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Abundance and distribution of solid waste and microplastics in southeastern Brazilian islands: a comprehensive analysis

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ABSTRACT

Marine debris is one of the environmental problems highlighted in this decade. These pollutants are present in various environments worldwide, ranging from highly urbanized beaches to even the most remote islands. This study aimed to understand the factors involved in the origin and distribution of solid waste and microplastics via their characterization and quantification on beaches of three islands in southeastern Brazil: Trindade Island/ES, Grande Island/RJ, and Paquetá Island/RJ. These islands vary in their proximity to the continent and exhibit distinct patterns of occupation and use. Sediments were collected at three points in wet and dry sand on each beach and then analyzed and quantified. The results showed that the highest density of solid waste was 0.27 items.m^{-2} on Trindade Island, followed by Paquetá Island/RJ, with 0.10 items.m^{-2}, and Grande Island/RJ, with 0.07 items.m^{-2}. Plastic was the most abundant material on the three islands studied. The highest concentration of microplastics was found on Paquetá Island (21.98 items.kg^{-1}), followed by Grande Island (8.85 items.kg^{-1}) and Trindade Island (2.44 items.kg^{-1}). The blue color and fragments were prevalent on the three islands, accounting for 31 and 74% on Trindade Island, 44 and 77% on Grande Island, and 31 and 68% on Paquetá Island, respectively. Microplastics smaller than 1,000 µm predominated on Trindade Island (76%) and Grande Island (68%), whereas, on Paquetá Island, microplastics with sizes ranging from 1,000 to 5,000 µm prevailed (62%). This research demonstrated that the abundance and distribution of solid waste and microplastics are determined by several factors, including oceanographic processes and anthropic influence, resulting from the different forms of use and occupation of the islands studied.

Keywords: Marine and coastal environments, Marine litter, Paquetá Island, Grande Island, Trindade Island

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INTRODUCTION

In the 21st century, the issue of solid waste in coastal and marine environments has been recognized as an ecological and economic problem of global significance (Andrady, 2015; Videla and

Araújo, 2021). These residues can originate from terrestrial sources such as sewage, river transport, winds, and improper disposal by the population, or from marine sources such as fishing, oil, and navigation activities (Munari et al., 2017). Among the different types of waste, plastic is the most prevalent in the environments mentioned above (Gall and Thompson, 2015). Plastic is extensively used in industries due to its characteristics, such as versatility, resistance, low cost, and high durability (Andrady, 2011; Audrézet et al., 2021). The increasing demand for plastics and the inefficient management of this waste have caused this material to spread throughout the coastal and marine environments (Chiba et al., 2018; Napper and Thompson, 2020; Shen et al., 2020).

In marine and coastal environments, plastics degrade into smaller fragments due to the effects of solar radiation, wave dynamics, precipitation, winds, and salinity (Andrady, 2015), ultimately becoming microplastics when they are smaller than 5 millimeters (Andrady, 2011; Wright et al., 2013). In addition to microplastics resulting from the fragmentation of larger plastics, there are primary microplastics used in industrial production processes, such as those found in cosmetics and toothpaste (Thompson et al., 2004). Due to their small size, microplastics can enter the trophic chain at the first trophic levels, accumulating throughout it. (Fossi et al., 2012; Carson, 2013; Vendel et al., 2017; Rizzi et al., 2019). Moreover, microplastics are also present in the sandy sediments of various beaches, including continental and oceanic islands (Andrady, 2015).

Factors such as currents, winds, and proximity to polluting sources play a significant role in the dispersion of solid waste and microplastics in marine and coastal environments. The impact of currents and winds on the ocean surface can be considerable. Depending on the buoyancy of the waste and its direct exposure to wind direction, it may be trapped in ocean gyres and subsequently washed ashore on islands (Carlton et al., 2017; Monteiro et al., 2018). Conversely, the proximity to urban centers, ports, and commercial and tourist activities also contributes to the presence of these pollutants on beaches (Kiessling et al., 2015; Hayati et al., 2020). Many experts suggest an allochthonous origin for most of the waste found on islands (Scisciolo et al., 2016; Imhof et al., 2017), facilitating its deposition on exposed and sheltered beaches in these areas (Póvoa et al., 2022).

Thus, this study aimed to compare and characterize the concentration of solid waste and microplastics among beaches on three islands, considering their proximity to pollution sources, different forms of occupation, and varied influences of winds and currents. We tested the following hypotheses: 1) Islands near pollution sources exhibit higher concentrations of solid waste and microplastics when compared to more distant islands; 2) Plastic is the primary material found on islands, regardless of their proximity to pollution sources.

MATERIALS AND METHODS

Study Area

The study area of this research comprised three islands (one oceanic and two coastal) on the Southeast coast of Brazil. These islands were Trindade Island/ES (20°30’ S; 29°20’ W); Grande Island/RJ (23°05’ S and 23°14’ W); and Paquetá Island/RJ (22° 45’ S, 43° 06’ W) (Figure 1). These islands were selected based on their geographic positioning and their diverse forms of occupation and utilization.

Trindade Island (20°30' S; 29°20' W), is an oceanic island located approximately 1,200 km from the Brazilian coast and 4,200 km from the African coast. Situated in an area of high water circulation, the island shows restricted activities and prohibits tourism (SECIRM, 2017). Additionally, it hosts a military base of the Brazilian Navy, with a contingent of approximately 40 personnel who rotate every four months (Ivar do Sul et al., 2014). Trindade Island holds ecological significance due to its numerous endemic flora and fauna species, many of which are at risk of extinction (Mohr, 2009; Almeida et al., 2011; Medeiros et al., 2022). Trindade Island is influenced by the Brazil Current, which originates from the South Equatorial Current, traversing the Atlantic from east to west, and forms three branches near the Brazilian coast. A portion of water transported westward by the southern branch of the South Equatorial Current, moves southward near 10°S, giving rise to the Brazil Current (Castro Filho and Miranda, 1988).

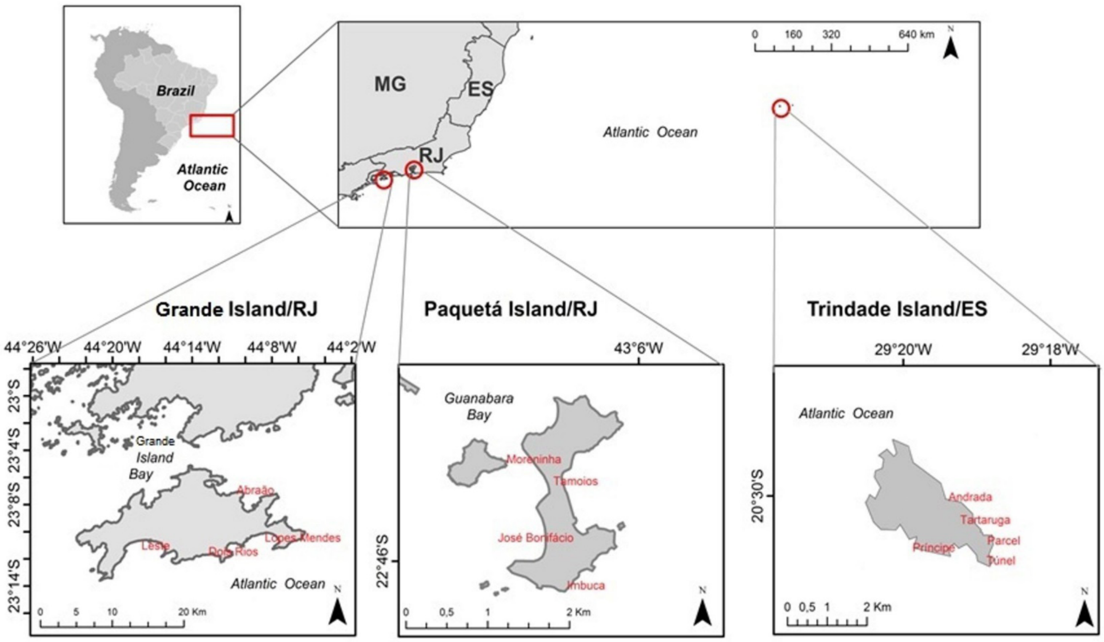

Figure 1. Location of the studied islands: Trindade Island/ES, Paquetá Island/RJ, and Grande Island/RJ.

The Brazil Current flows southward until it nears Abrolhos Bay, where it encounters the sub-Antarctic waters of the Falklands Current, deflecting southwestward. As it veers southwestward, it approaches the platform near Vitória/ES, reaching depths of 200 meters while carrying its water mass (Lavers and Bond, 2017). An important characteristic of the island is its proximity to the oceanic gyre of the South Atlantic (Lebreton et al., 2012).

The beaches studied on Trindade Island include Andradas (20°30' 37" S; 29° 18' 30" W), Parcel (20° 31' S; 29° 18' W), Principe (20° 31' S; 29° 18' W), Tunel (20° 31' S; 29° 17' W), and Tartaruga (20° 30'S; 29° 18'W). These beaches show lengths of 860 meters, 270 meters, 251 meters, 481 meters, and 350 meters, respectively (Andrades et al., 2018). Grande Island (23°05' S and 23°14' W) is a coastal island located on the southern coast of the State of Rio de Janeiro, within Ilha Grande Bay in southeastern Brazil. The island is influenced by the Brazil Current (Kjerfve et al., 2021) and local currents which can be unidirectional or cyclonic, particularly following the passage of cold fronts (Godoi et al., 2011; Kjerfve et al. al., 2021). With significant ecological and tourist value, Grande Island faces pollution primarily from ferry stations, bars, restaurants, and hotels due to the high number of visitors and tourist activities On Grande Island, the selected beaches include Abraão (23°08'S; 44∘10' W), Dois Rios (23° 11'S; 44°11'W), Leste (23° 10'S; 44° 16'W), and Lopes Mendes (23° 10'S; 44°08'W). These beaches exhibit lengths of 1,300 meters, 3,000 meters, 2,500 meters, and 1,200 meters, respectively (Macedo et al., 2019; Póvoa et al., 2022).

The Island of Paquetá (22° 45'S, 43° 06' W) is a coastal island that belongs to Rio de Janeiro municipality and is situated near the mainland. With a total population of 3,612 inhabitants (IBGE, 2021), it is located within Guanabara Bay, one of the largest bays on the Brazilian coast and also one of the most degraded environments in the country (Soares Gomes et al., 2016).

The beaches studied on Paquetá Island include José Bonifácio (22° 76'S; 43° 11'W), Imbuca (22° 76'S; 43° 10'W), Moreninha (22° 75'S; 43° 11' W), and Tamoios (22° 75'S; 43° 10'W), with lengths of 620 meters, 108 meters, 810 meters, and 115 meters, respectively (Silva et al., 2016). The main causes of this degradation include the discharge of untreated sewage, accidental oil spills, and a large volume of garbage entering via its river systems (Baptista Neto and Fonseca, 2011). Paquetá Island is situated near the Guapimirim Environmental Protected Area and within the deep navigation channel of Guanabara Bay, where there is regular water renewal. The island's beaches are located within Guanabara Bay, characterized by low wave energy environments (Rodrigues et al., 2020).

The beaches studied on Paquetá Island include José Bonifácio (22° 76'S; 43° 11'W), Imbuca (22° 76'S; 43° 10'W), Moreninha (22° 75'S; 43° 11'W), and Tamoios (22° 75'S; 43° 10'W), with lengths of 620 meters, 108 meters, 810 meters, and 115 meters, respectively (Silva et al., 2016). The beaches of Trindade and Grande Islands studied in this research are characterized by high wave energy, except for Praia do Abraão on Grande Island, which is situated in a low-energy environment (Andrades et al., 2018; Macedo et al., 2019; Póvoa et al., 2022). Conversely, the beaches of Paquetá Island are also classified as having low wave energy (Silva et al., 2016).

Sampling and processing of solid waste

Solid waste was manually collected along the tide line (within ±1 m), during low tide in the morning. This collection was conducted along the entire length of the beach arc in March 2019 on Trindade Island, August 2019 on Paquetá Island, and February 2020 on Grande Island. Each of the 13 sampled beaches underwent collection. The collected materials were transported to the laboratory for sorting, which involved separation, classification, and quantification using a spreadsheet designed specifically for this study. The waste items were categorized into various types, including plastic, styrofoam, fishing materials, rubber, modified wood, glass, metals, and others such as cigarette filters, fabrics, candles, and construction materials. The concentrations of these residues were expressed as items.m^{-2} (total number of collected residues/ length of the beach arc).

Sampling and processing of sediments for microplastic analysis

The sediment collection process involved marking three equidistant points (sides and center) in both the wet and dry sand on each beach (Figure 2). At each marked point, a quadrant measuring 30 × 30 cm (900 cm^2) was established, following the methodology outlined by Costa et al. (2010), Ivar do Sul et al. (2009), and Monteiro et al. (2018). The top two centimeters of sediment were collected from each quadrant using a stainless steel spatula marked with this measurement.

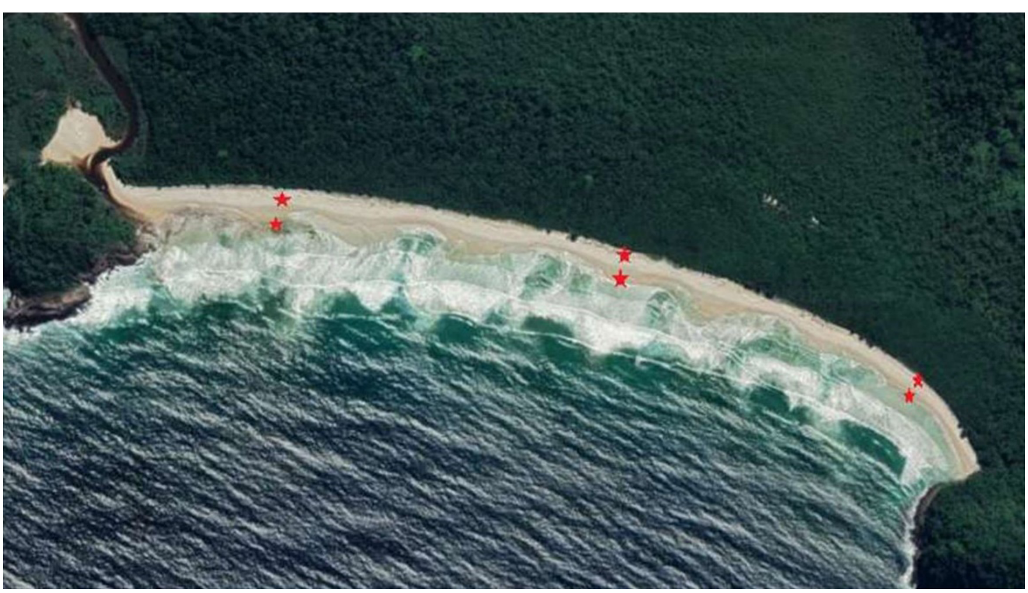

Figure 2. Map showing the arrangement of collection points on the beaches: wet sediments in the darker sand area near the water and dry sediments in the lighter sand area near the vegetation. Leste beach, Grande Island, RJ.

The depth of sediment collected was 2 cm, consistent with the methodology employed by Monteiro et al. (2018). The collected sediment samples were stored in sealed plastic bags, labeled with the names of the beaches/islands of origin and the collection point, and then transported to the laboratory for further processing. In the laboratory, the sediment samples were transferred to stainless steel trays and placed in an oven set at 60° C to facilitate the drying process. Once dried, the material was weighed using a balance to determine the amount of sediment removed in each quadrant. Microplastic extraction from the sediment was conducted using the density separation method with a hypersaline solution of Sodium Chloride (density – 1.2 g/cm^3). The hypersaline solution was stirred for 5 minutes using a magnetic stirrer and then filtered to remove any contamination present in the salt.

The filtered hypersaline solution was then added to the sediment samples, which were shaken for 3 minutes and left to settle for 24 hours. After decantation, the supernatant was filtered using a vacuum system equipped with a glass fiber filter (pore size 1.2 µm, Whatmann). The filters containing the microplastics were transferred to Petri dishes and dried at room temperature, following the methodology outlined by Sobral et al. (2011) and Castro et al. (2020).

The Filters were examined under a stereomicroscope and photographed for documentation purposes. A visual evaluation was conducted to identify microplastics among the filtered marine debris, categorizing them based on various criteria: color (blue, green, red, yellow, orange, purple, pink, gray, black, white, translucent, and beige), shape (fragment, film, fiber, styrofoam, pellets, foam, rubber, and microbeads), and size (<1,000 µm, 1,000 µm – 5,000 µm and >5,000 µm). This classification methodology was adapted from the approach outlined by Castro et al. (2020). The concentrations of microplastics were expressed as items.kg^{-1} and items.m^{-2}.

Contamination control

In addition to the precautionary measures adopted to prevent cross-contamination, such as filtering the solutions, cleaning the workbench, and wearing a cotton coat, a control experiment was performed to assess contamination of airborne fibers in the laboratory (Nuelle et al., 2014; Lusher et al., 2014; Pagter et al., 2018). Contamination-free Petri dishes containing ultrapure water were exposed during the sample processing time. This allowed for the collection of any airborne fibers that may have been present in the laboratory environment. The methodology for this control experiment followed the procedure described by Castro et al. (2020).

The contamination present in the control samples was analyzed and quantified. Any fibers observed in the control samples were identified and removed from the raw data for each sampling site. This process ensured that the data accurately reflected the presence of microplastics in the sediment samples, without the interference of contamination from the laboratory environment (Blair et al., 2019).

It is important to note that the samples from Trindade were processed before the COVID-19 pandemic, whereas the samples from Grande Island and Paquetá were processed during the pandemic. During this time, access to the laboratory was restricted to maintain social distancing measures. This difference in processing timelines may have implications for the data interpretation and comparability between the samples, particularly in terms of any potential impacts on laboratory procedures and workflows.

Statistical Analysis

The differences between the groups of beaches (sheltered and non-sheltered, coastal and oceanic) were considered fixed factors and were tested using permutational analysis of variance (PERMANOVA). The data were transformed using a log transformation (log x+1) due to the non-normal distribution of residue concentration. Additionally, a non-multidimensional scaling (nMDS) analysis was conducted based on the Bray-Curtis similarity index to visualize the clustering of beach samples. All tests were performed using a significance level of 0.05 and conducted in R software. These statistical analyses provide insights into the variability and similarities between different groups of beaches, aiding to understand the factors influencing microplastic distribution and abundance in coastal environments.

RESULTS

Quali-quantitative analysis of solid waste

A total of 1,434 items were found across the three studied islands: (0.07 items.m^{-2}), 610 on Trindade (0.27 items.m^{-2}), and 206 on Paquetá (0.10 items.m^{-2}) (Figure 3). On Trindade Island, the highest density of solid waste was observed on the beaches of Túnel (0.39 items.m^{-2}) and Tartaruga (0.28 items.m^{-2}). Meanwhile, on Grande Island, the highest density was found on Lopes Mendes beach (0.09 items.m^{-2}) and Leste (0.08 items.m^{-2}). On Paquetá Island, the highest density was observed on the beaches of Tamoios (0.27 items.m^{-2}) and Imbuca (0.11 items.m^{-2}) (Figure 4).

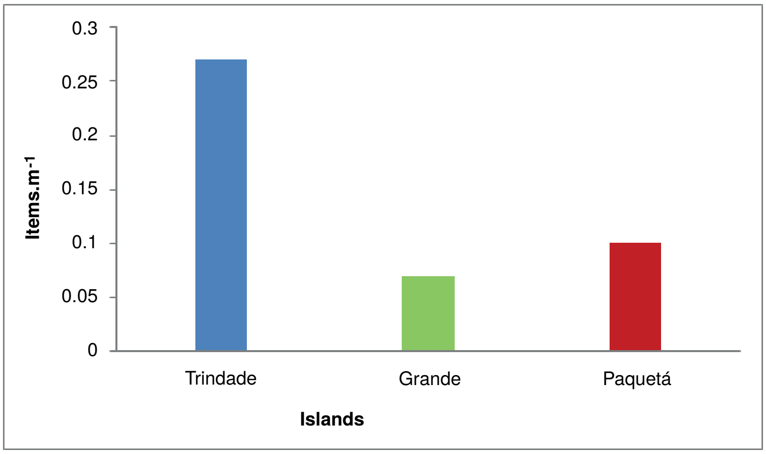

Figure 3. Density of solid waste (items.m-²) collected on the beaches of Trindade, Grande and Paquetá Islands.

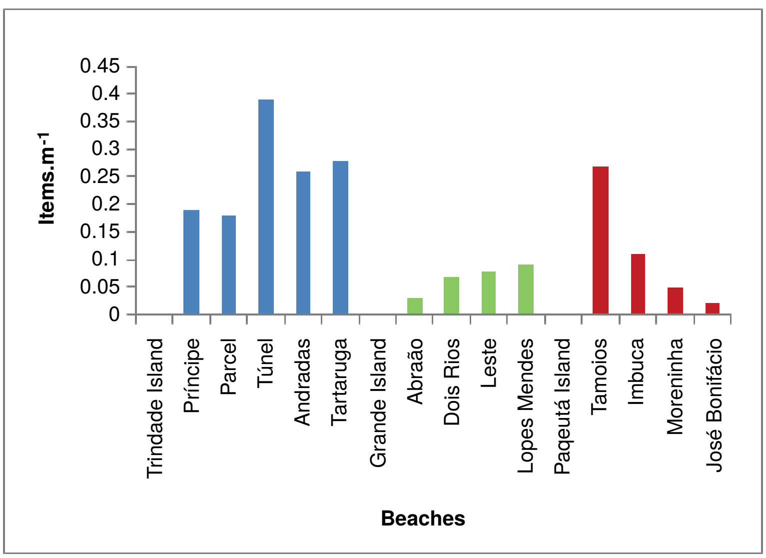

Figure 4. Density of solid waste (items.m^{-2}) on each beach studied.

The predominant type of waste across all the islands studied was plastic. In Trindade Island, plastic accounted for over 80% of all materials collected, with particularly high proportions found on beaches such as Andradas (85%), Túnel (76%), Tartaruga (74%), Príncipe (68%), and Parcel (55%). Similarly, on Grande Island, plastic comprised 76% of the total, with higher concentrations observed on beaches such as Dois Rios (79%), Lopes Mendes (74%) and Leste (49%). However, Abraão beach on Grande Island exhibited a different pattern, with glass (30%) and other materials (30%) such as fabrics, sails, and construction materials being predominant.

In Paquetá Island, plastic accounted for 62% of the total items, with particularly high proportions found on beaches like José Bonifácio (88%), Tamoios (84%), and Moreninha (81%). Interestingly, the beach of Imbuca on Paquetá Island showed a different trend, with glass being the most observed material (42%) (Figure 5).

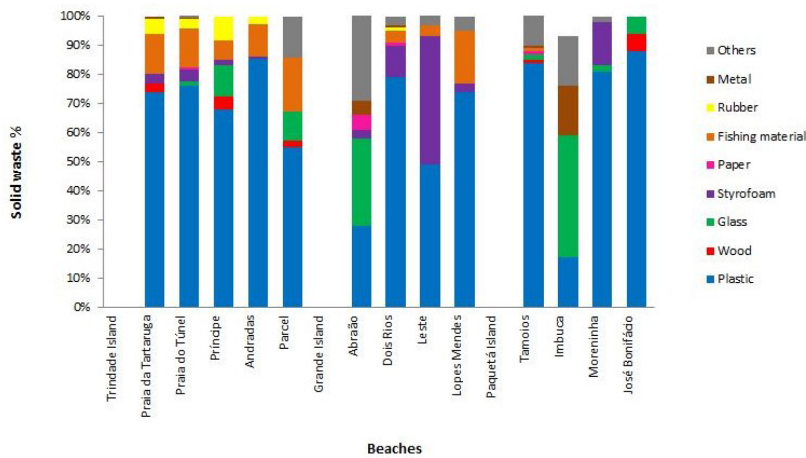

Figure 5. Percentage composition of solid waste collected on the beaches studied on Trindade, Grande, and Paquetá islands.

Quali-quantitative analysis of microplastics

A total of 651 items were found across the three islands (Figure 6), with the highest average concentration observed on Paquetá Island (21.98 items.kg^{-1}/144.9 items.m^{-2}), followed by Grande Island (8.85 items.kg^{-1}/93.05 items.m^{-2}) and Trindade Island (2.44 items.kg^{-1}/50.74 items.m^{-2}). Microplastics were found in both the dry and wet sand of all sampled beaches.

Generally, the highest concentrations of microplastics were detected in dry sand samples, with some exceptions such as the beaches of Tartaruga and Tunel on Trindade Island and Tamoios on Paquetá Island (Table 1 and Figure 7). On Trindade Island, the highest concentrations of microplastics were found in the wet sand of Tartaruga beach (8.84 items.kg^{-1} or 203.63 items.m^{-2}) and the dry sand of Andradas beach (4.55 items.kg^{-1} or 96.29 items.m^{-2}). Intermediate concentrations were observed in other beaches, with the lowest concentrations found in the wet and dry sands of Príncipe beach (Table 1 and Figure 7).

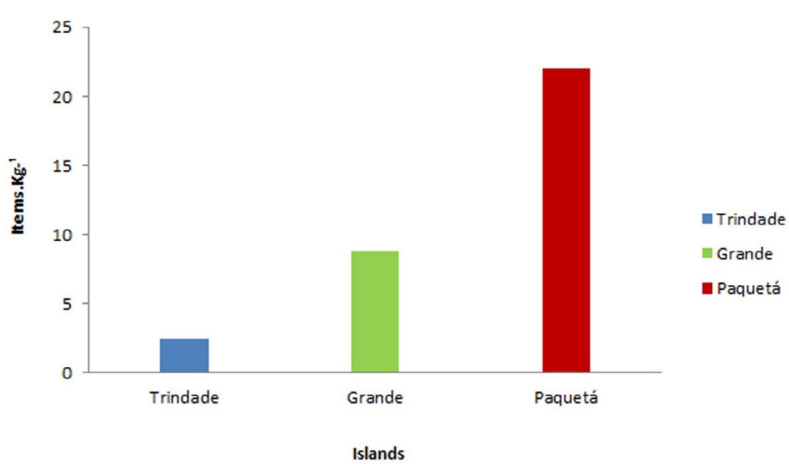

Figure 6. Density of microplastics (items.kg^{-1}) in beach sediments collected on Trindade, Grande, and Paquetá Islands.

Table 1. Densities of microplastics in items.m^{-2} and items.kg^{-1} found in the dry and wet sands of the beaches studied on Trindade, Grande, and Paquetá islands.

Beaches	Dry sand		Wet sand	
	items.m^{-2}	items.kg^{-1}	items.m^{-2}	items.kg^{-1}
Trindade Island				
Tartaruga	44.44	2.70	203.63	8.84
Túnel	18.51	0.99	48.15	2.16
Parcel	40.74	2.91	11.10	0.52
Andradas	96.29	4.55	25.92	1.05
Príncipe	11.11	0.47	7.40	0.32
Grande Island				
Abraão	262.96	36.46	25.92	3.65
Dois Rios	107.40	10.42	74.07	5.89
Leste	77.77	7.72	18.51	1.82
Lopes Mendes	100.00	8.57	77.77	5.18
Paquetá Island				
Tamoios	51.85	7.12	118.51	18.08
Imbuca	122.22	27.41	22.22	3.44
José Bonifácio	662.96	88.30	96.29	14.13
Moreninha	55.55	8.15	29.62	4.29

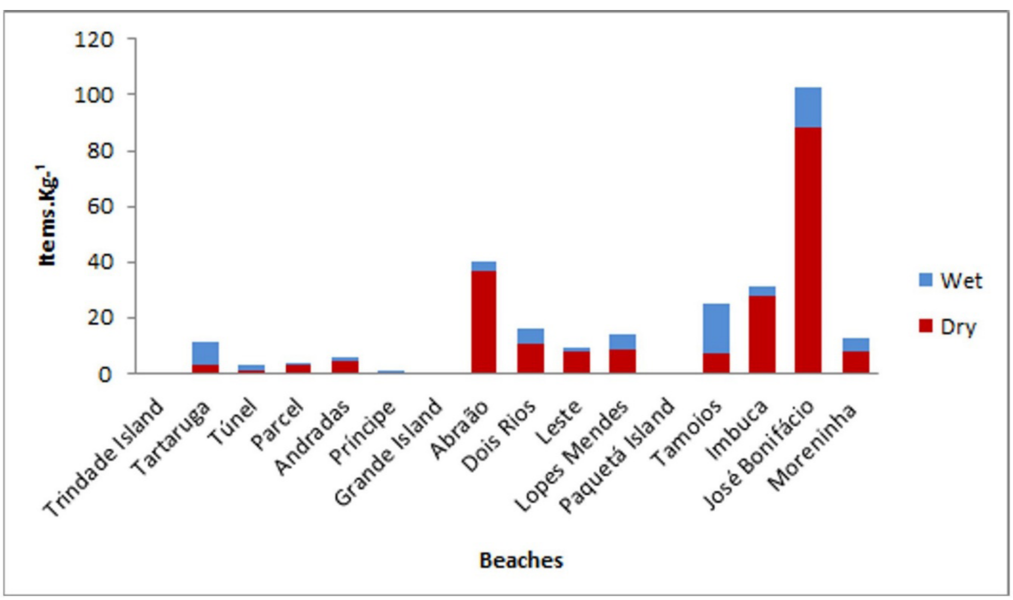

Figure 7. Density of microplastics (items.Kg-1) found in dry and wet sediments from the beaches on Trindade, Grande and Paquetá islands.

In Grande Island, the highest concentrations were generally found in the dry sands of all beaches, with the lowest concentrations in the wet sands. Similarly, in Paquetá Island, the highest concentrations were typically found in the dry sands of José Bonifácio and Imbuca beaches, with lower concentrations in the wet sands (Table 1 and Figure 7).

Characteristics of microplastics: color, type, and size.

Blue was the predominant color on all three islands. In Trindade Island, 31% of microplastics were blue, followed by 18% red and 18% beige. Similarly, in Grande Island, blue was the most predominant color, accounting for 44% of microplastics, followed by red at 18%. In Paquetá Island, blue microplastic accounted for 31% of the total, followed by translucent at 17% and white at 13% (Figure 8). Fragments were the dominant type of microplastic found in all three study islands. In Trindade Island, 74% of the microplastics collected were fragments, followed by 14% fibers and 11% film. Similarly, on Grande Island, fragments accounted for 77% of microplastics, followed by fibers at 17% and film at 5%. On Paquetá Island, 68% were fragments, followed by film at 16% and fibers at 11% (Figure 9). Microplastics <1,000 µm were the most abundant category on Trindade Island (76%) and Grande Island (68%). Conversely, on Paquetá Island, microplastics in the 1,000–5,000 µm category (62%) were the most observed in this study (Figure 10).

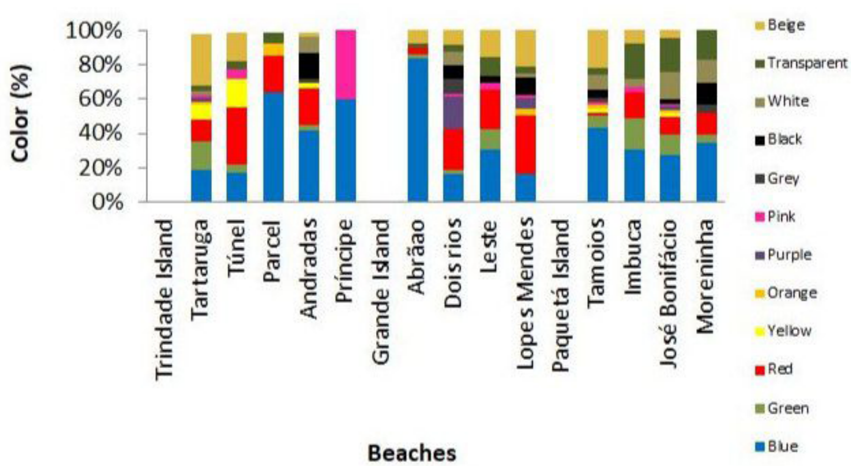

Figure 8. Classification of different colors observed in microplastics collected in the sediments of the beaches on Trindade, Grande, and Paquetá islands.

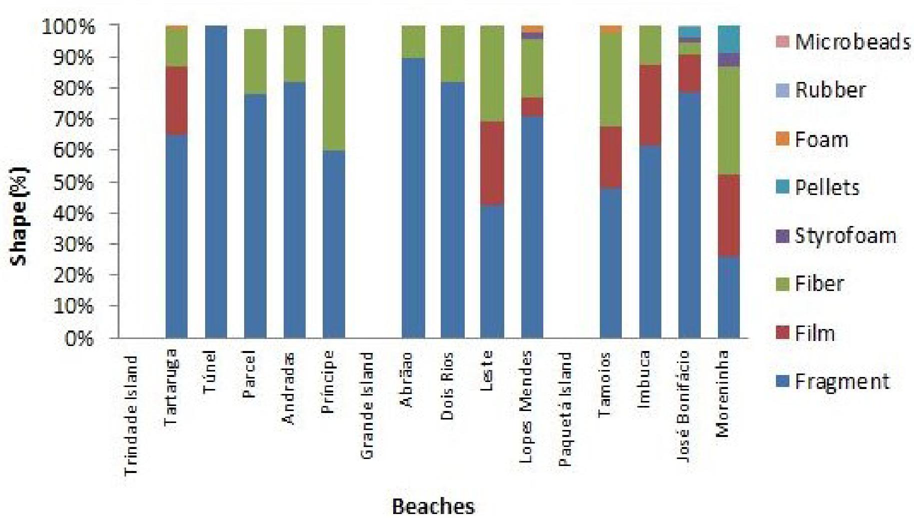

Figure 9. Classification of different types of microplastics collected in the sediments of the beaches studied on Trindade, Grande, and Paquetá islands

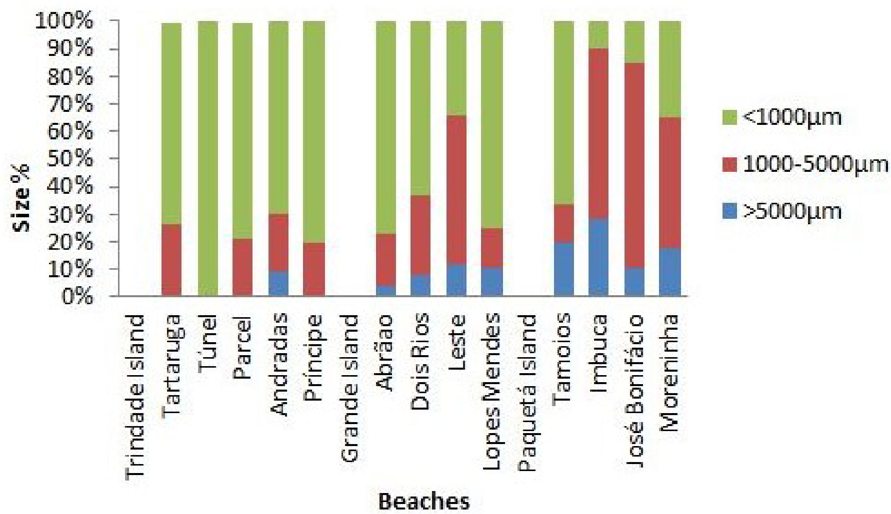

Figure 10. Size classification of microplastics collected in the sediments of the beaches studied on Trindade, Grande, and Paquetá islands

Control analysis of microplastics

A significant number of fibers (247) were observed during the control experiment. Subsequently, during the analyses of samples from Trindade Island, 218 fibers were found, whereas during the analyses of samples from Grande and Paquetá islands, 21 and 8 fibers were observed, respectively. The sizes of these fibers varied from 1 to 5 mm. The predominant colors observed among the fibers were blue, black, and red.

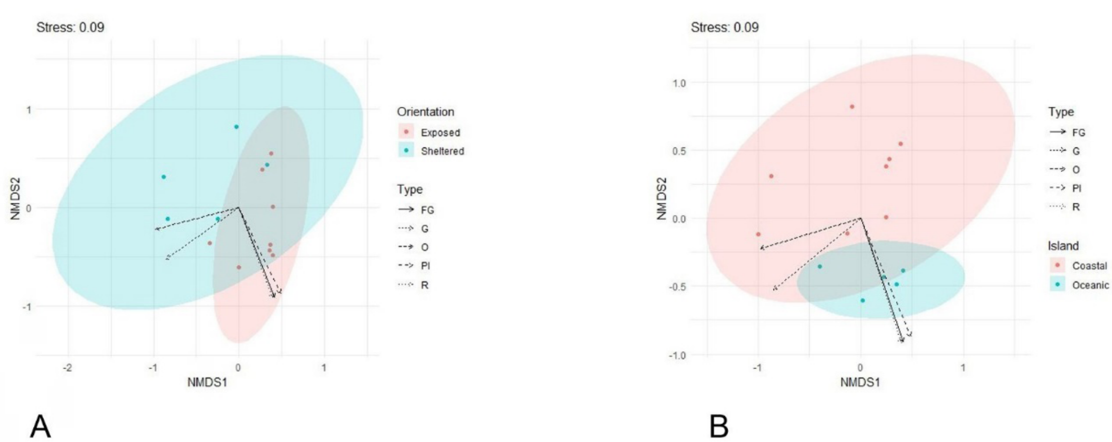

Figure 11. Non-Metric Multidimensional Scaling (nMDS) ranking based on categories of solid waste found in the tide line. A- Exposed vs Sheltered beaches; B- Coastal vs Oceanic beaches. FG = Fishing Gear; G = Glass; O = Others; Pl = Plastic; R = Rubber

Statistical Analysis

The nMDS ordination diagram revealed a clear distinction between the sampling sites based on the categories of solid waste. Specifically, the non-metric multidimensional scaling (nMDS) analysis based on the solid waste categories demonstrated an association between plastic materials, fishing gear, rubber, and wood on oceanic island beaches and exposed beaches (Figure 11). However, when comparing the characteristics of microplastics, no significant differences were found between the sampling sites for color and shape categories but a notable variation was observed regarding size (Figure 12).

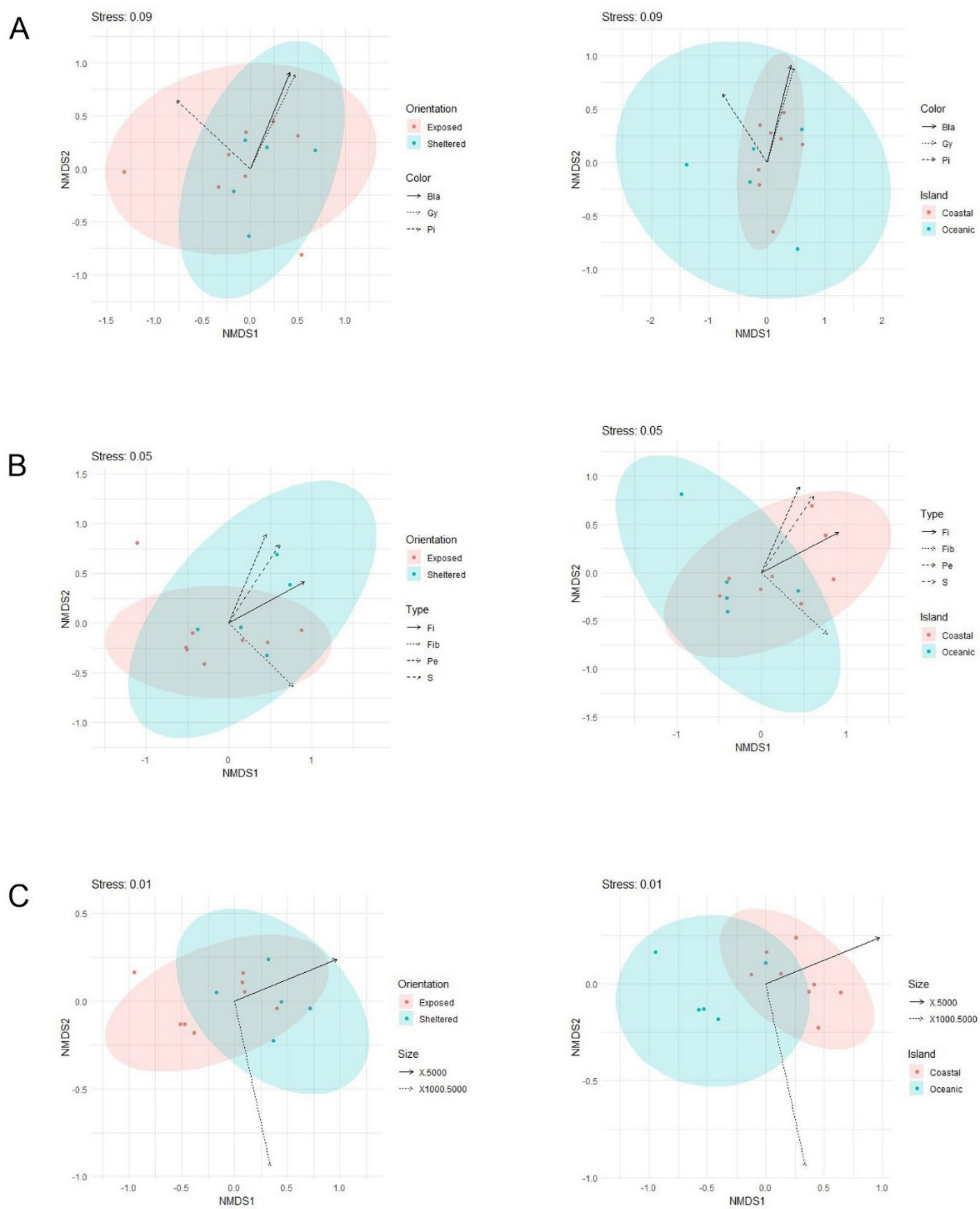

Figure 12. Non-Metric Multidimensional Scaling (nMDS) ranking based on characteristics such as (A) Color (Bla = Black, Gy = Gray, Pi = Pink); (B) Type (Fi = Film, Fib = Fibre, Pe = Pellets, S = Styrofoam); and (C) Size, found in microplastics.

DISCUSSION

Solid waste

Solid wastes are present on several islands distributed worldwide, from those closest to the mainland to the most remote ones, with varying concentrations (Table 2). Comparing values of solid wastes found by different studies should be performed with caution, as factors such as location, proximity to polluting sources, collection period, and oceanographic and climatic conditions can influence the outcomes.

In this study, the highest density of solid waste was found on Trindade Island, the furthest from the mainland and polluting sources, with a density of 0.27 items.m^{-2}. On this same island, Andrades et al. (2018) reported a density of 0.5 item.m^{-2}. This result is consistent with the findings of Schmuck et al. (2017), who found higher solid waste densities on uninhabited islands compared to accessible islands in the Cayman Islands. Despite being the island furthest from the mainland and, consequently, from polluting sources, Trindade Island showed the highest accumulation of solid waste. This can be explained by the fact that this island is located at the edge of the South Atlantic Subtropical Gyre (SAG), a rotating system where residues possibly transported by marine currents accumulate (Lebreton et al., 2012; Van Sebille,2015). As this island is off a maritime route, much of this waste comes from ships, which explains the presence of waste from several countries, as shown in Figure 13. Ryan and Schofield (2020) discuss that vessels are responsible for the greater presence of stranded bottles on remote islands, such as those found on Pitcairn Island.

Table 2. Density of solid waste collected on beaches of various islands worldwide

Reference	Country	Island	Ocean/Sea	Unit	Density
Grillo & Mello, 2021	Brazil	Fernando de Noronha	Atlantic	g.m^{-2}	0.248 ± 0.047
Hayati et al, 2020	Indonesia	Tidung	Indian/Pacific	items.m^{-2}	1.83
Buckingham et al, 2020	UK	Orkney Scots	Atlantic	items.m^{-1}	5.33
Portz et al, 2020	Colombia	Albuquerque Atoll	Caribbean	items.m^{-2}	0.5
Ryan and Schofield, 2020	UK	Pitcairn	Pacific	items.km^{-1}	45
Waluda et al, 2020	UK	Bird	North	items.km^{-1}	99
Alvarez et al, 2020	Portugal	Madeira	Atlantic	items	52
Verlis and Wilson, 2020	Polynesia	Moorea/Taiti	Pacific	items.m^{-2}	0.71
Dunlop et al, 2020	Seychelle	Cousine	Indian	items.m^{-1}.d^{-1}	0.0082
Reinold et al, 2020	Spain	Canary	Atlantic	items.m^{-2}	0 - 498.75
Vesman et al, 2020	Russia	Nova Zembla	Arctic	items.km^{-2}	1.500
Andrades et al, 2018	Brazil	Trindade	Atlantic	items.m^{-2}	0.5
Povoa et al, 2022	Brazil	Grande	Atlantic	items.m^{-2}	2.78
Schmuck et al, 2017	5 Nations	24 islands	Caribbean	items.m^{-2}	0.10 - 48.25
McDermid & McMullen, 2004	USA	Hawai	Pacific	items	19.100
Lavers and Bond, 2017	UK	Henderson	South Pacific	items.m^{-2}	0.35 - 1.05
Present study	Brazil	Trindade, Grande, Paquetá	South Atlantic	items.m^{-2}	0.07 - 0.27

Legend: Plastic was the predominant material in all observed studies

Other islands far from the mainland, such as Easter Island and Henderson Island near the South Pacific Gyre, and Midway Atoll and Hawaii near the North Pacific Gyre, also exhibited a significant tendency for waste accumulation due to the interaction between the system of currents and winds (McDermid and McMullen, 2004; Lavers and Bond, 2017).

Exposure of islands to wind and current flows is the main factor in the deposition of waste on remote islands (Duhec et al., 2015; Pieper et al., 2015; Lavers and Bond, 2017). The largest accumulation of solid waste on Trindade Island was observed on Túnel and Tartaruga beaches. These beaches are oriented to the eastern quadrant of the winds (Nogueira et al., 2020), which justifies the greater deposition of waste due to the interaction between currents and prevailing winds in the region. The accumulation of waste on beaches is influenced by different oceanographic conditions such as weather, wind, and local currents (Ryan and Schofield, 2020; Macedo et al., 2020; Póvoa et al., 2022).

Figure 13. Solid Wastes found on beaches of Trindade Island.

On Grande Island, the beaches with the highest concentration of solid waste were those exposed to the ocean (Lopes Mendes, Leste, and Dois Rios), which are subject to the occurrence of high-energy waves that reshape solid waste. Sea currents and winds interfered in the deposition of residues in the tide line of these beaches, which corroborates the study of Póvoa et al. (2022). Additionally, these beaches are subject to south and southwest winds after the entry of cold fronts, which leads to the deposition and accumulation of waste on these beaches (Macedo et al., 2019; Silva et al., 2020; Póvoa et al., 2022).

The exposed beaches of islands experience high wave dynamics, currents, winds, and cold fronts, making them high-energy beaches, which implies greater deposition of waste influenced by energy dynamics (Park et al., 2021). Sheltered beaches, on the other hand, typically have small amplitude waves under good weather conditions, with waves reaching a maximum height of 1 m during storms (Jackson et al., 2002). These waves are primarily generated by local winds, and such beaches are considered low-energy beaches, suggesting lower deposition of residues influenced by the energetic dynamics of the beach, as observed in this study and by Macedo et al. (2019) and Póvoa et al. (2022) in Grande Island Bay.

On Grande Island, there is no regular beach cleaning on Dois Rios and Leste (Póvoa et al., 2022). On Lopes Mendes beach, solid waste is only removed by street vendors on the west side (Macedo et al., 2019), accumulating on the rest of the beach. On the other hand, Abraão beach, facing north, undergoes regular cleaning by the *Brigada Mirim Ecológica*, as well as by the owners of kiosks and local restaurants (Macedo et al., 2019; Póvoa et al., 2022). On Paquetá Island, the greatest accumulation was found on Tamoios beach, facing the municipality of São Gonçalo. The solid waste present in Guanabara Bay partly originates from the rivers that flow into it, primarily at the bay's bottom. These residues enter the bay via rivers through surface runoff, urban drainage, or irregular disposal by the population (Baptista-Neto and Fonseca, 2011). Although Guanabara Bay receives solid waste from the ocean, primarily in the municipalities of Niterói and Rio de Janeiro (Baptista-Neto and Fonseca, 2011; Luz, 2018), those reaching Tamoios beach likely come from the rivers flowing into the bay's bottom and are transported by winds and currents, ultimately being deposited along the tide line.

According to Lazzari (2012), the beaches of Imbuca, José Bonifácio, and Moreninha in the region of Paquetá Island are influenced by the main circulation channel, and the best environmental conditions are found due to the greater contribution of seawater reaching the island of Paquetá. It is important to highlight that many residues collected were accompanied by encrusting fauna such as bryozoans, mainly on Trindade and Grande Island. This phenomenon is an ecological process called rafting, in which species are encrusted in different types of waste and are transported from one place to another by sea currents and winds, and the waste acts as a vector for the possible transport of species (Rech et al., 2018; De-la-Torre et al., 2021). In Rio de Janeiro state, solid waste rafting is reported only for Grande Island Bay (Póvoa et al., 2022), although it has been observed in other bays in the state (personal observation).

Plastic was the most abundant material on the three islands. This result corroborates findings on other islands in the Atlantic (Grillo and Mello, 2021; Buckingham et al., 2020), in the Pacific (Ryan and Schofield, 2020; Verlis and Wilson, 2020), and in the Indian Ocean (Dunlop et al., 2020; Krishnakumar et al., 2020).

The predominance of plastic as the most abundant material in all ocean basins is expected due to its widespread use in modern life, durability, malleability, and primarily its low cost (Cheshire et al., 2009; Gregory, 2009; Castro et al., 2020; Póvoa et al., 2022). In general, nMDS were well evaluated, as stress results <0.2. The association between plastic, fishing gear, rubber, and wood within the area representing the oceanic island supports the hypothesis of an allochthonous origin for solid waste on Trindade Island. Plastic, rubber, and wood were more frequently found due to their mobility, predominantly associated with the weight and buoyancy of these items, leading them to be carried to areas further away from the continent (Lebreton et al., 2018). Additionally, the significant presence of fishing material on the oceanic island is linked to professional fishing activities, primarily pelagic and amateur longlines (Pinheiro et al., 2010). Among the fishing gear, lightsticks used in longline fishing were found, consistent with findings by Ortiz (2020) in a study conducted on Trindade Island. The glass and metal categories are farther away from the oceanic island area. This is attributed to the direct influence of regulars on the island, as these residues do not arrive via currents, but rather from onsite disposal.

The results demonstrate the influence of the specificities of the islands on the materials found. Although Parcel and Príncipe beaches have been classified as exposed beaches due to their high ocean dynamics, they exhibited characteristics similar to sheltered and coastal island beaches. In a Cluster analysis for oceanic and continental beaches conducted by Ortiz (2020), Parcel beach also had a greater similarity with a continental beach.

Microplastics

Microplastic concentrations differ between the three islands studied, and also vary from those found in previous studies on the same or other islands (Table 3). In this study, the highest concentrations of microplastics were observed predominantly in dry sands, unlike was reported by Sunitha et al. (2020), who found the highest average values in the wet sands of Marina beach in India. Conversely, De la Torre et al. (2020) found no distribution pattern on beaches in Lima, Peru, with higher concentrations of microplastics varying between the wet and dry sands of the four beaches studied.

Table 3. Results and methodologies used in articles published on microplastics collected on beaches of various islands worldwide

Country	Island	Location	Sampling methodology (superficial quadrats)	Extraction methodology*	Concentracion (items.kg-¹)	Concentracion (Items.m-²)	References
Grecia	Kea	oceanic	1.0 x 1.0m	sieves	-	130.52	Kaberi et al., 2013
New Zeland	Canterbury	coastal	0.5 x 0.5m	density-separation	0 - 45.4	-	Ross et al., 2016
Brazil	Trindade	oceanic	0.3 x 0.3m	density-separation	-	311- 333	Pinheiro, 2017
Brazil	Trindade	oceanic	0.3 x 0.3m	density-separation	-	400	Ivar do Sul et al., 2014
Brazil	Fernando de Noronha	oceanic	0.3 x 0.3m	density-separation	-	33.3 – 266.6	Monteiro et al.,2020
Spain	Tenerife	coastal	0.5 x 0.5m	density-separation / sieves	-	2971.5	Álvarez-Hernández et al., 2019
Brazil	Grande	coastal	0.25 x 0.25m	density-separation	-	144 - 3200	Macedo, 2020
Maldives	Naifaru	oceanic	top 5cm	sieves	55-1127.5	-	Patti et al., 2020
Colombia	San Andres	oceanic	0.5 x 0.5m	density-separation	-	32 - 201	Ostin Garcés-Ordóñez et al., 2020
EUA	Hawai	oceanic	0.3 x 0.3m	sieves	-	700 – 1700	Rey et.al., 2021
Ecuador	Galapagos	coastal	0.5 x 0.5m	sieves	-	74 – 2524	Jones et.al., 2022
Fiji	Yasawa	oceanic	1.0 x 1.0m	manually separated	-	4.5 ± 11.1	Nabhani et al., 2022
Brazil	Paquetá	coastal	0.3 x 0.3m	density-separation	3.44 – 88.3	22.22 – 662.96	Present study
Brazil	Grande	coastal	0.3 x 0.3m	density-separation	1.82 – 36.46	18.51 – 262.92	Present study
Brazil	Trindade	oceanic	0.3 x 0.3m	density-separation	0.52 – 8.84	7.40 – 203.63	Present study

Legend: * All density separation methods used hypersaline NaCl solution.

The highest density of microplastics was obtained on Paquetá Island, followed by Grande Island and Trindade Island. These results could suggest that their presence is more strongly associated with greater proximity to a polluting source as observed by Patchaiyappan et al. (2021). Comparing our results with previous results conducted on the same islands or nearby areas, we observed that the densities found in the present study are lower. It is worth noting that the concentrations found in each location/study may vary according to several factors, as mentioned earlier regarding solid waste, such as proximity to waste sources, oceanographic and climatic conditions, and collection period (dry or rainy). Castro et al (2020) observed values (between 30 and 50 items.kg^{-1}) close to ours (21 items. kg^{-1}) in sediments from beaches of the Jurujuba Cove (also within the Guanabara Bay, as well as Paquetá Island) in collections carried out during the dry period. The methodology used to extract microplastics from sediment samples can also explain the difference between the results of different studies. In our study, the values found for microplastics may be underestimated, as polymers such as PET and PVC, exhibiting higher densities (> 1.2 g/cm^3) than the hypersaline solution used to separate microplastics from sand samples, might not float. Paquetá Island is situated within a polluted bay characterized by low hydrodynamics, surrounded by an urban area with nearly 20 million inhabitants and lacking basic sanitation (IBGE, 2021). Studies indicate that sediments in Guanabara Bay are more contaminated by microplastics when compared to other aquatic ecosystems worldwide (Alves and Figueiredo, 2019; Castro et al., 2020). Costa (2018) suggests that open coastal areas typically undergo greater dilution conditions when compared to bays. This could explain the higher density of pollutants in bays, as there is limited water renewal in these regions, leading to the accumulation of microplastics.

On Paquetá Island, the highest accumulation of microplastics was observed on beaches frequented by visitors, which boasted greater tourist infrastructure, including restaurants, bars, hotels, pedal boats, and kayaks. Additionally, untreated sewage from the island contributes to the deposition of microplastics on its beaches, notably at José Bonifácio beach. De Carvalho and Baptista-Neto (2016) identify fluvial contribution as the primary source of microplastics in Guanabara Bay.

Grande Island ranked as the second island with the highest density of microplastics. The most significant accumulation of microplastics on Grande Island was observed on Abraão beach, the most visited beach, boasting the largest tourist infrastructure with restaurants, bars, and accommodations (Macedo et al., 2019). In contrast, beaches facing the south/southwest direction exhibited lower concentrations of microplastics. This reduced density suggests lower pollution levels, as these beaches are less frequented by tourists and lack the infrastructure found in Abraão.

On Trindade Island, the density of microplastics was lower. The highest accumulation of microplastics was detected in the wet sediment samples. This observation is likely linked to the heightened influence of surface currents on the transportation of solid waste and microplastics, given the absence of bathers or tourist infrastructure on the beaches of this island. Winds and currents are regarded as the primary influencing factors affecting the deposition of microplastics on this island (Kulkula et al., 2016).

Thus, this study demonstrates that Paquetá and Grande Island are influenced by tourism and urbanization, resulting in a higher presence of microplastics on sandy beaches. This explains the smaller amount observed on Trindade Island, where the deposition of microplastics from currents and winds shows a greater impact. Identifying microplastic sources is crucial, as sources are often identified as indigenous terrestrial, originating from wastewater treatment (Liebezeit and Dubaish, 2012) or beach use (Jayasiri et al., 2014), whereas, on remote islands, sources are allochthonous (Hidalgo-Ruz and Thiel 2013). These findings highlight the variability in microplastic concentrations across different beach environments and the importance of considering dry and wet sand samples in microplastic research.

Various colors were observed in the samples but blue was the most predominant color on all three islands. Blue is consistently identified as the most common color in microplastic studies (Li et al., 2016; Peters and Bratton, 2016). This hue has also been found in greater abundance in plastics ingested by seabirds (Rodríguez et al., 2012), sea turtles (Bugoni et al., 2001; Schuyler et al., 2012), and fish (Carson., 2013; Choy and Drazen, 2013). These various colors of microplastics likely stem from dyes and additives (Da Costa Araújo et al., 2020). The color of microplastics is significant as it influences the ingestion of microplastics by marine organisms, possibly due to color-based predator capture behaviors (Abayomi et al., 2017; Kühn et al., 2018). On the islands of Trindade and Grande, in addition to blue color, beige was found in significant quantities, suggesting that these microplastics may have aged over a longer period, as color fading in the microplastic polymer is an indicator of the degradation process (Gewert et al., 2015; Pan et al., 2021).

The microplastics found were predominantly represented by fragments and fibers on all three islands. That result is consistent with the study by Maes et al. (2017) and Patchaiyappan et al. (2021), in which fragments and fibers were the predominant group of microplastics observed. The morphology of microplastics is closely linked to their origins. Fragments are likely derived from the breakdown of larger plastic items such as containers, cutlery, furniture, and toys, resulting from mechanical forces and UV radiation exposure (Horton et al., 2017). On the other hand, fibers can originate from textile materials, fishing gear, and deposition of airborne particles (Cesa, 2017).

A major source of microplastic fibers on the islands of Trindade and Grande is the fragmentation of abandoned fishing nets, lines, and ropes commonly found in these environments (Abayomi et al., 2017) These items are typically composed of polyamide (Nylon) fibers, contributing to microplastic pollution in the marine environment (Prarat and Hongsawat, 2022). On Paquetá Island, in addition to fishing gear, the fibers may originate from sewage and wastewater discharges from coastal areas or the island itself, resulting from washing synthetic clothing materials like polyester or nylon (Prarat and Hongsawat, 2022).

Pellets were observed only on Paquetá Island. They typically originate from direct releases (primary microplastics) during plastic manufacturing (Di and Wang, 2018). The pellets found in the research were of industrial origin, typically deposited near their industrial source (Karlsson et al., 2017). Therefore, the presence of the pellet category on the island, situated in a bay near industrial areas, confirms the influence of over 12,000 industries in the Guanabara Bay region (De Carvalho and Baptista Neto, 2016)

Moreover, in the plastics industry, most plastic resins show a base color of white or transparent (Ta and Babel, 2020), which were the colors of the pellets found on Paquetá Island. The size <1,000 μm was predominant on the islands of Trindade and Grande. Small microplastics (< 1,000 μm) have been demonstrated in various studies in the Nansha Islands, South China Sea (Nie et al., 2019), the Changjiang Estuary, China (Xu et al., 2018), and coastal area in Zhuhai, China (Wang et al., 2018). The prevalence of small-sized microplastics can be attributed to their longer exposure time in the environment, leading to the breakage and degradation of plastic particles (Andrady, 2011). The distribution and harmful effects of microplastics are determined by their size. Smaller microplastics show greater impacts on the biota and ecosystem, as they can be ingested by various organisms (Prairat and Hongsawat, 2022). On Paquetá Island, the predominant size category was 1,000–5,000 μm, consistent with a study by Castro (2020) on sediments at Jurujuba beach, also located in Guanabara Bay. Since this island is closer to the polluting sources, these larger sizes are likely due to the shorter duration of these plastics in the water when compared to those found on more distant islands, such as Trindade and Grande.

This suggests that, while the composition of solid waste may vary based on environmental factors such as island type and exposure, microplastics exhibit more consistent characteristics across different sampling sites, with size being a key distinguishing factor. Despite the precautions taken during sample processing in the laboratory, they showed contamination. Fibers, resembling those found in control samples were identified in microplastic samples and were subsequently excluded to prevent an overestimation of microplastics (Blair et al., 2019). However, these fibers were still quantified and characterized to investigate potential sources of contamination. The colors observed in the fibers were linked to clothing worn by laboratory staff and the researcher herself. Multiple sources can contribute to the release of microplastics into the air, with synthetic fabrics from clothing being one of them (Catarino et al., 2018). The increasing use of these by the textile industry has directly and indirectly contributed to the contamination of microplastics in the air (Gasperi et al., 2018).

The samples from Trindade Island analyzed at the end of 2019 and the beginning of 2020 exhibited significantly higher levels of contamination compared to the analyses conducted in 2021 during the COVID-19 pandemic. This discrepancy is attributed to the laboratory environment, where the researcher processed the samples alone on-site due to the social isolation measures implemented during the pandemic. These findings support the hypothesis that the fibers found in the control samples are associated with the presence of other researchers in the laboratory.

CONCLUSION

Our results showed that proximity to the source of contamination was not the primary factor for solid waste presence on the studied islands. Surprisingly, the highest density of solid waste was presented on the island furthest from the mainland, particularly on exposed beaches with a higher energy incidence, influenced by climatic and oceanographic factors. This contrasts with the findings for microplastics, where their highest values were observed on Paquetá Island, a location with significant anthropogenic influence.

Plastic, widely used across various sectors of society and plagued by issues of improper disposal, remained the predominant type of waste on all three islands, regardless of their proximity to pollution sources, highlighting the significance of currents and winds in their distribution.

Factors such as periodic beach cleanings may impact the presence of solid waste but not that of microplastics, indicating the latter as a persistent issue for these environments. The predominantly blue microplastics found, primarily as fragments smaller than 1,000 μm and often present in wet sand, pose a concern as they can be easily transported into the marine environment by waves and tides, thus posing a threat to biota.

Our results suggest that plastic is an important source of pollution in island environments, regardless of proximity to polluting sources. Therefore, measures to reduce the presence of plastic on beaches should be a priority in all locations, regardless of distance from polluting sources.

AUTHORS CONTRIBUTIONS

C.S.A.I.: Investigation, Formal Analysis, Writing – Original Draft, Writing – Review & Editing.

A.A.P.; P.D.: Formal Analysis, Writing – Original Draft, Writing – Review & Editing.

B.G.: Investigation, Writing - Original Draft, Writing – Review & Editing;

R.O.C: Conceptualization, Supervision, Writing – Original Draft, Writing – Review & Editing.

F.V.A.: Conceptualization, Formal Analysis, Validation, Supervision, Writing – Original Draft, Writing – Review & Editing.

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