediments. Maritime activities, particularly fishing, also contribute to microfiber pollution, given that fishing nets are primarily made of fibers (Villagran et al., 2020).

3.2.2. MP colors

Five colors of sediment MPs were identified (Fig. 4), with transparent being the most common (52.1%), followed by blue (33.3%) and black (11.1%), present in all three tidal channels. Transparent MPs are often associated with coastal environments due to solid waste from fishing

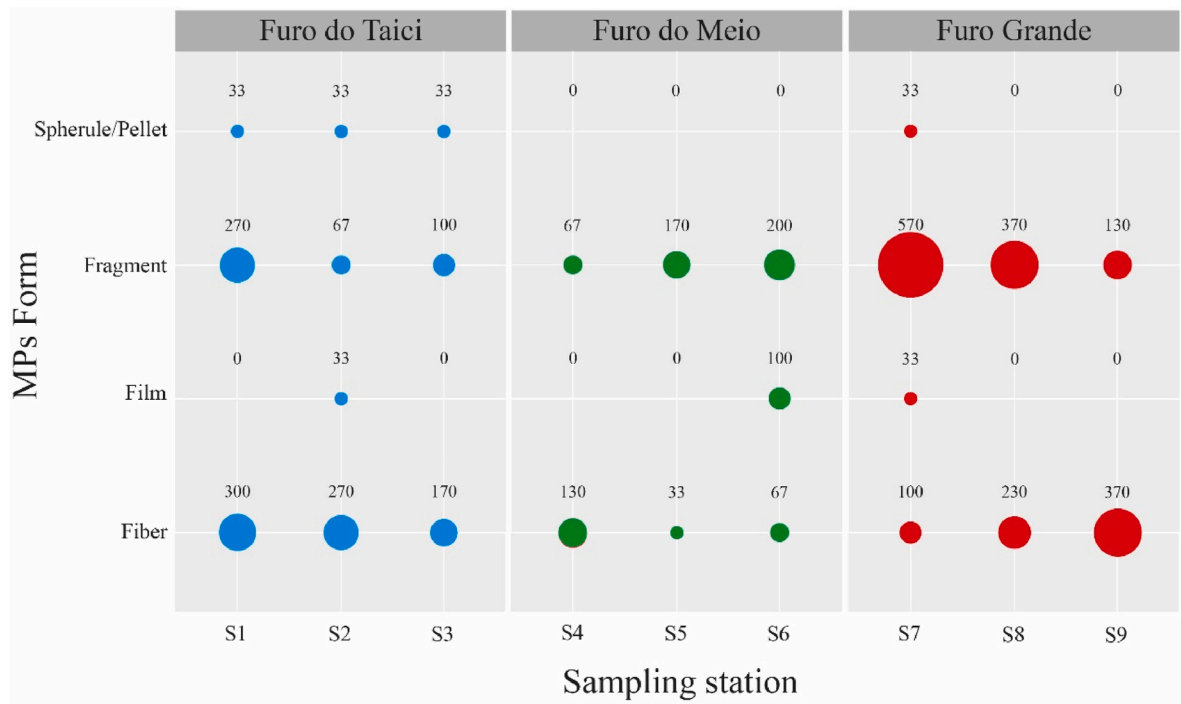


Fig. 3. Presence of MPs (average of three replicates) with the contribution by form (fiber, film, fragment, and spherule/pellet) for each sampling station of the mangrove tidal channels on the Ajuruteua Peninsula, Bragança, Pará, Brazil.

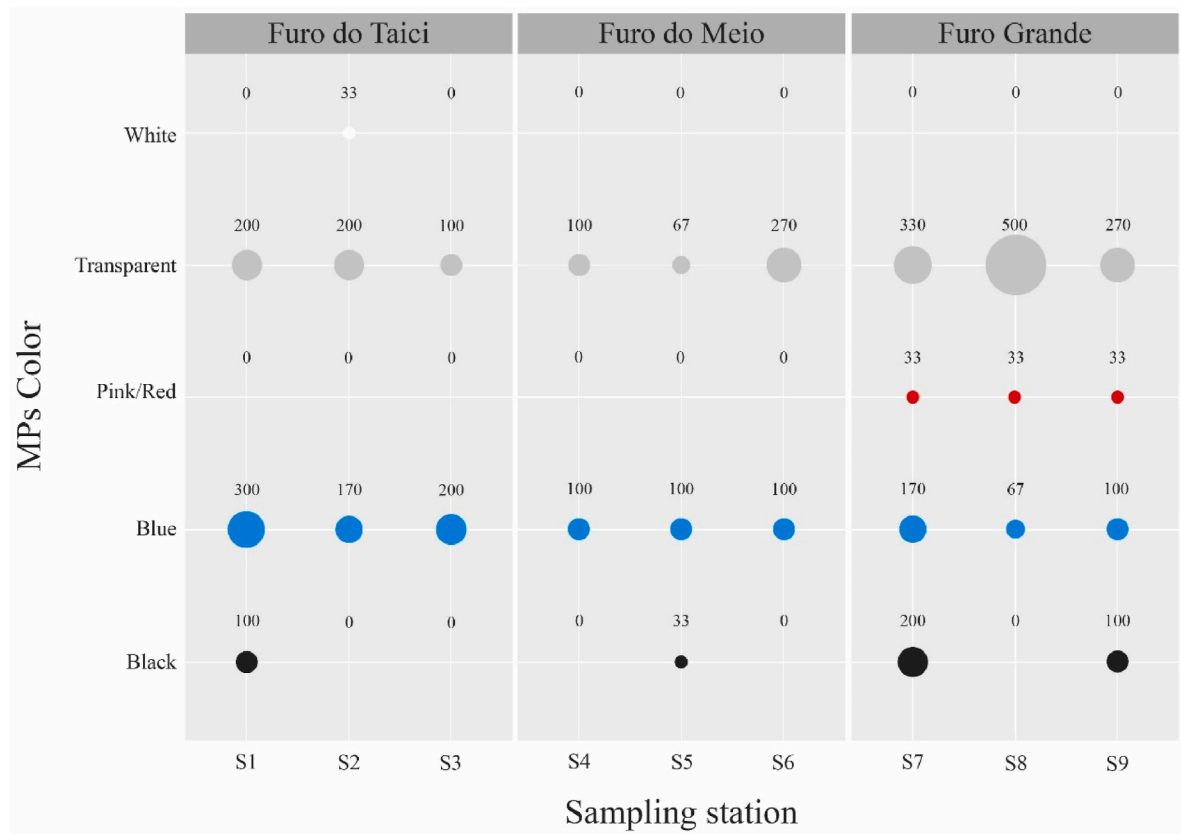


Fig. 4. Presence of MPs (average of three replicates) with the contribution by color (transparent, blue, black, white, and pink/red) for each sampling station in the mangrove tidal channels of the Ajuruteua Peninsula, Bragança, Pará, Brazil. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

nets (Di and Wang, 2018), clothing (De Falco et al., 2019), and disposable plastic packaging (Firdaus et al., 2020). Blue and black MPs are commonly associated with fishing gear and activities (Choong et al., 2021). White (0.9%) and pink/red (2.6%) accounted for just 3.5% of the colors identified, with white MPs found only in Furo do Taici and pink/red MPs solely in Furo Grande. Similar color distributions were observed in sediments from Amazonian rivers (Gerolin et al., 2020), Indonesian estuaries (Firdaus et al., 2020), Iranian wetlands (Ashjar et al., 2023), and mangrove areas in Brazil and India (Kannankai et al., 2022; Paes et al., 2022). Transparent MPs are predominant in mangrove sediments (R. Li et al., 2020; Maghsodian et al., 2021; Zhang et al., 2020), comprising over 70% of particles (Deng et al., 2020; J. Li et al., 2020; R. Li et al., 2020).

MP color influences bioavailability to aquatic organisms, with transparent MPs frequently ingested by aquatic species, posing harmful effects (Koongolla et al., 2020). The visual resemblance between MPs and prey contributes to ingestion, as observed in estuarine fish species (Maharana et al., 2020). In Amazonian rivers, fish species have been recorded ingesting-colored MPs (Pegado et al., 2018), highlighting the importance of proper MP identification despite challenges posed by exposure periods and environmental conditions. Ultraviolet radiation and other photochemical processes can alter MP properties and colors over time, explaining the presence of transparent MPs in all samples (Cole et al., 2011; Firdaus et al., 2020; Prata et al., 2019).

3.2.3. MPs size

The MPs identified were classified into six categories: <100 μm , 100–500 μm , 500–1000 μm , 1000–2000 μm , 2000–5000 μm , and

>5000 μm . The most common size range was 100–500 μm (41.9%), followed by 1000–2000 μm (21.4%), 500–1000 μm (17.1%), 2000–5000 μm (11.1%), <100 μm (6.8%) and >5000 (1.7%) (Fig. 5). The average size of the MPs was $948.41 \pm 1137.17 \mu\text{m}$, and the smallest particle size was 60 μm (fragment), which was only observed at station S7, in Furo Grande. The average of the replicates at the sampling stations is shown in Fig. 7. In Furo Grande, 970 MPs are divided at stations S7 to S9 in sizes 100–500 μm , followed by Furo do Taici, with 470 MPs in sizes 100–2000 μm at stations S1 to S3 (Fig. 5). There was no significant difference between tidal channels from the comparative analysis of the sizes recorded for the MP particles ($p = 0.1032$), although the distribution of MP with different sizes varied between the stations.

The findings align with previous research conducted on surface sediments from the Kayamkulam estuary in southwest India (Radhakrishnan et al., 2021). Moreover, the degradation of larger plastic particles can lead to the formation of numerous small fragments, resulting in MPs of varying sizes, which may indicate their origin and degree of weathering (Zayen et al., 2020). The aging process and weathering conditions of plastic can further contribute to fragmentation into smaller particles, with that smaller than 1000 μm posing a heightened risk of ingestion by aquatic organisms compared to larger ones (Ferreira et al., 2016; Lima et al., 2016) which may eventually enter the food chain (Govender et al., 2020), and exacerbate MP pollution. The distribution of large and small particles across sampling stations (Fig. 5) corresponds to observed variations in MP size proportions (Leslie et al., 2017). However, differences in size range analysis criteria hinder direct comparisons (Gerolin et al., 2020; Martinelli Filho and Monteiro, 2019; Paes et al., 2022; Ye et al., 2023). Notably, MPs larger than 500 μm are more

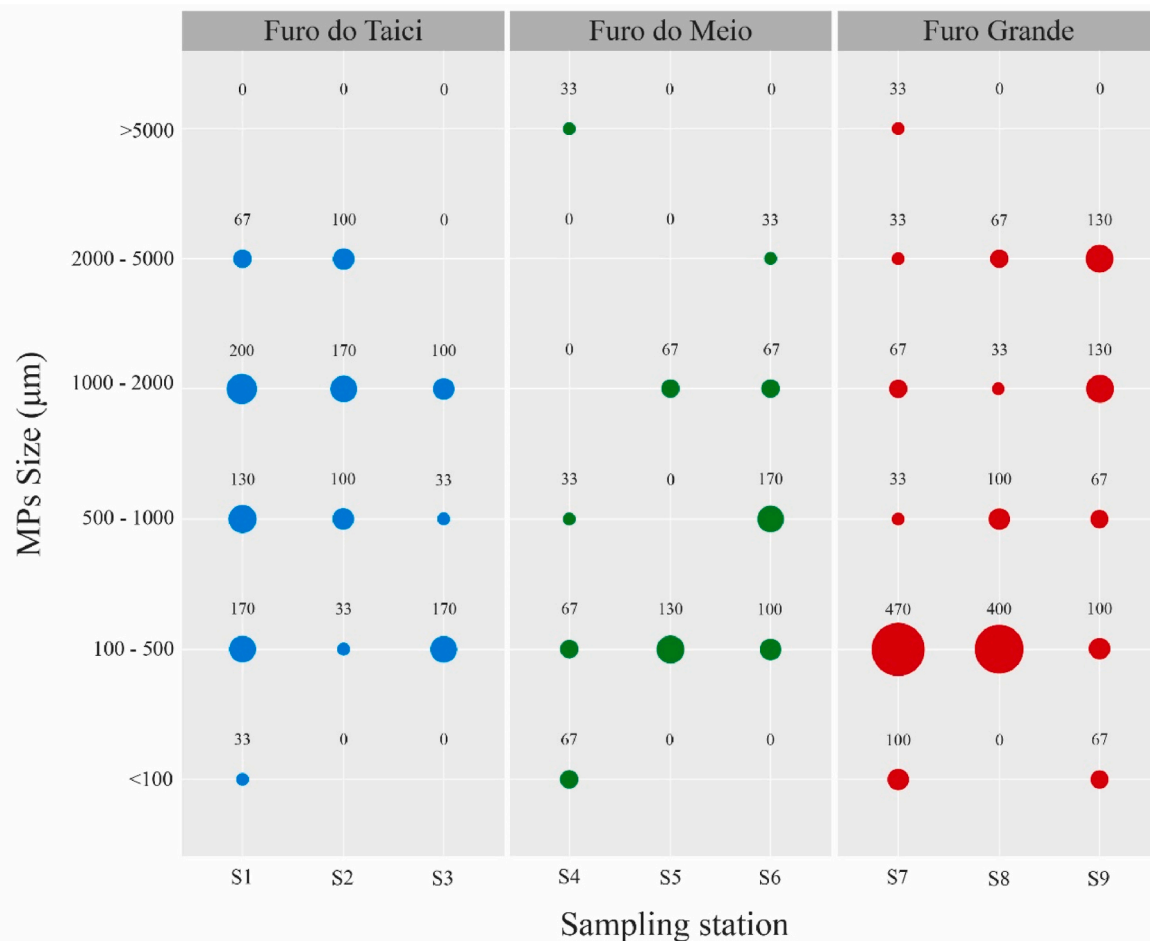


Fig. 5. Presence of MPs (average of three replicates) with the contribution by size (<100 μm , 100–500 μm , 500–1000 μm , 1000–2000 μm , 2000–5000 μm , and >5000 μm) for each sampling station in the mangrove tidal channels on the Ajuruteua Peninsula, Bragança, Pará, Brazil.

frequently detected in the inner parts of mangrove areas (R. Li et al., 2020; Zhou et al., 2020; Zuo et al., 2020), suggesting that mangrove roots may act as a sieve, trapping larger MPs while smaller ones escape into the environment (Duan et al., 2021). MPs ranging from 1000 to 5000 μm may be ingested by larger organisms, including benthic megafauna and demersal fish, posing contamination risks in commercially significant areas such as the tidal channels of the Ajuruteua Peninsula mangroves. Although research on MP abundance in such environments is limited, addressing sediment compartments is crucial due to their role as natural habitats for diverse species, including nursery areas, and as sinks for ocean pollutants.

3.2.4. Polymer types of MPs

Determining the chemical composition of MP is paramount as it can provide valuable information on the likely source of plastic pollution (Kumkar et al., 2021). Most of the polymers identified in this study are commonly used in the manufacture of plastic products (Maghsodian et al., 2021), confirming the link between anthropogenic actions and plastic pollution through fishing and tourist activities in the vicinity of the study area, although the polymers identified are somewhat different from those found elsewhere (Alves and Figueiredo, 2019; Kannankai et al., 2022; Queiroz et al., 2022). The identification of MPs via FTIR analysis revealed the presence of four types of polymers: AV, RD, CPE, and polyethylene-polypropylene PE-PP (Fig. 6). The degree of correlation between the reference spectra and the sample spectra is shown by Pearson's correlation coefficient (r), which ranges from 0 to 1, indicating a stronger statistical correlation the closer it is to 1. Only coefficients greater than 0.8 were accepted for the identification result (Fig. 6). The results of the Raman analysis identified two more types of polymers: LDPE and HB (Fig. 7).

Of all the polymers identified, CPE was the most common, being present in the three zones sampled (Furo do Taici, Furo do Meio and Furo Grande) along the peninsula (Fig. 6), while AV, RD, LDPE and HB were only found in the innermost zone of the peninsula (Furo do Taici) and PE-PP in the intermediate zone and the one furthest from the mainland (Furo do Meio and Furo Grande). The PE-PP polymer refers to

a mixture of polyethylene (PE) and polypropylene (PP), two of the most common plastics and widely used in the manufacture of various consumer products, such as packaging, bags, bottles, disposable products, tools, and fishing gear (e.g., nets and buoys) (Picó et al., 2021). These plastics are known for their durability, flexibility, and low cost and are the most abundant polymers in mangrove sediments (Govender et al., 2020; Rose and Webber, 2019; Zhang et al., 2020; Zhou et al., 2020). A study of mangrove forest sediments in Indonesia revealed that 50% of the MPs identified were PE, and the other 50% were PE-PP (Cordova et al., 2021). These two polymers, together with CPE, form part of the thermoplastic polymer group, of which around 90% of the world's plastic production is part (Jagadeesh et al., 2022).

CPE has a unique combination of characteristics that make it versatile and suitable for various applications (Jagadeesh et al., 2022). It has good resistance to temperature, weathering, chemicals, and flame-retardant properties. These properties make CPE suitable for coatings, waterproof membranes, cables, wires, pipes, extruded profiles, and various rubber products. Unfortunately, CPE is not biodegradable, which means that it can persist in the environment for long periods (Ahmed, 2015; Zhang and Zhou, 2022). As a result, it fragments into smaller pieces over time, contributing to MP contamination. LDPE is used to make fishing tackle (Dowarah and Devipriya, 2019; Lusher et al., 2013; Syakti et al., 2019). In addition, LDPE is widely used, but it is single-use plastic and, therefore, rarely recycled (Parashar and Hait, 2021). As a result, LDPE MPs accumulate in large quantities in the environment over time, and this accumulation can be observed in urban mangrove areas, such as those in Mangalavanam, Kerala, India, where these mangroves are under serious threat from microplastic pollution, with LDPE being the most abundant polymer identified (Kannankai et al., 2022).

AV is a type of coating that contains alkyd resin and is widely used in products such as paints, varnishes, and enamels (Civan Çavuşoğlu and Acar, 2022). These coatings are produced by reacting polyols, such as glycerol or pentaerythritol, with polybasic acids, such as phthalic anhydride or maleic anhydride (Civan Çavuşoğlu and Acar, 2022). AV is a common type of polymeric binder in industrial paints, including marine

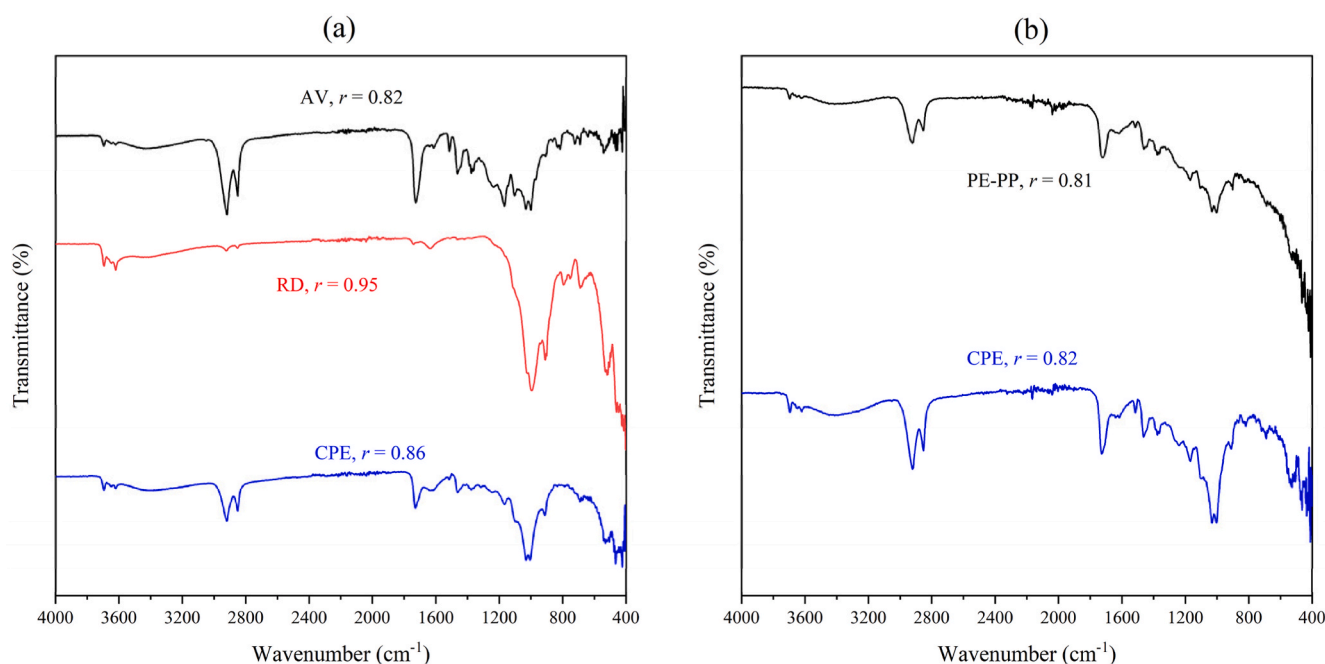


Fig. 6. FTIR spectra of the MPs found in the surface sediments of the mangrove tidal channels: (a) Furo do Taici - alkyd varnish (AV): black, resin dispersion (RD): red, chlorinated polyethylene (CPE): blue, (b) Furo do Meio e Furo Grande - polyethylene-polypropylene (PE-PP): black, chlorinated polyethylene (CPE): blue, on the Ajuruteua Peninsula, Bragança, Pará, Brazil. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

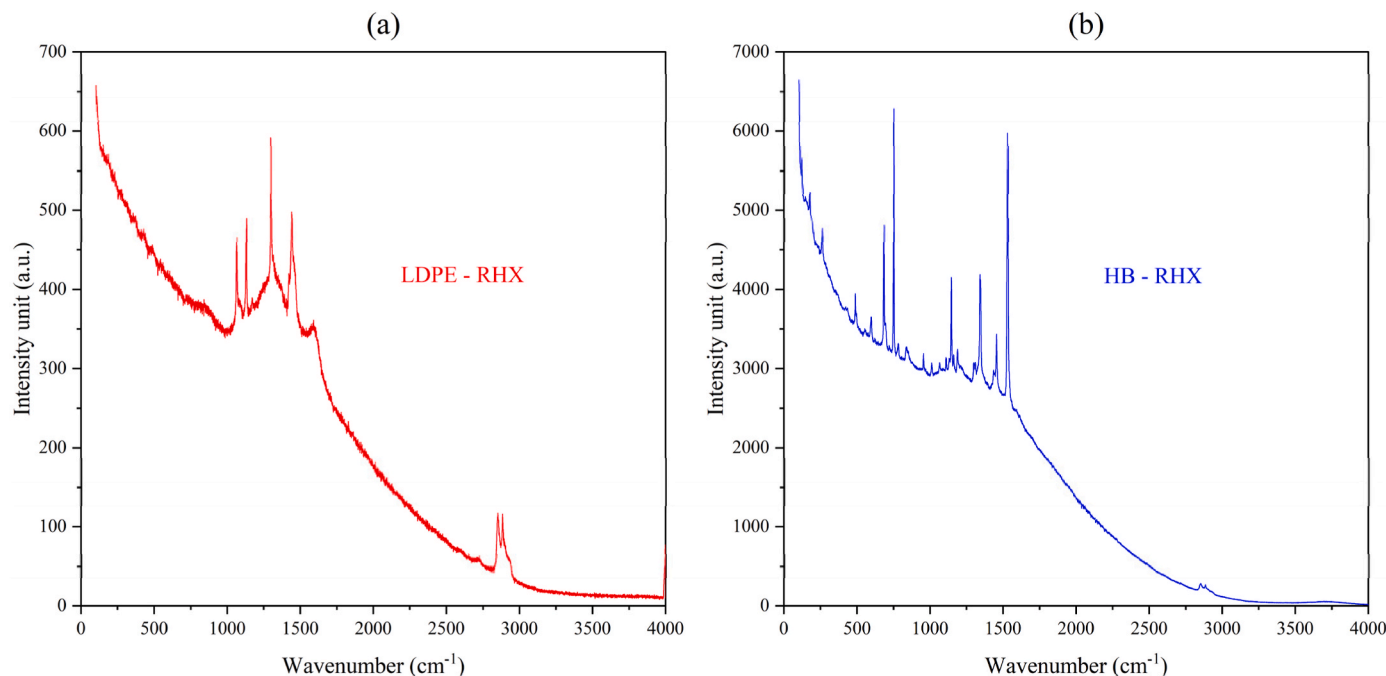


Fig. 7. Raman spectra (Raman Forensic Horiba (RHX)) of the MPs (a) low-density polyethylene (LDPE): red, (b) hostaperm blue (HB): blue, found in the surface sediments of the mangrove tidal channels of Furo do Taici on the Ajuruteua Peninsula, Bragança, Pará, Brazil. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

applications (Kojima and Watanabe, 1993; Nosal et al., 2016; Shtykova et al., 2006) as is RD, another form of MP consisting of small resin particles that are dispersed in the form of suspensions or emulsions (Nobel et al., 2007).

The strong Raman signal of certain pigments can make it difficult to identify the plastic polymer, such as HB, which falls into the copper phthalocyanine chemical class and is an industrial colorant used mainly in the plastics industry (Charvat, 2004; Karami et al., 2017). When present as MPs, HB pigment refers to the fine particles released into the environment during the manufacture, use, or disposal of products such as paints, plastics such as PP, and other products to provide color and opacity (Karami et al., 2017).

Our findings reveal that one of the main sources of MP entering the Furo do Taici area are the coating particles coming from the boats used for navigation and fishing activities carried out in the region, which are widely used near the more urbanized areas. Areas where solid waste management, water distribution infrastructure, rainwater control, sewage collection, and sewage treatment are limited basic services, reaching less than 8% of the population present in the coastal regions of the Brazilian Amazon. This situation contributes significantly to the potential for environmental contamination by (micro)plastic pollution since the waste originates in rivers and can disperse until it reaches the ocean (Queiroz et al., 2022).

3.3. Effect of circulation on the transport of MPs

MP pollution is a significant environmental problem, particularly in aquatic systems. Hydrodynamic processes encompassing various water movements and their associated forces act on the deposition and distribution of MPs. This discussion addresses the influence of factors such as the speed of water flow and the direction and amplitude of the tides on the movement and deposition of MPs, in addition to considering the role of mangroves as sinks for MPs.

Water flow velocity is a primary determinant of MP transport and deposition. Higher speeds generally result in greater transport distances for MPs due to increased kinetic energy. Small and light MPs can be easily suspended and transported by fast-moving water (Zhang et al.,

2017; Collins and Hermes, 2019). In rivers and streams, for example, high flow velocities during periods of heavy rainfall or snowmelt can promote substantial transport of MPs from urban areas to downstream aquatic environments, while lower flow velocities favor MP deposition. Studies indicate that regions where water flows more quickly tend to retain fewer MPs in the sediments due to the greater capacity to transport these particles out of the mangrove (Grbic et al., 2019; Zhang et al., 2022).

The direction of water flow determines the paths along which MPs are transported. In river systems, unidirectional flow generally transports MPs from upstream sources to downstream areas. Estuarine and coastal environments, however, exhibit more complex flow patterns due to the influence of tides, currents, and wave action (Cohen et al., 2019). These environments often experience bidirectional flow, which can lead to the redistribution of MPs and their deposition in different locations depending on tidal cycles and seasonal changes.

Tidal range, defined as the vertical difference between high tide and low tide, significantly affects the distribution and deposition of MPs in coastal and estuarine systems (Li et al., 2023). Large tidal ranges result in extensive intertidal zones that are alternately submerged and exposed. MPs can be deposited during high tides when water floods these zones and are adsorbed onto sediment grains as the tide recedes. This cyclical process can accumulate MPs in intertidal sediments over time (Cheng et al., 2024; Li et al., 2023). Tidal currents, on the other hand, can resuspend deposited MPs, especially during spring tides when the tidal range is at its maximum. This resuspension can redistribute MPs within the estuarine system, affecting their overall distribution and potentially contaminating previously cleaned areas. Field studies show that the environmental factors that influence the variability of MPs in intertidal sediments vary depending on local conditions (Leads et al., 2023). These same authors show that on Fernando de Noronha Island, off the Brazilian coast, the concentrations of PMs observed over a period of 13 days showed high variability, mainly attributed to wind direction and surface currents. In contrast, on Vavvaru Island in the Maldives archipelago, water currents, waves, and tidal cycles were identified as the main contributors to the high variability of MPs over seven consecutive days, with no direct relationship observed with speed or

wind direction (Imhof et al., 2017). Similarly, in the Paranaguá estuary in Brazil, concentrations of MPs in beach sediments varied significantly over several consecutive tidal cycles (Moreira et al., 2016).

During the rainy season, due to the increase in river discharge from the Caeté, the Maximum Turbidity Zone (MTZ) is positioned in the middle and lower portion of the estuary, precisely where the samples of this study are located. This factor contributes to the transport of MPs from Caeté to Taperaçu, considering that the highest concentrations of MPs are associated with the eastern portion of the peninsula (Caeté estuary), the sector most influenced by urbanization and activities that can generate MPs (Fig. 2). Regarding the variation in the abundance of MPs between the rainy and dry seasons, studies carried out in Guanabara Bay, Brazil, indicate that the amount of MPs in the sediments did not show significant variation between these periods (Alves and Figueiredo, 2019). A possible explanation for this discrepancy suggested by the authors is that currents and the entry of continental waters loaded with solid waste did not impact, at least in the short term, the concentrations of MPs in the sediments of Guanabara Bay (Alves and Figueiredo, 2019). Differently, in typical tidal channels in the lower reaches of the Dong River, the occurrence of MPs was examined during the wet and dry seasons, where continuous and high-frequency dynamic monitoring of MP was carried out in a cross-section during a tidal cycle. During the

rainy season, the abundance of microplastics ranged from 3.97 ± 28.63 items/m³, while in the dry season, the variation was from $5.43 \pm 56.43 \pm 14.32$ items/m³ (Li et al., 2023).

Turbidity currents have been identified as the main influencers on the distribution of sediments and suspended particles, including MPs (Hage et al., 2019; Pohl et al., 2020). These currents can contribute to the dispersion or deposition of MPs, thus influencing the quantity and distribution of these particles in the marine environment (Pohl et al., 2020). The interaction between estuarine hydrodynamics, mangrove vegetation, and sediment transport and deposition processes determines the distribution and retention of MPs in mangrove sediments. The longer MPs remain immobile in areas of fine sediment, the greater the risk it poses to benthic organisms, as prolonged exposure time increases the likelihood of ingestion (Boos et al., 2024).

In the present study, the circulation pattern of the Caeté and Taperaçu estuaries leads to the retention of MP particles in the environment. Aspects already described for estuaries, such as the formation of MTZ (Asp et al., 2018; Gomes et al., 2021), induce a distribution of sediment and organic and inorganic particles in suspension in the water column along the estuarine system and the hydrodynamic connectivity between estuaries (Asp et al., 2012; Gomes et al., 2020), which transfers water and sediment between estuaries (Fig. 8).

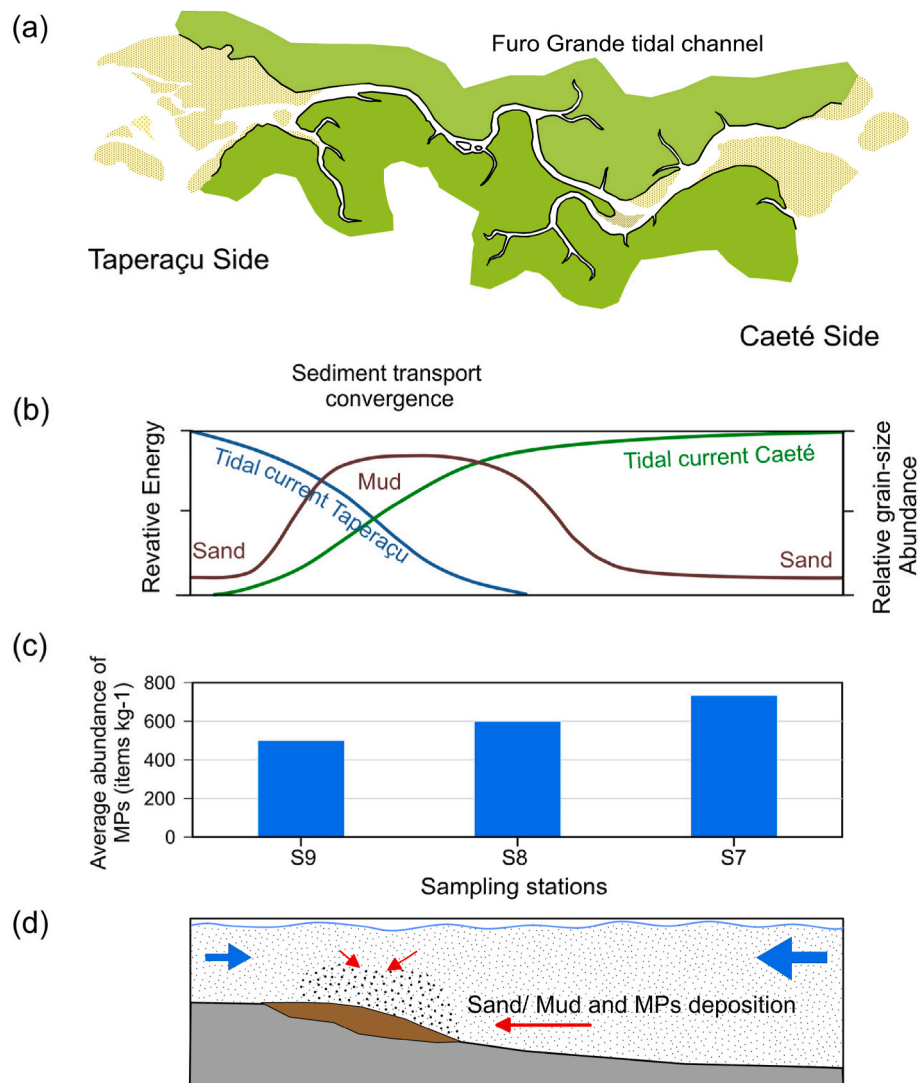


Fig. 8. (a)-Map of the Furo Grande tidal; (b)- Conceptual model showing similar tidal-energy propagation along the Furo Grande tidal channel between the two estuaries; (c)- Average abundance of MPs at each sampling point (d)- Representation of the transport and deposition processes of sediments and MPs in the study area (Modified from Gomes et al., 2020).

The formation of the MTZ in the Caeté estuary is influenced by the convergence of currents, which changes according to seasonal and tidal factors, causing the MTZ to occur upstream or downstream of the estuary (Asp et al., 2018). The occurrence of MTZs in estuaries influences the concentration of fine sediments deposited on the bed and inorganic particles adhered to the sediment due to their cohesive nature (Shiravani et al., 2023) (Fig. 8). Another important factor is the existence of tidal channels that generate hydrodynamic connections between the Caeté and Taperaçu estuaries, resulting in a flow of water and sediment between them.

The Ajuruteua peninsula is closely linked to the dynamics of current tidal channels, which are the focus of our research (Gomes et al., 2020). The theoretical model proposed by Gomes et al. (2020) provides a comprehensive understanding of the energy balance influencing sediment deposition in these channels (Fig. 8). Based on this theoretical model, which explains the circulation of water and sediments, it is possible to understand the concentrations of MPs found in these study areas. The process of sediment retention in tidal channels, known as tidal current convergence, results in greater sedimentation in the central part of these channels, increasing the retention of fine sediments, organic and inorganic particles, and MPs, as confirmed by significant concentrations observed in the middle sectors of tidal channels (Fig. 8). Additionally, friction and tidal attenuation effects promote the deposition of sediments and associated particles in tidal flats (Anderson et al., 2018).

Hydrodynamic processes play an important role in determining the distribution and concentration of MPs in estuarine environments. In estuaries such as Tamar, tidal currents significantly influence MP distribution, creating zones of convergence and accumulation of surface layers. Depending on estuary morphology and tidal range, tidal forces can disperse and concentrate MPs (Sadri and Thompson, 2014). Studies in the Pearl River, southern China, emphasize the role of river discharge in transporting MPs from upstream sources to the estuary. High river flows during certain seasons can lead to an increased contribution of PM, which is then redistributed by tidal actions (Mai et al., 2019).

The study of the Pearl River Estuary highlights the impact of urban and industrial discharges on MP concentrations. Areas with high human activity tend to have higher levels of PM, which are further influenced by the estuary's hydrodynamic conditions (Mai et al., 2019, 2021). This situation is similar to the context investigated in our study, where the locations with greater abundance of MPs (S1 and S7) (Fig. 2) are closer to areas with the presence of human activities, such as fishing activities.

Mangroves located in intertidal zones are characterized by calm waters and low hydrodynamic energy, which facilitates the sedimentation of suspended particles, such as MPs. Mangrove areas with vegetation play a crucial role in directly intercepting MP deposition, serving as essential sites for the short- and medium-term accumulation of MPs (Deng et al., 2021; Ding et al., 2022; Wang et al., 2023). The density of mangrove structures captures and stabilizes sediments, creating a favorable environment for the deposition of MPs transported by tidal action and waves.

The retention process of MPs in the mangrove ecosystem is influenced by factors such as tides, vegetation, and salinity (Chen et al., 2021; Stead et al., 2020; Zhang et al., 2022). Different tidal zones within a mangrove can result in significant variations in the quantity and composition of MPs present in surface sediments (Zhang et al., 2022). For example, high tide areas tend to accumulate greater amounts of MP due to greater water entry and suspended particles (Liu et al., 2022; Zhang et al., 2022). Furthermore, mangrove vegetation can act as a natural filter, capturing and retaining waterborne MPs, especially in areas of higher plant density (Duan et al., 2021; Owowenu et al., 2023; Zhang et al., 2022).

During high tides, water carries MPs into mangroves, where the dense vegetation and intricate roots act as a physical barrier, trapping the MPs and allowing them to be deposited in the sediments. Studies reveal that mangrove sediments contain significant concentrations of

MPs, highlighting their role as effective sinks (Zamprogno et al., 2021). Mangrove vegetation can also influence the vertical distribution of MPs, with roots trapping particles both at the surface and in deeper sediment layers (Liu et al., 2022). Furthermore, MPs adhere to sediments and undergo sedimentation, suspension, and reprecipitation processes together with surface sediments (Liu et al., 2022). The effects of mangrove plants on MP distribution and pollution vary by species, especially due to the differential ability of roots to capture and retain plastic debris (Duan et al., 2021; Owowenu et al., 2023; Zhang et al., 2022). Each plant species has a distinct root system, uniquely influencing the efficiency of retaining MPs (Duan et al., 2021). In a study carried out in Shenzhen Bay, in southern China, a positive and significant correlation was recorded between the density of *Sonneratia caseolaris* pneumatophores ($225\text{--}675/\text{m}^2$) and the abundance of MPs ($2033\text{--}3733$ items/kg weight dry), where the abundance of MPs was higher in sampling areas close to the trunks of these mangrove trees (Duan et al., 2021).

Due to complex hydrodynamics, estuarine systems act as natural filters to retain organic and inorganic particles (Prandle, 2009). Especially in some areas where transport competence is lower, these particles settle in the estuarine bed, integrating into the bottom sediment (Almeida et al., 2023). Aquatic vegetation such as seagrass meadows influences the presence and distribution of microplastic particles in the Great Bay Estuary. The structure of these plants captures or slows the transport of particles within seagrass-containing estuaries, reducing erosion and bed shear stress and promoting sedimentation in these areas (Cheng et al., 2021).

Therefore, although hydrodynamic processes such as tidal currents, river discharge, and salinity gradients, among others, affect the distribution of MP in estuaries, the specific impact varies depending on local environmental conditions and human activities. Understanding these processes in detail is essential for effectively monitoring and managing MP pollution in estuarine and coastal environments, especially in the Brazilian Amazon mangroves, recognized as the world's largest and best-preserved continuous expanse of mangroves.

3.4. MP risk assessment

The PLI was used to assess potential pollution levels in different locations and organisms, the results of which are shown in Table S1. The findings of this study revealed that the level of MP pollution in the area studied is in the risk level I range, with values in the order of $2.5 > 2.0 > 1.6$ for Furo Grande, Furo do Taici and Furo do Meio, respectively, indicating a low level of pollution for the entire Ajuruteua Peninsula. The results obtained in the present study highlight the influence of hydrodynamic processes and proximity to urban areas on the levels of MPs present in the samples. The presence of these particles in the study area, even at a low level of pollution, can significantly impact the health of the ecosystem, also becoming a danger to the mangrove biota, especially for species used to feed traditional communities, in the medium and long term.

This same order shows the relationship between the study areas and the intensification of anthropogenic activities and the consequent potential for pollution/contamination by MPs, certainly from the fishing and tourist activities that take place in these three zones along the peninsula. In addition, MP pollution in mangrove sediment may have consequences for the productive activities of traditional communities that convert mangrove areas to rice cropping, which is an activity recorded in several places around the world (Nyangoko et al., 2022; Richards and Friess, 2016), including Brazil (Lacerda et al., 1993; Santos et al., 2014) and the Amazon coastal region (Fernandes et al., 2018).

According to the hazard class model based on the United Nations Globally Harmonized System of Classification and Labeling of Chemicals, plastic products with a chemical composition of $>50\%$ are classified as dangerous goods (Ranjani et al., 2021; Ye et al., 2023). Thus, MPs can contain hazardous additives in their composition, leading to

environmental contamination, mainly through the active action of physical, chemical, and biological factors. Given this, it is understood that an environment polluted by MPs can promote and intensify the contamination process with additives, representing a potentially significant risk to the organisms that inhabit them and, consequently, to human health. In the case of coastal estuarine environments, such as mangroves, humans can be directly affected by the consumption of contaminated animals, such as fish (Pegado et al., 2018, 2021) and seafood, i.e., prawns (Daniel et al., 2020; Daniel et al., 2021), mussels (Dellisanti et al., 2023), crabs (Piarulli et al., 2019; Waddell et al., 2020; T. Wang et al., 2021; Welden et al., 2018), and many other organisms, as well as the consumption of table salt (Lee et al., 2019), beer (Kosuth et al., 2018), tap water (Kosuth et al., 2018), and mineral water (Mason et al., 2018).

The PLI has already been used in several studies to assess the risk of pollution involving MPs, for example, in different rivers in China, such as the Xijiang River and the Pearl River estuary, showing a relatively low risk ($PLI = 1.0\text{--}2.0$) (Mai et al., 2021). Similarly, the risk of the presence of MPs in sediment has already been assessed in various regions of China, such as Liaodong Bay, where the results showed a risk level of I, with values of 2.80 in Panshan Coast; 2.22 in Geligang and 1.98 in Daliao Estuary (Ye et al., 2023). Studies in India have also used the PLI to assess the level of risk of pollution by MPs in aquatic environments, as can be seen along the east and west coasts of that country, which show PLI values = 1.0–6.1 and 3.0–15.5, respectively, the latter being presented as risk level II (Ranjani et al., 2021). The Dongshan Bay estuary in China also presented risk level II ($PLI = 14.2$) (Pan et al., 2021).

The presence of MPs in the estuarine, coastal, and marine environment is affected by regional activities such as inappropriate solid waste disposal, population density, and fishing activities (Jang et al., 2020; Pan et al., 2022). The PLI for MPs was calculated based on the lower abundance of MPs at the reference sampling sites, and the polymer diversity of the MPs did not influence the results since the PLI only addresses the ecological impact of the MPs themselves (Pan et al., 2021). The toxic effect of MPs is mainly related to hazard levels. Therefore, the PLI value is not a practical parameter for assessing health risk since it does not consider MPs as vectors of various organic and inorganic pollutants. Furthermore, the assessment of health risks in relation to exposure to MPs is still considered insufficient (Banik et al., 2022). Consequently, it is essential in the future to develop a unified research method for MPs and to carry out comprehensive studies on the possible routes of exposure to MPs and their threat to the human population.

4. Conclusions

This study is the first to report the presence and risk of MPs in the surface sediment of tidal channels in the mangrove forests of the Brazilian Amazon coast. The results show that MPs are present throughout the nine sampling stations on the Ajuruteua Peninsula. Where the hydrodynamic processes of estuaries and tidal channels explain the concentrations found, as circulation determines the pattern of sediment deposition and the particles adhered to it. Most of the MPs sampled are in the form of fragments and fibers and are composed of PE-PP, CPE, LDPE, AV, RD, and HB, revealing that they originate from the fragmentation of larger plastics and suggesting that their sources are of secondary origin. A preliminary risk assessment using the PLI for the entire peninsula showed hazard level I values, indicating low MP pollution risk in this region. The findings of this study are relevant and could help improve the management of solid plastic waste on and around the Ajuruteua Peninsula. However, a more comprehensive and systematic monitoring campaign is still needed to generate more regular information and thus expand and solidify knowledge about pollution and contamination by MPs in one of the most important mangrove areas on the planet, the Brazilian Amazon coast.

CRediT authorship contribution statement

Dayene Santiago Mendes: Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Daniel Nobre Nunes Silva:** Visualization, Validation, Methodology. **Luiz Eduardo Pereira Santiago:** Visualization, Validation, Methodology. **Vando José Costa Gomes:** Writing – review & editing, Visualization, Validation, Methodology. **Colin Robert Beasley:** Writing – review & editing, Visualization, Validation, Formal analysis. **Marcus Emanuel Barroncas Fernandes:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2024.121826>.

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