Marine Pollution Bulletin 175 (2022) 113161

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Evaluation of microplastic and marine debris on the beaches of Niterói Oceanic Region, Rio De Janeiro, Brazil

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ARTICLE INFO

Keywords:
Microplastic
ATR - FTIR
Marine plastic litter
Oceanic Region

ABSTRACT

The characterization of microplastics helps to improve sustainable management practices in aquatic ecosystems impacted by plastic litter. Plastic litter and microplastics from four ocean beaches in the Niterói municipality was evaluated in winter and summer. The collection and preparation of microplastic sample procedures followed on the protocol developed by the RLA7025 Project of the International Atomic Energy Agency. Marine debris followed to the United Nations Environment Program protocol. The polymer was characterized by ATR-FTIR technique.The Clean Coast Index was used to determine the degree of dirt on the beaches. Polyethylene (43%) and Polystyrene (52%) were the most abundant microplastics. The plastic is the most abundant category; representing 85% in winter and 73% in summer.The main sources are related to the consumption of drinks and food. These results emphasize the importance of reverse logistics and the value chain for packaging material and the need for effective actions managing solid waste.

1. Introduction

There is strong evidence that the global abundance and distribution of plastic particles has increased dramatically in the marine environment in recent decades, causing impacts on marine fauna. This spread was driven by rapid growth in the production and use of plastic, aggravated by the increase in single-use plastic consumption and the current culture of "disposal" (Geyer et al., 2017; Lebreton et al., 2019), reinforced by the linear economic models that ignored the need for integrated waste management. The occurrence of plastic debris in coastal and marine environments have been reported worldwide for at least 45 years (Carpenter and Smith, 1972; Shiber, 1979; Turner and Holmes, 2011; Eriksen et al., 2014; Veerasingam et al., 2016; Garcés-Ordóñez et al., 2020 and 2021). This debris can be classified according to size and range from microplastics to macroplastics (Gesamp, 2019; Mazariegos-Ortíz et al., 2020).

The term microplastic is used for water-insoluble solid plastic particles of 5 mm or less in size (Olivatto et al., 2018), but some researchers consider even lower values (Andrady, 2011). Microplastics originate from different polymers that, due to characteristics such as size, low density, composition, and persistence in the environment, contribute to their global dispersion through marine currents (Endo et al., 2005; Ogata et al., 2009; Heskett et al., 2012).

Microplastics are classified as primary and secondary. The primaries are plastics produced on the microscale to be used in the cosmetics industry, pharmaceutical industry, abrasives, personal care products, paints, cleaning products, among other applications (Li et al., 2016). Depending on the application, primary microplastics may vary in shape, size and composition (Li et al., 2016). Secondaries are the microplastic that comes from the degradation and fragmentation of relatively larger plastics. This fragmentation can be caused by physical efforts, chemical and biological reactions, and weather conditions, which end up affecting the integrity of the material when it is discarded in the environment (Li et al., 2016). In this context, state that secondary microplastics are the majority, and their multiplication in the ecosystem are due to the entry of plastic debris from different sources.

Each year, 400 Mt. of plastic waste is generated, of which 175 Mt. goes into landfills and the natural environment (Geyer et al., 2017). The risks posed by microplastics to the marine ecosystem and human health are consequences of decades of production without alignment with the

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https://doi.org/10.1016/j.marpolbul.2021.113161
Received 12 August 2021; Received in revised form 11 November 2021; Accepted 12 November 2021
Available online 25 November 2021

proper disposal of these materials. The entry of this waste into the open ocean and beaches is influenced by several factors such as weather and tidal patterns, proximity to urban, industrial, and recreational areas, seaways, and fishing areas (Galgani et al., 2015). The accumulation rates on the surface, seabed, or sediment, vary with proximity to urban activities, wind and ocean currents, coastal geography and points of entry into the systems (Galgani et al., 2015; Barnes et al., 2009). Thus, the microplastic distributions in marine environments, both primary and secondary, can occur through several paths (Dris et al., 2015). The dispersion of the continent to the marine environment can occur due to atmospheric precipitation, runoff and occasional discharges (wastewater treatment plants, combined sewage overflows), wind, rivers, rainwater, accidental spills, or improper disposal of solid waste (Browne et al., 2015; Dris et al., 2015).

Plastics have been harming marine animals for years, but recent research on microplastics shows that because they act as transports for toxic substances, they provide a greater risk than what is figured (Olivatto et al., 2018; Silva et al., 2019a, 2019b). Field and laboratory studies have demonstrated the widespread occurrence of microplastic ingestion by aquatic fauna at different trophic levels in the aquatic food chain. Moura and Vianna (2020) evaluated the main interactions between marine fish and plastic debris from a scientometric perspective and registered 116 documents reporting high intake and low entanglement interactions for 310 species.

Once ingested, microplastics can induce uncertain consequences for the health of aquatic organisms. Exposure to microplastics causes various adverse effects on marine biota and primary producers to even top predators, including humans. So far, studies on the toxicity of microplastics have focused mainly on the possible harmful effects of ingested microplastics (including associated toxins) on aquatic fauna (Wang et al., 2019). Microplastics can be a source or vector for some chemical contaminants (Naik et al., 2019) that could increase or be the principal cause for bioaccumulation on the trophic levels.

Some evaluation studies of microplastics and marine debris have been developed on beaches in the State of Rio de Janeiro (Olivatto et al., 2018; Silva et al., 2016; Silva et al., 2019a, 2019b). However, these studies only address the quantification and physical characterization of these materials. There is a lack of studies involving the chemical characterization of microplastics, allowing the inference of possible sources of these pollutants.

The oceanic region of Niterói has a coastal plain with beaches, lagoons, rocky shores, sandbanks, and preservation areas of the Atlantic Forest, of great importance for environmental preservation and biodiversity. The region has been undergoing an urbanization process since the 1940s, intensified in the 1970s, causing a series of transformations in the landscape of this coast, through the destruction of restinga vegetation, removal of dunes, and occupation of banks of the Piratininga and Itaipu lagoons. Since then, problems related to garbage and sewage pollution have become frequent and affect the region's beaches and lagoons (da Silva et al., 2009).

In this context, this paper aims to identify, quantify, and characterize marine debris and microplastics in beach sands of the Oceanic Region of Niterói and evaluate the beach's cleanliness through the Clean Coast Index (CCI). Niterói has its beaches as tourist spots, and waste management was a major challenge in the 2013–2033 strategic plan (Niterói, 2020). It is expected that the results of this work will contribute to supporting actions for the reduction of marine litter sources and the conservation and sustainable use of the oceans and marine resources, as defined in Objective 14 - Life in Water, which comprises the Sustainable Development Goals (SDG) - of the United Nations (UN).

2. Materials and methods

2.1. Study area

The municipality of Niterói is in the eastern portion of Guanabara Bay (22°53′00" S, 43°06′13" W), has an approximate area of 129.3 km^2. Niterói is one of the 22 municipalities that integrate the Metropolitan Region of the Rio de Janeiro State, also known as Grande Rio. The beaches of the Itaipu (22°58′S, 43°02′W), Piratininga (22°57′S, 43°05′W), Sossego (22°57′S, 43°04′W) and Camboinhas (22°57′S, 43°03′W), make up the Ocean Region of Niterói, totaling an area of about 50 km^2 (Fig. 1). The Piratininga is considered the most urbanized beach and the longest in the Oceanic region, with approximately 2.7 km (Eccard et al., 2017). Its left end is connected to the Piratininga Lagoon through an artificial channel. The Sossego Beach, located between the Piratininga and Camboinhas beaches, shows a discreet sand strip of 140 m in length. It was defined by Davis and Fitzgerald (2004) as "pocket beaches", nestled between rocky promontories that difficult the sediment transport between this confined beach and adjacent areas. Due to its difficult access to tourists, it is one of the cleanest beaches in Niterói. The Camboinhas and Itaipu beaches formed a single beach arch of 3.3 km in length. From the 70s onwards, they were divided due to the opening of a channel to connect the Itaipu Lagoon to the sea (Santos et al., 2004). Currently, the Itaipu beach is 0.8 km long and has an approximate north-south orientation, located at the eastern end of the Itaipu cove. It is home to a colony of artisanal fishermen and small restaurants. Its sands are often crowded with tourists on weekends. The Camboinhas beach, currently 2.4 km long, is mainly made up of high-end residential homes. However, the area close to the sand strip has suffered a disorderly occupation (including areas on fixed dunes), housing several kiosks (bars) that are usually crowded with tourists in the summer (Farias, 2016).

Therefore, the Oceanic Region of Niterói stands out as one of the important leisure centers in the Rio de Janeiro State. The high season periods are essential for the local community's economy, from which tourist and artisanal fishing activities stand out. However, their urban and residential areas show several environmental issues, such as engineering structures failures (several buildings have been constructed practically inside the post-beach), high concentrations of commercial establishments, disorderly occupation of kiosks on constituted land of fixed dunes. The main consequences are, for example, the suppression of restinga vegetations and erosive process occurrence. In addition to suffering from local insufficient basic sanitation, these beaches receive significant marine litter contributions from the Guanabara Bay, brought by marine currents. Therefore, insufficient basic sanitation, improper disposal of solid and toxic wastes, real estate speculation, and unsustainable tourism create serious negative environmental impacts like infectious diseases, land and water pollution, obstruction of drains, and loss of biodiversity (Farias, 2016).

2.2. Marine litter sampling

The methodology used for marine litter analysis was based on the collection, qualification, and quantification of samples, by using the Guidelines on Survey and Monitoring of Marine Litter (UNEP, 2009). The marine litter samplings were carried out in September 2019 (during the winter or low season) and January–March 2019 (summer or high season) to represent contrasting scenarios for beach tourism (UNEP / IOC, 2009) in the Piratininga, Sossego, Camboinhas, and Itaipu beaches. In order to obtain amount and type distributions of debris, 20 m length longitudinal transects (measured parallel to the high tide line) were set up on each one of the beaches. Each transect had variable width since they ranged from the high tide line to the beginning of restinga vegetation. Marine litters larger than 1 cm size were manually sampled by three researchers for 20 min. This procedure was adopted because it facilitated visual debris detection on each beach. The waste samples were individually packed in properly identified plastic bags.

At the laboratory, the marine litter was weighed, segregated, and subdivided according to its type of material or original use, such as rubber, foam, styrofoam, metal, nylon, paper, plastic, fabric, Tetra Pak packaging, glass (UNEP / IOC / FAO, 2017).

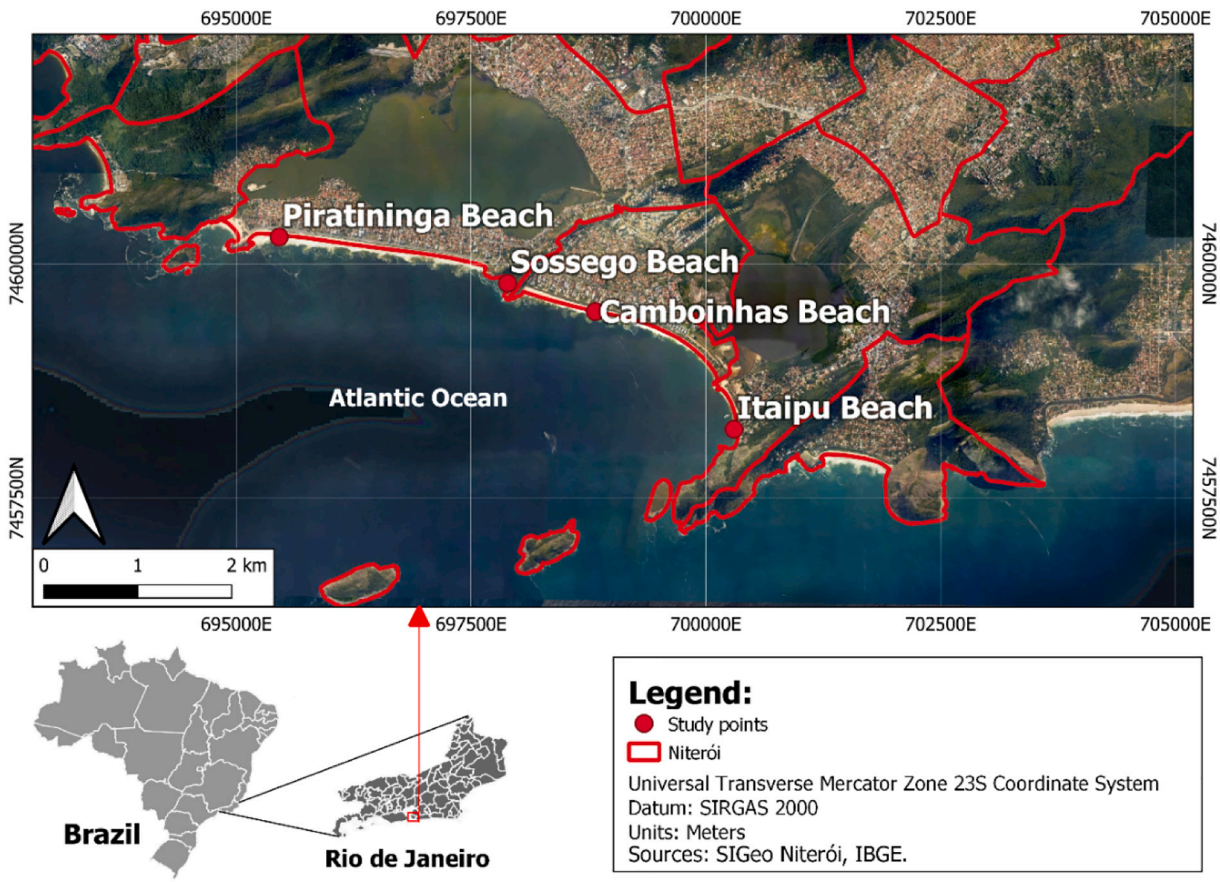

Fig. 1. Map of the study area showing the sampling points.

2.3. Microplastic sampling

The beach sand samplings in the Piratininga, Sossego, Camboinhas, and Itaipu also took place in September 2019 (winter or dry period) and January–March 2019 (summer or wet period). For this purpose, 100 m length horizontal transects on the high tide line of each beach were established. Each transect was divided into five equidistant points and georeferenced by a portable GPS receiver (GARMIN). In each point, a quadrant of 0.25m^2 (50 cm × 50 cm) was delimited. The superficial sand layer (1.0 cm thick) of each quadrant was collected by using a stainless-steel spatula. This procedure allowed collecting five sand samples per beach per season, totaling 20 sand samples. The samples were identified, stored in aluminum buckets, and transported to the LARA for analysis. Once at the laboratory, each sand sample was previously weighed (wet weight), deposited on an aluminum tray, and covered with a perforated aluminum sheet, which facilitates water evaporation while avoiding cross-contamination of airborne particles. Then, they were dried at 60 °C for about 72 h, reaching the dry weight (d.w.).

Although the microplastic size range is defined between 1 μm and 5 mm, in this study, microplastic debris was considered as particles ranging between 1 mm and 5 mm due to methodological limitations (our ATR-FTIR system can produce good analyses in this size range). Therefore, a set of three sieves was used in a sieve shaker: 4.75 mm, 2.36 mm, and 1.00 mm meshes. The material retained in the 4.75 mm mesh was discarded. The separation of the microplastic from the sand was performed by the flotation or density separation process using a NaCl saturated solution (1.2 g/cm^3). The dry sand samples were then individually mixed in the saline solution and manually stirred for 2 min. The beckers were covered with aluminum foil and left to rest for 5 h, adequate time for better microplastic separation from the sand particles. The Beckers were covered with aluminum foil and left to rest for 5 h, adequate time for better microplastic separation from the sand particles. This process was repeated three times to ensure greater efficiency in the plastic material extraction (Besley et al., 2017). In the end, about 80% of the microplastics present in the sample were obtained.

2.4. Microplastic characterization

For the physical characterizations, the microplastic samples were visually quantified and classified by size shape and color categories using an optical stereomicroscope (Micros Austria, model Ladybird MZ1240 Trinocular that uses a Microvisible Image Analyzing Software), which allows a sample magnification of up to 40 times. The photographic images obtained were stored and used for detailed observation of the morphological characteristics of each microplastic category, facilitating both the evaluation of the plastic material degradation process and as an initial diagnosis of its source (Fig. 2).

For the chemical characterization, the polymer types were identified applying the mid-infrared spectroscopy (MIRS) technique. Therefore, it was used an attenuated total reflectance-Fourier transform infrared (ATR-FTIR) spectrometer, with an ATR holder in a Tensor II Fourier transform spectrometer (Bruker Optics Inc., Ettlingen, DE). For each sample spectrum, 16 scans (at a resolution of 4 cm^{-1}) were combined in the mid-infrared range of wavelengths from 4000 to 400 cm^{-1} (Anjos et al., 2020). The polymeric identification was carried out by comparing the characteristic peaks of the spectra obtained with the characteristic peaks of each polymer based on the library of Bruker's OPUS 7.5 software and confirmed with (Jung et al., 2018). Absorption bands represent specific wavelengths in the electromagnetic spectrum characteristic of a particular substance and can be used to identify it (Fig. 3).

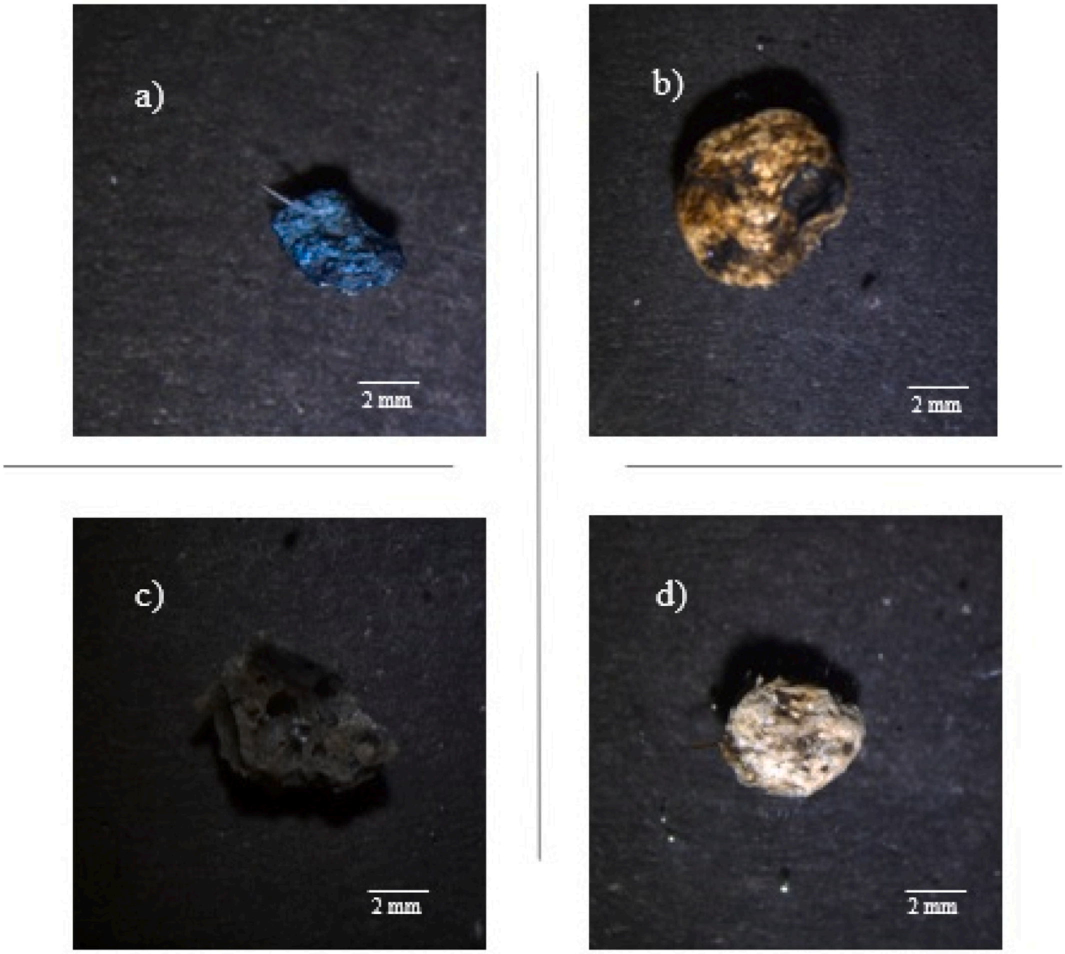

Fig. 2. Illustration of de physical characteristics (shape, color, and size categories) of microplastic samples observed under a binocular stereo microscope: (a) fragment, (b) styrofoam, (c) fragment, and (d) styrofoam.

2.5. Clean Coast Index and statistical analysis

The Clean Coast Index (CCI) was initially proposed by Alkalay et al. (2007) as a statistical method to determine the number of items in the sampling frame (sampled area) on the Israel beaches. This index is exclusive for plastic items and classifies the degree of pollution of the beaches according to the amount of plastic in its sand. This measurement tool is derived from the "Clean Coast" Program and can be used as an index to assess the plastic debris pollution level on the beaches. According to the CCI, plastic debris is solid wastes larger than 2 mm in size and manufactured by artificial (or semi-artificial) materials, such as styrofoam scraps, plastic bags, plastic containers, etc. Table 1 shows the CCI classifications.

The CCI calculation is performed following Eqs. (1) to (2). The density of items on each beach (D) is calculated through the relationship between the number of sampled debris and the transect area:

$$D = \frac{\text{n}^\circ\text{de items}}{\text{X (m)}x\ 20\ (m)} \quad (1)$$

where X is the transect length and 20 m is its fixed width. The result is expressed in items per m-^{2}. If only plastic items are considered, the CCI can be calculated by multiplying the plastic density (Dp) by a correction coefficient (K):

$$\text{CCI} = \text{Dp}\ K \quad (2)$$

K is a coefficient entered by statistical convention to facilitate the result interpretation. Its function is only to avoid the presence of fractional numbers (for example, 0.1 item/m^2). Alkalay et al. (2007) suggest K = 20, which facilitates the analysis when adopting a whole number. Although the CCI can demonstrate the anthropic potential of polluting sources, environmental perception is the one that reveals how much man understands his unsustainable actions and how they impact the environment (da Silva et al., 2021).

Principal Component Analysis (PCA) and Cluster Analysis were applied to integrate all the analyzed parameters. Shape and chemical classifications of the microplastics were the parameters considered for the PCA. For Cluster Analysis, marine debris and MPs were considered. These statistical analyzes were performed using software R version 3.5.1. (R CORE TEAM, 2018).

3. Results and discussion

3.1. Marine debris

Tourism and recreation activities on the Brazilian beaches are traditionally more intense during the summer season. However, the highest abundances/concentrations of marine litter in the Sossego and Camboinhas beaches were observed during the winter (Fig. 4). The debris was mainly distributed along the high tide line and close to the restinga vegetation, similarly observed by Silva et al. (2015).

There are two possible explanations for the increased abundance of

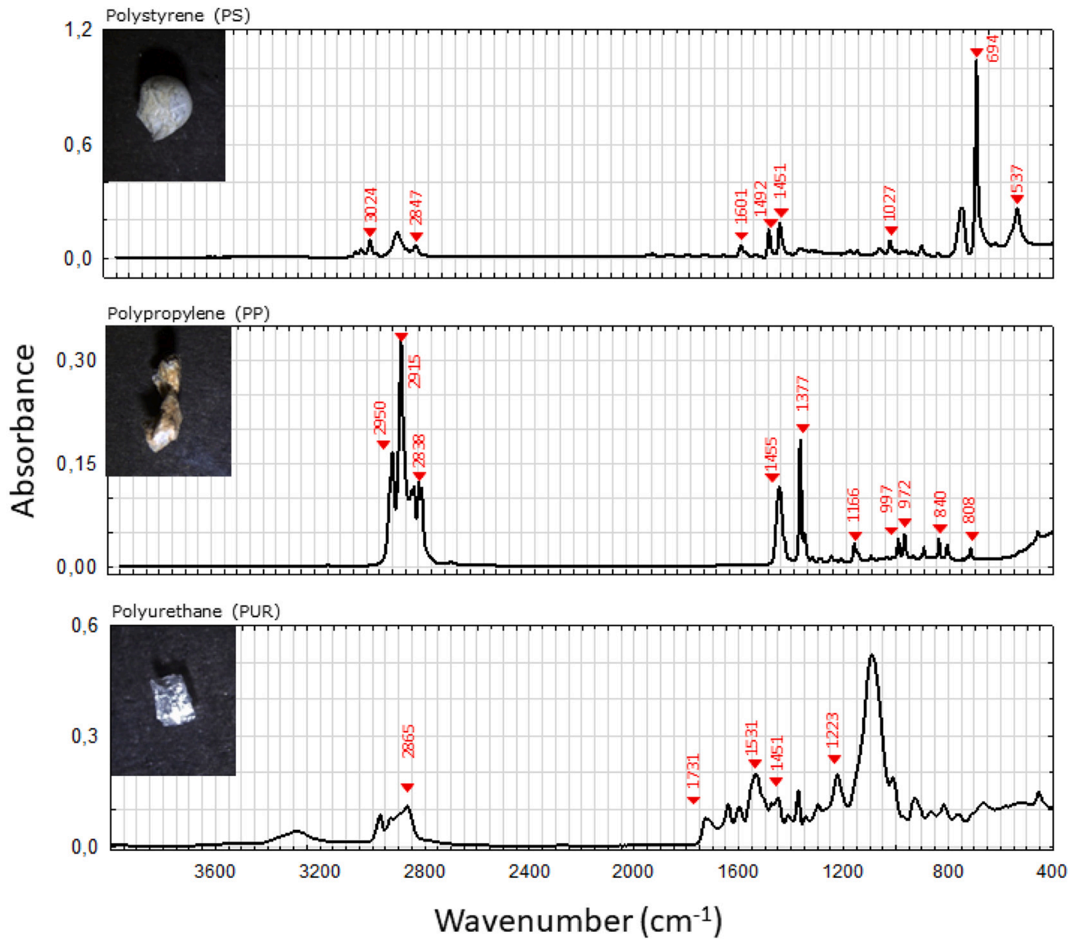

Fig. 3. Mid-infrared spectra of the three main polymers observed in our microplastic samples: a) polystyrene - PS, (b) polypropylene - PP and (c) polyurethane -PUR.

Table 1
Clean Coast Index (Alkalay et al., 2007).

CCI	Very clean[a]	Clean[b]	Moderate[c]	Dirty[d]	Extremely dirty[e]
Numeric Index (K)	0–2	2–5	5–10	10–20	20+
Density (Unit/m^2)	0–0.1	0.1–0.25	0.25–0.5	0.5–1	>1

[a] No debris is observed in the coastal region.
[b] No debris is observed in much of the coastal region.
[c] A few debris are observed in the coastal region.
[d] Several debris are observed in the coastal region.
[e] The coastal region is fully covered by debris.

marine plastic litter during the winter. Marine litter can be transported by actions of the wind, tide and ocean currents, favoring the temporary or permanent solid material accumulations in the coves, which can be considered as garbage sinks. These physical actions are usually more pronounced during winter (Storrier et al., 2007a, 2007b). The higher marine litter abundance on Sossego and Camboinhas beaches may be associated with the wave convergence zone formation during this period that, associated with stormy tides, can favor the solid trash and litter depositions on the coastal zone. During the winter, it occurred high sediment mobility in coves or sheltered bays due to both actions of longshore drifts and emerged and submerged shorelines, which promote the strong return of marine currents, being more prominent in the Sossego beach (Eccard et al., 2017; Andrade and Gerson, 2014). Therefore, the morphological and hydrodynamic characteristics of the Piratinginga, Sossego, Camboinhas, and Itaipu beaches could favor the marine litter accumulations in a few specific coastal areas (Santos et al., 2004; Araújo et al., 2011).

On the older hand, the Municipal Urban Cleaning Company of Niterói (CLIN) carries out the “Summer Operation” between October and March, in which informational folders and plastic bags are distributed to make tourists aware of the marine and coastal pollution issues. They are encouraged to dispose of the solid waste correctly. In addition, nighttime beach cleaning activities are intensified (Niterói, 2013, 2020, 2021). However, these tasks do not occur with the same intensity in the winter, with the cleaning being carried out only on holidays and a few weekends.

The tourist flows and cleaning activity efficiency in the beaches can be evaluated by small debris detection, such as cigarette butts. Fig. 5 highlights that the highest percentage of inadequate cigarette butt disposals on the beaches occurs mainly in the summer. The Itaipu beach stood out to show the largest tourist flow and, consequently, a high discard of cigarette butts during the summer. Similarly, it was the beach that showed the greatest abundance of marine litter in the summer. This trend is corroborated by Garcés-Ordóñez et al. (2020) since the greatest abundance of small debris that generates toxic plastic pollution in Santa Marta Beach (Colombia) comes from cigarette butts, pieces of plastic, and metal. They accumulate in the sands despite daily beach cleaning, as common garbage collection mechanisms are ineffective in removal small garbage. Santa Marta Beach is famous for its high tourist occupation during the summer.

Although Sossego Beach is characterized by a small stretch of sand (140 m) surrounded by small rocky cliffs, located in an environmental preservation area (Niterói, 2013) and difficult access for bathers (only by a small trail), it presented a high concentration of debris in its sands.

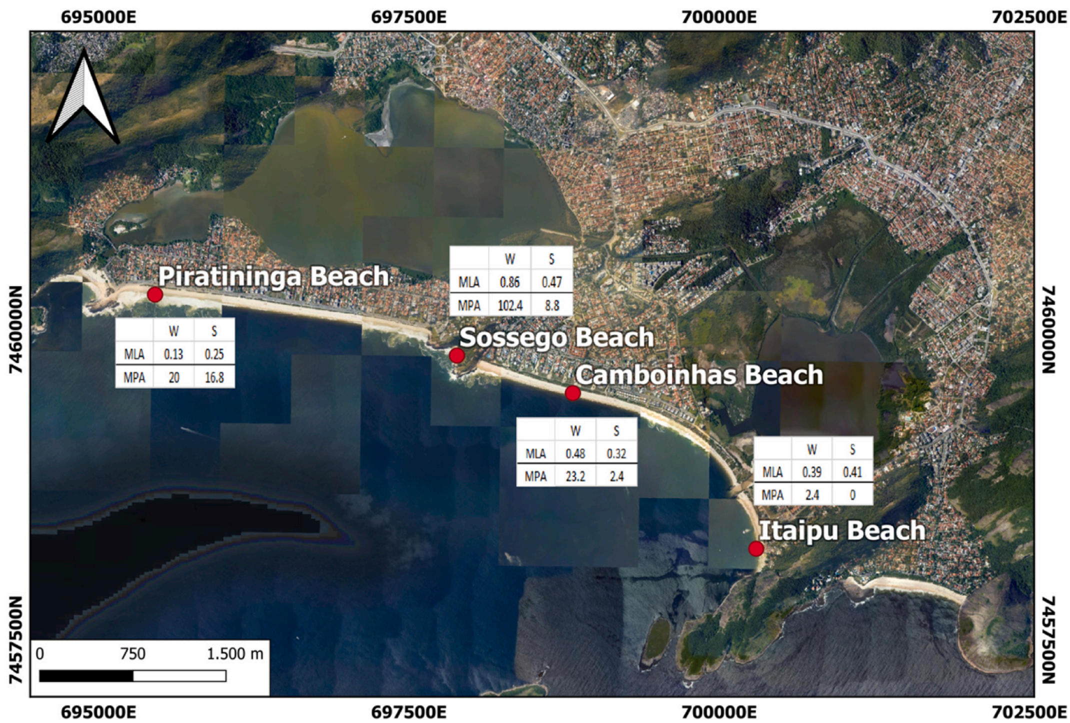

Fig. 4. Marine Litter and microplastic abundances (MLA and MPA in units of item/m^2, respectively) observed in the winter (W) and summer (S) in the Piratininga, Sossego, Camboinhas and Itaipu beaches.

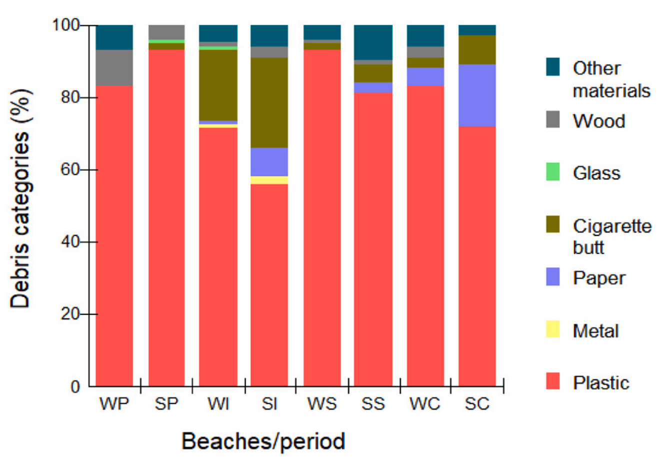

Fig. 5. Small debris abundance from the beach sands. WP - winter Piratininga; SP - summer Piratininga; WI - winter Itaipu; SI - summer Itaipu; WS - winter Sossego; SS - summer Sossego; WC – winter Camboinhas and; SC – summer Camboinhas.

The results are consistent with its high use by tourists during summer (11 to 20 m^2 per bather; Silva et al., 2016) and the lack of mechanized public cleaning. It should be noted that even with the high intensity of use, there is no access to this beach by bus, and the cars that arrive are parked far from the beach due to its natural structure. The place does not have kiosks and restaurants, with only beach vendors (mainly residents), as reported in a study by Solinho (2016). The absence of basic actions taken by users was also evidenced, such as collecting their debris and disposing of it in dumps, aligned with an adequate management, structured by signs with information to users in order to maintain it through awareness and preservation. Due to the difficult access, there is a deficiency in public cleaning, which is carried out only when the sands are full of anthropic and natural debris.

It is worth mentioning that the scenic beauty and the quality of the waters of Sossego and Camboinhas beaches favor the intense frequency of bathers. Despite the high rate of debris in the sand, recent water quality results (2012 to 2019) of the beaches of Niterói classify the Sossego beach as excellent concerning water quality (INEA, 2020). Silva et al., 2016 showed that the average area occupied by bathers was 2 m^2 of sand in the rainy season (very high) and 12 m^2 in the dry season (normal) for Sossego beach and approximately 6 m^2 of sand in the rainy season (high) and 16 m^2 in the dry season (normal) Camboinhas beach. Camboinhas's extension allows more space for users and favorable conditions for the daily mechanized night cleaning service (carried out through agricultural tractors with attached cleaning screens), as described in the Municipal Solid Waste Plan of Niterói (Niterói, 2012).

In the present study, the categories were classified into plastic, metal, paper, cigarette butts, glass, wood, and other materials (different materials in their composition, such as plastic, aluminum and cardboard). The most abundant item category was plastic, representing 85% of all items collected in winter, and 73% in summer. These results reflect a worldwide trend and corroborate with other results (Alkalay et al., 2007; Silva et al., 2015; Turra et al., 2014). The results are also in line with what has been published on marine pollution in Brazil. Silva et al. (2019a, 2019b), when compiling works carried out on marine pollution in Brazil, showed plastic waste as the most abundant in a total of 16 articles, seven in the Northeast, five in the Southeast, and four in the south region of Brazil.

It should be noted that Marin et al. (2019) identified that plastic items corresponded to most (69%) of the items collected on 25 beaches in Santa Catarina, noting that on most beaches, plastic items reached a percentage higher than 80% of the total items collected. The percentage of poorly managed plastics reaching the sea is highly variable and dependent on local factors such as weather conditions, topography, vegetation, waste removal infrastructure, beach cleaning and rainwater capture that can carry improperly disposed materials (Jambeck et al., 2015; Sebille et al., 2015; UNEP, 2009).

The data referring to Itaipu beach corroborate the results presented by Silva et al. (2015), who showed a greater amount of debris in the summer (January and February), justified by a much higher number of visitors and associated consumption of food and drinks. The authors also highlighted the drag caused by rain and wind, pointing out that bathers usually collect their garbage and leave it on the high part of the beach. Araújo et al. (2011) and Portz et al. (2011) also showed that the largest amounts of debris accumulate on the beaches during high season.

Timbó et al. (2019), in the diagnosis of the environmental perception of users of the beaches of Itaipu and Piratininga, revealed that the beach of Itaipu was considered dirty by its users and plastic was identified as the most abundant waste in both beaches. The users interviewed, even claiming that they deposit their waste in the trash, attribute the presence of these in the sand to the lack of education of the population, citing that the responsibility of maintaining the beach clean is everyone's duty (government, traders, bathers and residents) (Timbó et al., 2019).

In the present study, the percentage of the plastic category stood out on all beaches in the two periods (Fig. 3), with Sossego and Piratininga beaches being the most representative, 93% in winter and 93% in summer, respectively. The predominance of plastic is relevant and similar to other studies, like Silva et al. (2016) that found a large amount of marine debris on Sossego beach (1390 units), equivalent to 18.6 kg, with the prevalence of plastic with 966 units. The authors justified the intensity by the lack of adequate supervision and management and the low frequency of garbage collection, corroborating our results. These results show similarities with others, such as the MARPLAST Project, which highlighted that 90% of the monitored waste on beaches and sandbanks on the Brazilian coast consists of plastic waste (Turra et al., 2014).

In this study, after plastic, the most representative category was the cigarette butt, standing out on the beaches of Itaipu and Sossego. It is worth mentioning that this category was not seen at Piratininga Beach in the winter period. There are debates about the classification of cigarette butts as plastics. In this study, it was considered that they are mainly composed of cellulose acetate and was highlighted when presented as categories; however, they were considered as plastic for calculating the CCI (ISO 472: 2013 defines the terms used in the plastics industry, including terms and definitions that appear in the plastics standards and terms and definitions general polymers science used in all aspects of plastics technology). The concern with the presence of cigarette butts is justified because they have contaminants and chemical substances produced during combustion, which can be lethal to microorganisms (Moerma, 2009), in addition to being confused with food by marine organisms (Bezerra et al., 2009).

It is observed that the paper category (Fig. 5) had its prominence after the plastic item on Camboinhas beach, representing 17% of the material collected in the summer, with a predominance of the kiosk order pad. The paper also stood out on the Itaipu beach, representing 8% in the summer. These beaches are similar, having several kiosks in their extension. Santos and Barros (2018) reported 17 kiosks along Camboinhas beach, portraying several points of conflict and inefficient beach management by the actors involved. These authors also pointed out the non-compliance with the plan for cleaning and selective waste collection, indicating that the results found showed the compliance of the kiosks could contribute to the overall process of governance and competence of the bodies involved, mitigating other existing conflicts and attracting investments to the beach.

Fig. 6 indicates the percentages of the main debris found on analyzed beaches. Food packaging (involved in the plastic category) stood out, representing 45% on Piratininga beach in summer and 36% in Camboinhas in winter. It is estimated that the packaging sector is the most relevant in the world production of plastics, constituting around 40% of all global production of plastic materials (Kaza et al., 2018). These generally have a very short service life as they are single-use materials. Thus, the packaging sector is dominant in the issue of waste generation and its losses to the environment, being responsible for about half of the waste generated globally and need to be the main analysis focus on the problem of plastic pollution (Plastics Europe, 2018). The absence of the possibility of recycling contributes to the high volume of plastic material generated, which makes plastic packaging predominant in the waste found in recycling cooperatives (Aramian, Ghellere and Carmo, 2019). These materials have a high impact when disposed of on the environment as debris. They are products with low added value but with high possibilities of being managed in closed supply chains. When this waste is disposed of in the environment, it does not undergo an integrated management attributed to the residues (reverse logistics or shared responsibility). This would enable the relocation of plastic material as a by-product in industry or for proper disposal.

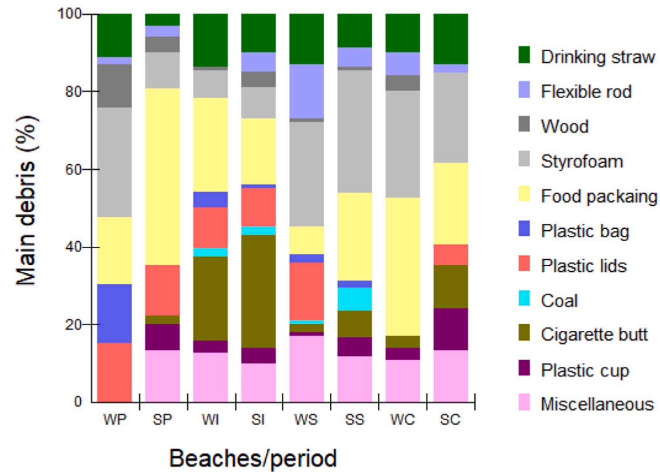

Fig. 6. Percentage of the main debris found on the beaches (WP - winter Piratininga), (SP - summer Piratininga), (WI - winter Itaipu), (SI - summer Itaipu), (WS - winter Sossego), (SS - summer Sossego), (WC – winter Camboinhas) e (SC – summer Camboinhas).

It is interesting to note that, in this study, the absence of aluminum cans were observed in the beaches of Piratininga, Sossego and Camboinhas in both periods. Since the consumption of beer and soft drinks in this type of container is common in a beach environment, the absence of this material could be associated to the fact that it is collected by waste pickers for recycling. According to the Brazilian Aluminum Association (ABAL), aluminum recycling in Brazil currently operates with efficiency rates above the world average. Thus, in 2018, Brazil remained among the leading countries in the recycling of aluminum cans. Of the 330.3 thousand tons of cans that were sold in the period, 319.9 thousand tons were recycled. Other authors have also identified a small number of bottles or glass fragments and the absence of aluminum cans (Rosa, 2020) and associated with a socioeconomic consequence because they have economic value as recyclable materials and be collected and sold by many waste pickers. Therefore, the importance of reverse logistics and the value chain for packaging material is emphasized, aiming to reduce marine pollution.

The styrofoam category stood out on the beaches of Sossego, Camboinhas and Piratininga (winter). The styrofoam category was subdivided into two different classes: fragments of styrofoam and food packaging (styrofoam). These items are related to the consumption of food and drinks on the beaches since they use styrofoam containers to keep beverages and food cool when at the beach, which points to the relevance of bathers and other users in local pollution, also observed in other studies (Kuo, 2014; Pasternak et al., 2017).

Farias (2016) found in a study on the beach of Piratininga, a greater amount of marine debris in the rainy season (summer), contrary to what is observed here, the greatest amount was seen in the dry period (winter). Due to its geographical location and sea currents, the amount of garbage on Piratininga beach is influenced by Guanabara Bay, which indicates that the beaches of Sossego and Camboinhas, which are on the west side of Piratininga beach, are also influenced by the same currents (Farias, 2016; Silva et al., 2016).

In the other materials category, charcoal stood out in the summer at

Sossego beach and was also evidenced, in a smaller amount, at Itaipu beach, originated from a point source (users/bathers).

It is observed that the plastic bag item was not found on Camboinhas beach. At Piratininga beach, plastic bags represented 15% of the total debris collected in winter. In the summer, even with a higher amount of debris, this item was not evidenced. This result can be associated with the frequency of cleaning attributed to the beaches, as well as the implementation of State Law No. 8473 of July 15, 2019 (Rio de Janeiro, 2019), whose main objective was to reduce the excess of plastic bags discarded in the environment. According to ASSERJ (2019), in the first year of implementation of the law, the reduction exceeded the target of 40%, with a reduction of 50%.

According to these results, the possible sources of the waste materials found were generated by beach users, in line with an inadequate waste management structure by the municipality.

3.1.1. Waste container points and Clean Coast Index (CCI)

A total of 22 baskets were recorded on the Piratininga beach boardwalk, with an average distance of 123 m between points. It is observed that from the sampling point of the debris (beach sand) to the nearest point of the container, an approximate distance of 54 m was recorded. On Camboinhas beach, 06 (six) waste containers were distributed on the boardwalk, with an average distance of 123 m between the spots. It is observed that from the sampled point to the nearest point of the container, an approximate distance of 61 m was recorded.

At Sossego beach, only 01 (one) container point was registered for the storage of waste generated by bathers, which is located near the guardhouse. In this place, the bather has access when arriving at the beach and when leaving the beach. An approximate distance of 129 m was recorded from this point to the beach sand, where the debris was sampled. At Itaipu beach, 02 (two) waste containers were recorded, with an average of 47 m of distance between points. It is observed that from the sampled point of collection of debris (beach sand) to the nearest point of the container, an approximate distance of 190 m was recorded. Correlating the number of container points and the amount of debris sampled, the beaches of Sossego (winter) and Itaipu (summer) stand out, both with the largest number of debris and the lowest number of waste containers available.

Table 2 presents the results considering the CCI and the degree of cleanliness for the points sampled during the study. Debris was found at all points, totaling 2242 items. The highest concentration of debris occurred at Sossego beach with 0.86 items.m^{-1} (winter), being classified as "dirty", and the lowest at Piratininga beach with 0.13 items.m^{-1} (winter), classified as "clean". Piratininga beach has a larger number of containers, which cooperates with the result found, with the lowest number of debris in both periods. Sossego beach, with only one point and more difficult access, presented the greater amount of debris in the winter, as well as in Itaipu, with only 02 points and greater distance between the sample collection point and the containers of garbage, presented the greater amount of debris in the summer.

Plastic is the main component of marine debris, and in the Clean Coast Index, this item is used as an input variable for the calculation, which is satisfactory in this study, as all beaches presented this category as a highlight, representing 89% of the debris found. Fernandino (2012) evaluated the CCI on beaches in São Vicente (São Paulo, Brazil), and also found a predominance of plastic (82.16%).

Another issue to be addressed refers to the structure of the waste containers: there is no standardization (color and identification of residues) between the beaches. At Piratininga and Sossego beaches, containers are identified with the CLIN company logo (orange color). In Camboinhas, these are identified with the gray logo of the Residents' Association – SOPRECAM (Society for Urban and Ecological Preservation of Camboinhas). In Itaipu, it was not possible to assess the color and identification of the containers due to physical wear and tear.

Reducing inappropriate waste disposal will require proactive involvement, public awareness, and a better understanding of users' needs and behaviors. A scenario of attention is observed since the fact that the container points are far from the beach sand will imply a change in user behavior. The awareness of being responsible for his own waste is an essential factor to contribute to the environmental quality of the place. However, it is the duty of the public power to guarantee an adequate structure and to ensure the citizen's right to sustainable cities, such as the right, among others, to environmental sanitation, for present and future generations (Federal Law No. 10,257 / 2001 - Art. 2 - Item I. - Brasil, 2001). Thus, environmental education actions can be stimulated with guidelines or warnings, with environmental themes in order to involve the population as responsible for the waste generated and the environment preservation.

Based on the provisions of Brazilian legislation (Law No. 12,305 of August 2, 2010, in Article 9 - Brasil, 2010), when establishing that, in the management of solid waste, the following order of priority must be observed: non-generation, reduction, reuse, recycling, solid waste treatment and environmentally appropriate final disposal of waste. In this line, it is worth assessing that, for non-generation, reduction and reuse demand, changes imply economic activities, new technologies, and the applicability of environmental management, aiming for better use of the goods involved in the production process.

Table 2
CCI results and degree of cleanliness of each beach - winter and summer.

Beaches	Period	Density (items m-^{2})	Density PL (items m-^{2})	CCI	Degree of Cleanliness
Itaipu	Winter	0,39	0,36	7,3	Moderate
	Summer	0,41	0,34	6,8	Moderate
Piratininga	Winter	0,13	0,11	2,2	Clean
	Summer	0,25	0,24	4,8	Clean
Sossego	Winter	0,86	0,80	16,0	Dirty
	Summer	0,47	0,41	8,2	Moderate
Camboinhas	Winter	0,48	0,43	8,5	Moderate
	Summer	0,32	0,25	5,0	Clean

3.2. Microplastics

It was observed that of the total number of MPs collected ($n = 220$), 84% was evidenced in the winter period and 16% in the summer, as shown in Fig. 2. All beaches presented a higher density of microplastics in the winter period. Sossego Beach presented the highest density of microplastics, with 102.4 MPs.m^{-2} in winter and 8.8 MPs.m^{-2} in summer, followed by Piratininga beach, which presented 20 MPs.m^{-2} in winter and 16.8 MPs.m^{-2} in summer, and Camboinhas beach, with 23.2 MPs.m^{-2} in winter and 2.4 MPs.m^{-2} in summer. In summer, the higher frequency of users can cause a more intense dedication of cleaning by the municipality, which contributes to the removal and dispersion of MPs, mainly in mechanized cleaning that occurs in Piratininga, Camboinhas, and Itaipu beaches.

For the winter period, Sossego beach becomes evident, with 69% of the items collected (102.4 MPs.m^{-2}), in line with the marine debris results (degree of cleanliness classified as dirty). With the accumulation of macroplastic debris ($>$ 2 cm), an increase in microplastics in the marine environment is expected since macroplastics exposed to environmental conditions suffer fragmentation and wear and tear, forming smaller particles (Julienne et al., 2019).

In Itaipu beach, 2.4 MPs.m^{-2} was collected in winter and 0 MPs.m^{-2} in summer. Compared with other MP studies carried out in Rio de Janeiro, the number of MPs found at Itaipu beach was relatively low. However, when compared to the study carried out on this same beach by Pereira (2019), these results corroborate those found by the author (5.6 MPs.m^{-2}). The beaches' format can be mentioned as a favorable factor to the scenario of the number of MPs found on Itaipu beach. As it is more internal, and consequently, the most sheltered within the Itaipu cove, this format makes it less dynamic (Eccard, 2017).

Santos et al. (2004) pointed out that the different coastal behavior in Camboinhas and Itaipu beaches during periods of extreme waves is due to the incidence and energy of the different waves along the beach, which may impact the number of microplastics that reach the beach through the oceans. Another favorable factor observed in this study, also punctuated by Pereira (2019), is the fact that Itaipu beach is highly frequented, and this causes movement in the sand, generating dispersion of the polymer particles and the movement of the superficial layer to a deeper layer.

3.2.1. Physical characterization

Of the total MPs collected during monitoring ($n = 220$), 52% were classified as styrofoam, 20% filaments, 20% fragments, 4% films, 2% pellets and 1% fibers. It is observed that this characterization highlighted the secondary MPs that arise from the fragmentation of macroplastics in the sea or on land through light, heat, chemical or physical processes (Andrady, 2011).

Fig. 7 presents the classification by type of particle for each beach and the referring period. The Styrofoam category was the predominant category in the results. Sossego beach in the winter period has the highest amount. This material is commonly used in various industrial, commercial, fishing and domestic activities, such as packaging, disposable cups, food containers, buoys and construction materials (Mazariegos-Ortíz et al., 2020). Their classification in this study was considered as secondary MPs, products of the fragmentation of macroplastics that, after undergoing a process of degradation and weathering, originate smaller fragments.

Correlating this category to the marine debris mentioned in this study, food packaging and styrofoam containers are the most abundant debris found on all beaches. This fact reinforces the cited by Silva (2016), that the presence of fragments, styrofoam and fibers can also have an origin of the discard by the population in the environment and by fishing activities. The beaches listed in this study have a strong anthropic influence related to debris. The qualitative analysis of the main detritus showed similarities between the beaches in relation to the most prevalent items (food packaging, styrofoam and straw).

It is observed that primary MPs, such as pellets, occurred in very low quantities, only at Sossego beach. The other beaches did not have the format pellet and fiber, differentiating the Itaipu beach, which also did not have the format fragments.

Regarding the characterization by color, the results indicate a predominance of white. In winter, they accounted for 62% and 49% in summer. It is observed that this percentage was highlighted by the Styrofoam category. These percentages are similar to those found by Silva (2016), who evidenced the predominance of white MPs (57%) in a marine protected coastal area, and by Lacerda (2019), who analyzed sources of plastics in ocean surface waters of Southern Brazil and Antarctica.

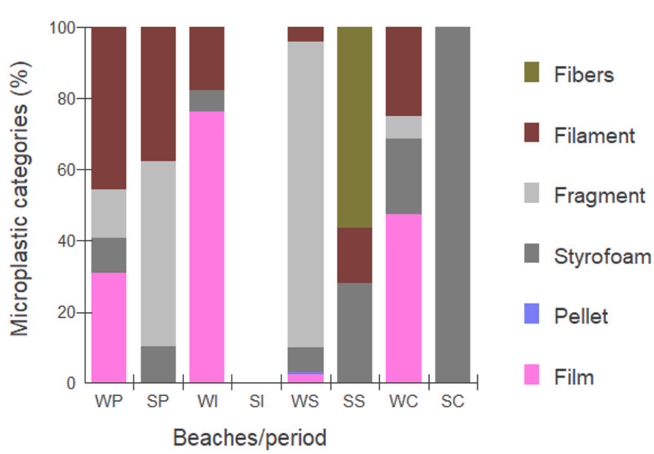

Fig. 7. Percentage by type of MPs collected in the beaches, (WP - winter Piratininga), (SP - summer Piratininga), (WI - winter Itaipu), (SI - summer Itaipu), (WS - winter Sossego), (SS - summer Sossego), (WC – winter Camboinhas) e (SC – summer Camboinhas).

The color classification criteria have a relationship with the time the material remains in the environment. Opaque and yellowish particles indicate a longer exposure time in marine environments (Brandon et al., 2016). The aged microplastics are those that have been suffering from wear and tear in the environment for a longer time, which is associated with the concentration of pollutants adsorbed on the material surface. Studies show that black-colored microplastics that age in the environment are the ones with the highest concentrations of pollutants (Endo et al., 2005; Frias et al., 2010). In a study by Mazariegos-Ortíz et al. (2020), the white-colored microplastics indicated that these particles were recent in the environment and emerged from local or nearby sources.

3.2.2. Chemical characterization

The MPs found and analyzed it is observed the highest presence of polystyrene (PS), polyethylene (PE) and polypropylene (PP) (Table 3). The higher concentration of these types of polymers may reflect the greater demand by society, as these are classified as the most used, consequently, most discarded by modern society and are the most evident in coastal marine studies (Sagawa et al., 2018; Simon-Sánchez et al., 2019). These are classified as thermoplastic and considered mechanically recyclable (due to their characteristics). PP is often used to make packaging, bottle caps, strings, laboratory equipment and straws, and PE is used in grocery bags and plastic bottles. Because PS is considered a cheap and fragile material, it is widely used in the manufacture of disposable products or products that require high transparency (Farias, 2016). This polymer is widely used in single-use articles, mainly for food packaging, which favors its presence in a beach environment. In this study, the PS corresponded mainly to the Styrofoam material in physical characterization and is in accordance with its main applications (Mazariegos-Ortíz et al., 2020). It is the material used in most disposable cups in Brazil.

To analyze the relationships between the abundance of MPs (chemical characterization and shape) throughout the study area, principal component analysis (PCA) and Cluster analysis (Fig. 9) were used. PC1 and PC2 were responsible for 82.8% of the data variability (Fig. 8). There is a high correlation between polystyrene and styrofoam, being the predominant shape and type in Sossego beach in the winter collection. In summer, Sossego beach had a lower quantity of MPs, the largest amount being characterized by the fiber shape. The Piratininga beach showed the greater influence of Polyurethane, both in winter and in summer. The Camboinhas and Itaipú beaches did not show any significant correlation, given the low amount of microplastics found.

For cluster analysis, a similarity matrix was made through the number of MPs and the amount of marine debris on the beaches, as shown in Fig. 9. In group 3, there is a similarity between the periods sampled at Itaipu beach due to the low incidence of MPs in both periods. Itaipu Beach still showed significant similarities with Camboinhas

Table 3
Distribution of polymers by percentage - winter and summer. *Anhydride Copolymer; Mixture of Polypropylene in Ethylen Propylen.

Polymer	Percentage / no. (Winter)	Percentage / no. (Summer)
Polystyrene - PS	52% ($n = 96$)	29% ($n = 10$)
Polyethylene - PE	23% ($n = 42$)	43% ($n = 15$)
Polypropylene - PP	10% ($n = 19$)	17% ($n = 06$)
Polyamide - PA	3% ($n = 05$)	3% ($n = 01$)
Polyurethane - PU	2% ($n = 03$)	6% ($n = 02$)
Polyethylene Terephthalate - PET	1% (n = 01)	–
Others*	13% (n = 19)	–

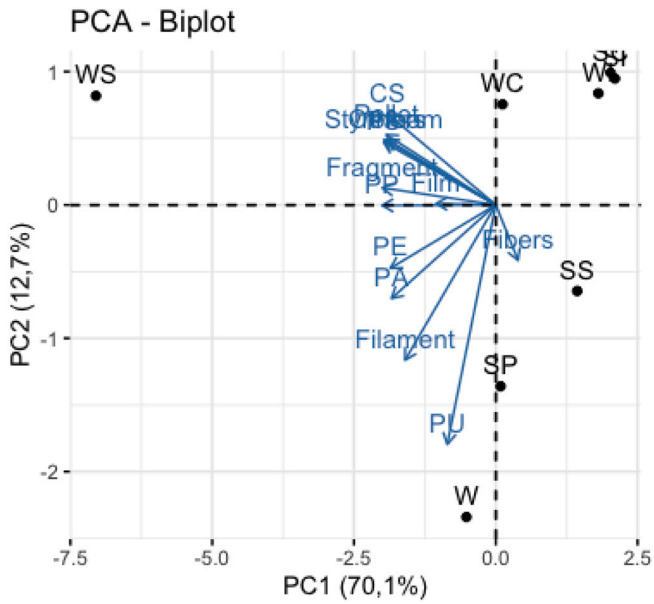

Fig. 8. Principal component analysis biplot correlating the physical and chemical classification of MPs and the beaches (SP - summer Piratininga), (WP - winter Piratininga), (SI - summer Itaipu), (WI - winter Itaipu), (SS - summer Sossego), (WS - winter Sossego), (SC – summer Camboinhas), (WC – winter Camboinhas).

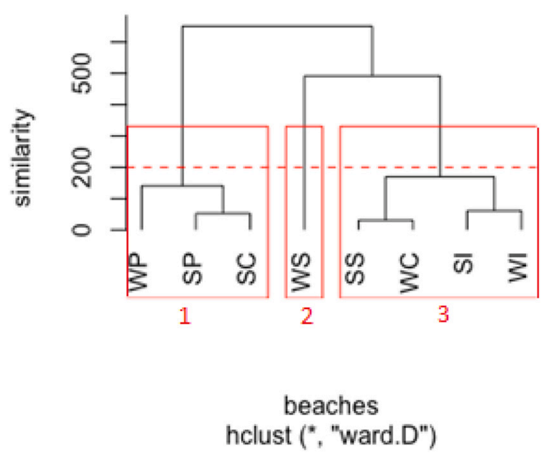

Fig. 9. Cluster analysis dendrogram based on MPs and debris data from the sampled beaches (SP - summer Piratininga), (WP - winter Piratininga), (SI - summer Itaipu), (WI - winter Itaipu), (SS - summer Sossego), (WS - winter Sossego), (SC – summer Camboinhas), (WC – winter Camboinhas).

beaches in the winter and Sossego in the summer. This similarity may be associated with the amount of detritus found on these beaches since all of them presented a degree of dirt classified as "moderate" for the periods mentioned (Table 2). Group 1 shows the similarity between the beaches of Piratininga (summer and winter) and Camboinhas in summer, associated with the fact that these were the beaches classified as "clean" from the classification of the CCI (Table 2). Sossego beach (winter) shows prominence for having a higher number of MPs and marine debris, the only one being classified as "dirty".

According to Free et al. (2014), plastics degrade more easily when they are dry and exposed on land than in water. The rate of degradation can be highly driven by factors occurring on land than in fresh or saltwater environments. According to Julienne et al. (2019), plastic polymers on the action of solar radiation facilitate the entry of oxygenated parts that lead to chemical modification and ultimately to oxidation.

In this study, it was observed that 38% of the MPs in winter were visually degraded (Fig. 2), of this percentage 22% polystyrene (PS) and 8% polyethylene (PE). In this period, the predominant beach was Piratininga. In the summer, 37% of the MPs were degraded, of this percentage 17% PE and 14% PS, showing Sossego beach as the highest influenced during this period. Some fragments of MPs had sharp and pointed edges, indicating a possible origin of the recent degradation of larger plastic parts or that were recently introduced into the marine environment. Those with rounded edges have probably been in the marine environment for longer period of time, being polished by other particles or by marine sediments (Doyle et al., 2011). Five pellets were characterized in this study, at Sossego beach, in the winter period. Of this number, three were evidenced by physical characterization as degraded, which may indicate that their deposition happened some time ago or that they were adrift for a significant time.

4. Conclusion

The marine debris results showed that plastic is the most prevalent item in the beach sands. Styrofoam and plastic packaging represented the most abundant, indicating that bath users are the likely source of these particles, since they use Styrofoam containers to keep beverages and food cool when at the beach. Based on the microplastics results, polystyrene (PS), polyethylene (PE) and polypropylene (PP) were the most abundant polymers. Styrofoam was the most representative category in the winter, and filament in the summer. Particles of these categories are considered secondary MPs and associated with the type of polymers, indicates terrestrial sources. Considering the use of these polymers, fisherman activities (fishing net filaments and Styrofoam containers) and beach users (food packaging, beverage bottles and Styrofoam containers) were the likely source, in line with an inadequate structure of waste management by the municipality (lack of garbage containers and mechanized cleaning of the beaches that can generate secondary microplastics).

The studied beaches have a strong anthropic influence related to the source of microplastics and marine debris, indicating that environmental education is a priority in the effectiveness of environmental management. Although bathers are part of the problem, the government must take its share of responsibility with more actions aimed at better management of beach cleaning, carry out actions to promote environmental education, in addition to generating more regulations for the handling of plastic.

Finally, preserving the oceans from the entry of plastics and MPs should be based on management aligned to the renewal of public policies created with a focus on controlling the production of these materials, as well as involving the plastic industries in a leading way so that initiatives and actions minimizing the presence of plastic debris on the beaches, be elaborated, based on the principles of reverse logistics and shared responsibility. Identifying the sources of plastic in the environment is crucial for defining environmental management strategies. Thus, the results of this work will contribute to supporting actions for the reduction of marine litter sources and the conservation and sustainable use of the oceans and marine resources, as defined in Objective 14 - Life in Water, which comprises the Sustainable Development Goals (SDG) of the United Nations (UN).

CRediT authorship contribution statement

EFS - Conceptualization, Methodology, Validation, Visualization, Formal & Statistical analysis, Investigation, Writing;

DFC - Conceptualization, Methodology, Validation, Visualization, Formal & Statistical analysis, Investigation, Writing, Supervision, Resources;

MCM – Conceptualization, Methodology, Investigation, Writing - Review & Editing;

CAS - Writing - Review & Editing, Visualization;

BBIC - Formal analysis, Writing - Review & Editing, Visualization;

DMOC - Statistical analysis;

RMA - Visualization, Validation, Writing - Review & Editing, Resources, Project administration, Funding acquisition;

MV - Conceptualization, Methodology, Validation, Visualization, Formal & Statistical analysis, Investigation, Writing, Supervision, Resources.

All authors read and approved the final manuscript.

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.

Acknowledgments

The authors would like to thank the funding agencies for their financial support: IAEA (International Atomic Energy Agency: RLA7025), CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico: 149052/2017-0 and 302112/2018-9), FAPERJ (Fundação Carlos Chagas Filho de Amparo Pesquisa do Estado do Rio de Janeiro (E-26/202.794/2017 and E-26/010.101100/2018).

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