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Subtidal benthic marine litter off the coast of Rio de Janeiro, Brazil

Fábio Vieira de Araújo[1,*], Eduardo da Silva Videla[2], Bruno Pereira Masi[3], André Luiz Carvalho da Silva[4]

[1] Departamento de Ciências – Faculdade de Formação de Professores – Universidade do Estado do Rio de Janeiro (Rua Dr. Francisco Portela 1470 – Patronato – São Gonçalo – RJ – Brazil – 24435-005).

[2] Programa de Pós-graduação em Biologia Marinha e Ambientes Costeiros – Instituto de Biologia – Universidade Federal Fluminense (Outeiro de São João Batista, s/n – Centro – Niterói – Rio de Janeiro – Brazil –24020-971).

[3] Departamento de Biotecnologia Marinha – Instituto de Estudos do Mar Almirante Paulo Moreira (Rua Kioto 253 – Arraial do Cabo – RJ – Brazil– 28930-000).

[4] Departamento de Geografia – Faculdade de Formação de Professores – Universidade do Estado do Rio de Janeiro (Rua Dr. Francisco Portela 1470 – Patronato – São Gonçalo – RJ – Brazil – 24435-005).

*Corresponding author: araujofv.bio@gmail.com

Abstract

Several studies have reported on the presence of litter on beaches and in the oceans, but this represents the smallest part of the litter that ends up in the sea. Little is known about the litter that settles on the ocean floor, especially near coastal regions. Thus, this study quantified, classified and determined possible sources of subtidal benthic marine litter input off the coast of Rio de Janeiro, Brazil. Different sites were selected in Guanabara Bay, an area with the greatest industrial and population concentration in the state of Rio de Janeiro, and on the coasts of Costa do Sol and Costa Verde, where tourism represents the main economic activity. Material was collected by scuba diving at depths of between 5 and 15 meters at 31 sites distributed among the study areas. A total of 1,209 items was found, with Guanabara Bay having the highest average concentration (92.40 items/km^2), followed by Costa do Sol and Costa Verde (14.15 items/km^2 and 9.91 items/km^2, respectively). Plastic materials are the most representative solid waste (55.08%), followed by metals (14.97%) and fishing gear (12.48%). Results indicated that local activities affected the composition of the marine litter on Costa do Sol and Costa Verde, whereas in Guanabara Bay, anthropogenic material carried by rivers influenced the marine litter composition at certain locations in addition to local activities. Environmental education actions associated with tourism and fishing activities and better waste management are necessary to minimize the presence of litter in subtidal benthic environments.

Keywords: Marine pollution, Benthic environments, Subtidal environment, Solid waste, Coastal environment

INTRODUCTION

Marine litter is a global concern that has been studied in several marine and coastal ecosystems (Silva et al., 2018), and has increased significantly worldwide in recent decades (Xanthos and Walker, 2017). About 15% of the litter that enters the marine environment remains adrift on the surface and another 15% remains in the water column, whereas the other 70% is deposited on the marine seabed (UNEP, 2005). Vertical distribution of marine litter increases its potential for contamination (Smith and Edgar, 2014). On the water surface, ingestion

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and entanglement are the main damages caused by litter to the marine biota; whereas in the benthic environment, where ingestion and entanglement also occur, marine litter creates artificial substrates for species that would not normally inhabit certain regions (Akoumianaki et al., 2008). Moreover, it prevents gas exchange between the substrate and the overlying water column (Corcoran, 2015). Damage to vessels and to fishing and tourism activities are among the economic damages caused by the presence of litter in subtidal benthic environments (Spengler and Costa, 2008).

Studies addressing the occurrence of marine litter in the subtidal benthic environment remain scarce, especially on shallow coastal waters (Corcoran, 2015) and those using diving as a sampling method (Machado and Fillmann, 2010). Usually, studies of subtidal marine litter are based on bottom trawling conducted under existing fishery stock or biodiversity assessment programs (e.g., Cau et al., 2017; Spedicato et al., 2019; Strafella et al., 2015). Marine litter assessments in shallow, nearshore waters over topographically complex rocky bottoms or sensitive ecosystems (e.g., coral reefs and seagrass) are, in turn, underrepresented and require alternative and non-intrusive techniques (visual surveys, either by divers or remotely operated vehicles) (Spengler and Costa, 2008). More recently, acoustic seafloor mapping using Side Scan Sonar (SSS) has also been used (Madricardo et al., 2020). In Brazil, studies on benthic marine litter have been conducted by Machado and Fillmann (2010); Carvalho-Souza and Tinoco (2011); Soares et al. (2011), Farias et al. (2018), and Oigman-Pszczol and Creed (2007), the latter being the only one performed off the coast of Rio de Janeiro state.

Global distribution of benthic marine litter is controlled by several factors, including proximity to urban centers, currents, geomorphology, river contribution, and dumping activities (Corcoran, 2015). Assessing benthic marine litter is essential for developing strategies to control this type of marine pollution (Spengler and Costa, 2008).

The coast of Rio de Janeiro has densely populated areas and places with intense tourism, fishing, industrial, commercial and oil exploration activities, which are all possible sources of litter for the marine and coastal environment. This study conducted a qualitative and quantitative assessment of subtidal benthic marine litter at different points off the coast of Rio de Janeiro to understand the contributing factors to its origin and dispersion, as well as to generate relevant data on the topic to provide support for management mitigating actions.

METHODS

Study areas

This study conducted benthic litter collection actions in three areas along the coast of Rio de Janeiro, Brazil: Costa Verde, Guanabara Bay and Costa do Sol (Figure 1).

Costa Verde

Costa Verde (23°11’7.5”S; 44°28’56.4”W) is located on the south coast of the state of Rio de Janeiro, approximately 140 km from Guanabara Bay (Figure 1). With a population of around 250,000 inhabitants (IBGE, 2020), it is one of the most important tourism regions in Brazil and has the municipalities of Angra dos Reis and Paraty as its main destinations. In 2019, the United Nations Educational, Scientific and Cultural Organization (UNESCO) recognized Paraty, together with the island of Ilha Grande (Angra dos Reis) as a cultural and natural heritage of humanity. These two coastal cities attract many visitors from different parts of Brazil and from around the world.

The Costa Verde region is characterized by a drowned coastline with numerous islands and a succession of small inlets, with many sheltered beaches separated by crystalline basement outcrops (Muehe, 2001). It has several small rivers and channels that bring sediment from the steep slopes of Serra do Mar and deposit it on the beaches (Pinheiro et al., 2021a). These rivers and channels are fed by a tropical rain regime concentrated in the summer months, with annual rainfall greater than 2,000 mm (Salgado et al., 2007).

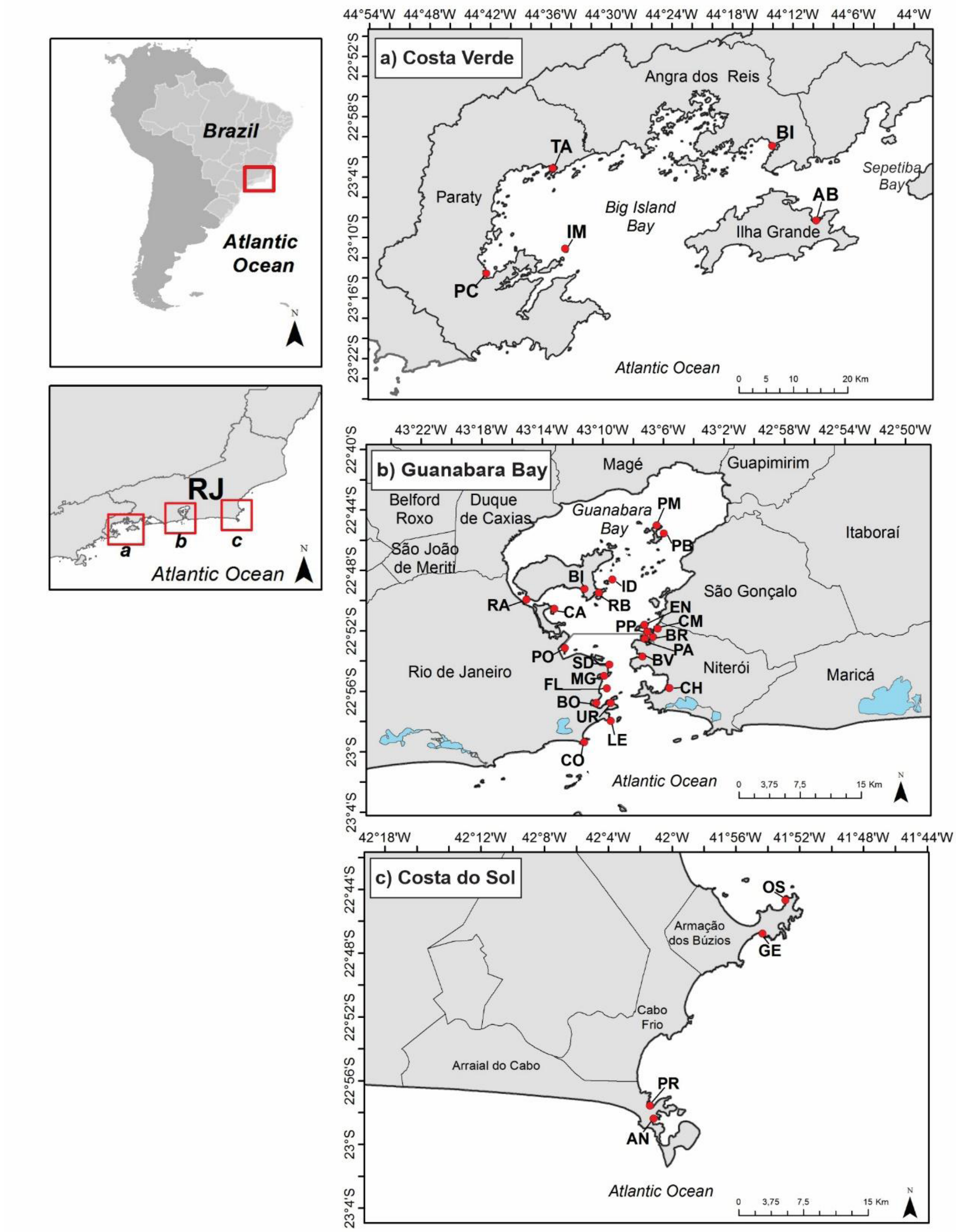

Figure 1. Sampling stations (red dots) distributed in the state of Rio de Janeiro: a) Costa Verde, Abraão Beach (AB), Biscaia Beach (BI), Tarituba Beach (TA), Paraty Pier (PC), Ilha dos Meros (IM); b) Guanabara Bay: Rio de Janeiro, Ribeira Beach (RB), Bica Beach (BI), Ilha D'água (ID), Ramos Beach (RA), Catalão Beach (CA), Paquetá – Ferry Station (PB), Moreninha Beach (PM), Ilha da Pombeba (PO), Santos Dumont Airport (SD), Marina da Glória (MG), Flamengo Beach (FL), Botafogo Beach (BO), Urca Beach (UR), Leme Beach (LE), Copacabana Fort (CO), Niterói, Brasco Logística Offshore (BR), Enave Shipyard (EN), Camorim Shipyard (CM), Rio-Niterói Bridge (PP), Ponta da Areia (PA), Charitas Beach (CH), Boa Viagem Beach (BV) and c) Costa do Sol, Ossos Beach (OS), Geribá Beach (GE), Prainha Beach (PR), Anjos Beach (AN). Lines represent the municipality limits and in b) the blue represents the water bodies (from left to right: the Barra da Tijuca lagoon complex, the Rodrigo de Freitas lagoon, the Piratininga and Itaipu lagoon and the Maricá lagoon complex).

In this region, the tide is semi-diurnal and does not exceed 1.5 meters (DHN, 1980). The waves are the main process responsible for the coastline dynamics, together with the coastal currents (Silva et al., 2020; Pinheiro et al., 2021b). Waves formed under good weather conditions predominate most of the year, coming from the south quadrant and, mainly, from the southeast (Godoi et al., 2011; Silva et al., 2020). Storm waves, almost always coming from the southwest, are caused by the occasional passage of cold fronts, reaching regions that are usually protected (Godoi et al. 2011; Pinheiro et al., 2021a). According to Belo et al. (2002), the marine relief of Ilha Grande Bay contributes to gradually decrease the energy of waves and currents along the bay, varying from east (higher energy) to west (lower energy).

Duque et al. (2008) presented a model of surface water circulation in Ilha Grande Bay and highlighted the existence of a strong current formed between the bays of Ilha Grande and Sepetiba, which usually hinders the mixing of water between the bays. Santos et al. (2018) observed that the rate of water renewal within Ilha Grande Bay is higher under storm conditions, when transport tends to be greater from east to west, contributing to greater water renewal within the bay.

The chosen study sites were Abraão Beach, where boats arriving on the island of Ilha Grande usually dock, and Biscaia Beach, both located in Angra dos Reis; and Tarituba Beach, Paraty pier, and the island of Ilha dos Meros, in Paraty (Figure 1). Besides its tourist appeal, the Terminal da Baía da Ilha Grande (Ilha Grande Bay Terminal – TEBIG) located at Biscaia Beach, is responsible for receiving, storing, and transferring oil. Tarituba Beach is a fishing village that receives many tourists. Ilha dos Meros is located in front of the beach of the same name and is very popular for line fishing and diving (Figure 1).

Guanabara Bay

Located in the metropolitan region of Rio de Janeiro state (Figure 1), Guanabara Bay (22°54’0”S; 43°12’0”W) has an area of approximately 380 km^2, with a maximum length of 36 km (north-south) by 29 km (east-west), and a 1.6 km narrowing at its entrance. This region concentrates a large number of services, industries and populous cities, strongly marked by a lack of urban planning that has led to many environmental problems.

The marine relief of Guanabara Bay varies considerably, with depths generally below 5 m (65%), contrasting with the central channel area, which reaches depths of around 50 meters at the bay entrance (Kjerfve et al., 1997; Dias et al., 2021).

Guanabara Bay receives most of the effluents produced along its drainage basin (Fistarol et al., 2015), making it one of the most degraded areas in Brazil (Baptista Neto et al., 2006; Carvalho et al., 2021). Currently, more than 11 million people live in municipalities located on the margins of Guanabara Bay. The bay receives approximately 18 m^3/s of domestic sewage daily from the more than forty rivers that flow directly into its waters, bringing solid waste and untreated sewage, of which only 25% receive secondary treatment (Carvalho et al., 2021). The garbage that reaches Guanabara Bay is a highly visible and accentuated pollution problem in the various marginal areas, including its inland beaches (Baptista Neto and Fonseca, 2011; Fistarol et al., 2015; Carvalho et al., 2021).

It is mostly a low wave energy environment, but the sites locations near the bay entrance or positioned in front of storm waves have greater dynamics and are susceptible to wave energy. Site locations in the southern part of the bay have very low dynamics (Silva et al., 2016). In Guanabara Bay, the sea is calm for most of the year, with waves of less than 1 meter high from 2 to 14 seconds, under good weather conditions (Silva et al., 1999). During storm conditions, however, waves can reach 1.5 meters or, more rarely, even greater heights (Silva et al., 2016).

Guanabara Bay is characterized by the occurrence of semi-diurnal micro-tides, with a maximum amplitude of 1.4 meters (DHN, 1980). Its currents are directly influenced by the bay’s bottom morphology. The more intense currents occur on the eastern side of the bay entrance, where surface velocities reach 1.56 m/s during flood and 1.37 m/s at ebb, whereas at the bottom of the water column the velocity during flood is 1.05 m/s and only 0.53 m/s at ebb. The most frequent winds come from the north and south, the latter predominating and occurring when cold fronts arrive, with speeds greater than 10 m/s (Filippo and Figueiredo, 2012).

The twenty-two sampled points in Guanabara Bay are distributed in different areas along the coasts of Rio de Janeiro and Niterói, from its innermost part (Ilha de Paquetá) to areas close to its entrance (Leme Beach and Copacabana Fort) (Figure 1). Ilha da Conceição, Ponta da Areia, Ilha do Governador, Ilha D'água, Marina da Glória, and Ramos Beach (Figure 1) are points of intense maritime activity, since they concentrate oil terminals, shipyards, marinas, and offshore logistics companies. The beaches of Botafogo, Urca, Flamengo, Charitas, and Boa Viagem (Figure 1) are in predominantly residential areas. Ilha de Paquetá, Leme, and Copacabana are areas with intense flow of tourists and Ilha do Fundão houses a campus from the Universidade Federal do Rio de Janeiro (Federal University of Rio de Janeiro) (Figure 1). Ilha da Pombeba (Figure 1) is an artificial formation built for dumping dredging waste from the Rio de Janeiro harbor.

Costa do Sol

Costa do Sol (22°51'30.6"S; 41°59'50.5"W), also known as Região dos Lagos, is located on the east coast, about 180 km from the Metropolitan Region of Rio de Janeiro (Figure 1). According to the IBGE (2020), it has an estimated population of 500,000 inhabitants. The region has a natural tourist appeal and although each municipality in the region receives thousands of visitors annually, the present study focused on the two centers with the highest concentration of tourists: Armação dos Búzios, for its international recognition as a tourist center, and Arraial do Cabo, considered the diving capital of Brazil (Ministério do Turismo, 2016) (Figure 1).

The presence of rocky promontories in Armação dos Búzios and Cabo Frio divides the coast into sheltered oceanic beaches with different levels of exposure to wave dynamics and distinct morphological and geographic characteristics (extension, orientation and slope) (Bulhões and Fernandez, 2016; Motta et al., 2018). The tide regime is semi-diurnal and micro-tidal, with a maximum amplitude of 1.2 meters for the spring tide (Bulhões et al.,2014).

Storm waves occur between the months of April and September (about 80%). In this period the waves can reach 5 meters high in deep water, mostly occurring between the south-southeast (158º) and south-southwest (203º) directions, directing more energy to the central and northern portions of the beach arcs between Cabo Frio and Armação dos Búzios. The small inlets and beaches located in the northern portion of Búzios are completely protected from storm waves and their processes are more linked to the good weather winds coming from the northeast quadrant, and the waves they generate (Bulhões et al.,2014).

Costa do Sol is considered a phytogeographical enclave (Ab'Saber, 2003) due to the presence of xeric formations such as dry forest and xeric shrubland with Cactaceae (also called "caatinga") (Araujo, 1997). Marine areas close to the municipalities of Armação dos Búzios and Arraial do Cabo are influenced by upwelling, whereby cold waters from the deepest layers emerge to displace surface waters, bringing a large amount of nutrients to enable high primary productivity, which is essential for several economically important marine species (Coelho-Souza et al., 2015). This phenomenon leads to a local decrease in precipitation and, consequently, to the establishment of a dry microclimate, with an average annual precipitation of 850 mm (Barbiere, 1984).

In Búzios (Figure 1), sampling was performed at Ossos Beach, known for its pier for mooring small boats and a busy nightlife, and Geribá Beach, one of the most popular beaches in the region. In Arraial do Cabo (Figure 1), the selected beaches were Anjos Beach, from where fishing and tourism boats depart, and Prainha Beach, which has a large number of kiosks.

Sampling methods

Sampling was performed by scuba diving at 31 sites distributed along the coast of the state of Rio de Janeiro (Figure 1 and Table S1) between July and September 2018 and June and August 2019. These months have less rainfall and lower presence of tourists, whose presence could result in an increase in litter production and mobility in these places. The greater amount of sampling dives in Guanabara Bay, compared to Costa do Sol and Costa Verde, occurred due to greater proximity to the laboratory, which facilitated collection; to the greater number of studies with marine litter in its waters and beaches; as well as the greater complexity of uses related to this environment, which allowed for better data comparison and analysis. The sample stations in each region were selected for their easy access to selected dive sites.

Table 1. Number of items by category and concentration (items/km²) of subtidal benthic marine litter collected at the stations located at Costa Verde, Guanabara Bay, and Costa do Sol, RJ. The fishing material category values were not considered when calculating the total of collected marine litter, since they were included in the categories (plastic or metal) that make up these materials.

Collection stations	Categories							Total of collected marine litter
	Modified wood	Fishing gear	Metal	Plastic	Glass	Others	Items/km²	
Costa Verde								
Abraão Beach – Angra dos Reis (AB)	0	6	2	8	0	0	17.69	10
Biscaia Beach – Angra dos Reis (BI)	0	0	1	2	0	1	7.08	4
Tarituba Beach – Paraty (TA)	0	0	0	0	0	2	3.54	2
Paraty Pier – Paraty (PC)	0	0	2	6	0	1	15.92	9
Ilha dos Meros – Paraty (IM)	0	3	0	3	0	0	5.31	3
Total in Costa Verde	0	9	5	19	0	4	49.54	28
Guanabara Bay								
Rio de Janeiro								
Ribeira Beach (RB)	4	0	0	38	2	3	83.16	47
Bica Beach (BI)	3	0	4	33	0	3	76.08	43
Ilha D'água (ID)	25	0	45	16	0	1	15.,93	87
Ramos Beach (RA)	10	0	23	68	8	17	222.93	126
Catalão Beach (CA)	10	2	1	129	0	9	263.62	149
Paquetá – Ferry Station (PB)	4	9	3	18	0	0	44.23	25
Moreninha Beach (PM)	0	32	6	58	0	0	113.23	64
Ilha da Pombeba (PO)	12	0	15	94	0	52	306.08	173
Santos Dumont Airport (SD)	0	0	9	11	0	2	38.92	22
Marina da Glória (MG)	0	12	6	16	0	0	38.92	22
Flamengo Beach (FL)	0	8	11	25	0	0	63.69	36
Botafogo Beach (BO)	0	9	4	22	2	0	49.54	28
Urca Beach (UR)	0	12	11	33	0	0	77.85	44
Leme Beach (LE)	3	27	5	44	2	1	97.31	55
Copacabana Fort (CO)	3	16	7	46	0	0	99.08	56
Niterói								
Brasco Logística Offshore (BR)	10	9	6	20	0	0	63.69	36
Shipyeard Enave (EM)	0	0	18	5	0	0	40.69	23
Shipyeard Camorim (CM)	0	0	15	16	1	0	56.62	32
Rio-Niterói Bridge (PP)	0	0	4	1	0	0	8.84	5
Ponta da Areia (PA)	2	1	8	14	2	0	46.00	26
Charitas Beach (CH)	0	0	0	16	0	4	35.38	20
Boa Viagem Beach (BV)	0	0	5	21	3	1	53.08	30
Total in Guanabara Bay	86	137	206	744	20	93	2032.87	1,149
Costa do Sol								
Ossos Beach- Búzios (OS)	5	2	2	3	0	1	19.46	11
Geribá Beach – Búzios (GE)	0	3	1	6	0	0	12.38	7
Prainha - Arraial do Cabo (PR)	0	0	2	3	1	0	10.61	6
Anjos Beach - Arraial do Cabo (AN)	0	0	0	7	0	1	14.15	8
Total in Costa do Sol	5	5	5	19	1	2	56.60	32
GENERAL TOTAL	**91**	**151**	**216**	**782**	**21**	**99**	**-**	**1,209**

Collection depths ranged from a minimum of 5 m at stations located in Guanabara Bay and a maximum of 15 m at Ilha dos Meros on the coast of Paraty (Figure 2a; Table S1). Divers used circular scanning as a search and recovery technique (Vecchioni, 2019) (Figure 2b), which involves placing an anchor point on the sedimentary bottom to demarcate the starting point of the sampling perimeter. From this reference, a cable is gradually released by the diver and sweeping is performed until the circle is complete. This technique enables scanning from the reference point (ascending) or from the end of the cable (descending).

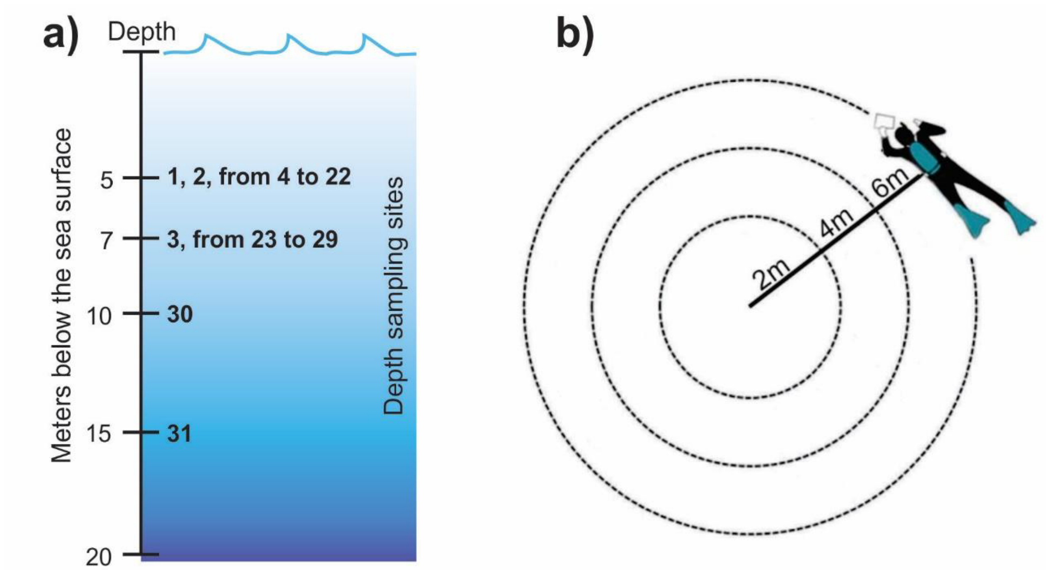

Figure 2. Scanning technique used in the search and recovery of subtidal benthic marine litter. Guanaraba Bay: Rio de Janeiro, 1 Ribeira Beach (RB), 2 Bica Beach (BI), 3 Ilha D'água (ID), 4 Ramos Beach (RA), 5 Catalão Beach (CA), 6 Paquetá – Ferry station (PB), 7 Moreninha Beach (PM), 8 Ilha da Pombeba (PO), 9 Santos Dumont Airport (SD), 10 Marina da Glória (MG), 11 Flamengo Beach (FL), 12 Botafogo Beach (BO), 13 Urca Beach (UR), 14 Leme Beach (LE), 15 Copacabana Fort (CO); Niterói, 16, Brasco Logística Offshore (BR), 17 Enave Shipyard (EN), 18 Camorim Shipyard (CM), 19 Rio-Niterói Bridge (PP), 20 Ponta da Areia (PA), 21 Charitas Beach (CH) and 22 Boa Viagem Beach (BV). Costa do Sol: 23 Ossos Beach (OS), 24 Geribá Beach (GE), 25 Prainha (PR) and 26 Anjos Beach (AN). Costa Verde: 27 Abraão Beach (AB), 28 Biscaia Beach (BI), 29 Tarituba, Beach (TA), 30 Paraty Pier (PC), 31 Ilha dos Meros (IM). Figure b was adapted from Machado and Filmann (2010).

The ascending method was chosen and a 6 m long cable was used. Demarcations were made at intervals of two meters, given the low visibility of some areas in the bay, totaling 113.04 m^2. A total of five collections were performed for each sampling point, totaling 565.2 m^2 of sampled area. To increase safety during sampling, a surface float was placed to indicate the location of the diver on the seabed. All macro litter (>25 mm) found within the demarcated area was collected and subsequently separated into five categories (modified wood, metal, plastic, glass, and others) following the methodology described by Silva et al (2015). Materials commonly used in fishing such as hooks, lines, sinkers, nets, and floats, were grouped into a specific category (fishing materials) to highlight this type of marine litter, but were accounted for in their respective categories (plastic and metals). Materials found in small quantities, such as foam, styrofoam, rubber, and fabrics were grouped as "others.".

Data analysis

Descriptive analysis of the marine litter was conducted to provide a wide perspective of items in different areas on the coast of Rio de Janeiro. Mean values and their respective standard deviations of the multivariate marine litter data in each region were calculated. Based on these values, 99 resamplings (simulation multivariate normal data based on correlation matrix, means, and sd's) were generated for each region, from which samples containing negative numbers were excluded. Ordination of marine litter composition was performed using metric multidimensional scaling (MDS) (Bray-Curtis dissimilarity index) and differences between regions were tested (Permutational Multivariate Analysis of Variance – PERMANOVA method). Types of litter that most contributed to the dissimilarity between sites were identified using SIMPER analysis (Clarke, 1993). All statistical analyses were performed using R Statistical Software version 4.2.2 (R Core Team, 2021) and RStudio version 2022.07.2 (RStudio Team, 2020) using the packages "vegan" and "ggplot2".

RESULTS

A total of 1,209 items were collected at the 31 sampling stations (Table 1 and Table S2). Most (95%) came from stations located in Guanabara Bay, 2.7% from the four stations located on the east coast of the state (Costa do Sol), and the remaining 2.3% from the five stations located in the southern region (Costa Verde).

Subtidal benthic marine litter concentrations varied from 3.54 items/km^2 to 306.08 items/km^2, with the lowest concentrations (all below 20 items/km^2) being found outside the metropolitan region of Rio de Janeiro. Within the metropolitan region, the values were all over 35 items/km^2, except for the Rio-Niterói bridge station, with 8.84 items/km^2.

No sample station showed all six categories of litter classification used in this work. At Ilha dos Meros and Tarituba Beach stations, at Costa Verde, only one of the six types of litter was found (Table 1). Plastic was the most collected item (782 items), being found at 30 of the 31 sample stations. Glass was the least sampled item (21 items), and was collected at only eight stations.

A total of 1,149 items were collected at the 20 stations located within Guanabara Bay and at the two located on the ocean beaches of Leme and Copacabana, at the bay's west entrance. The sites with the highest amount of subtidal benthic marine litter were Ilha da Pombeba in Caju (306.08 items/km^2), Catalão Beach (263 items/km^2), and Ramos Beach (222.93 items/km^2), all in the city of Rio de Janeiro. Plastics were the most common type of litter among all the categories, with 744 items (64.75%), followed by metals, with 206 items (18%). The site with the highest number of plastics was Catalão Beach with 129 items (17.06%) collected (Table 1 and Figure 3).

Pieces of modified wood (28.8%) and metals (51.7%) showed higher numbers at Ilha D'água, whereas fishing gear (32 items – 3 metals and 29 plastics) were more frequent at Moreninha Beach, on Ilha de Paquetá. Glass, with the lowest figure among the litter items, was more common at Ramos Beach (40.0%). In the category "others", materials such as foam, tires, and fabric clothes were grouped and found in small numbers. In Guanabara Bay, this category was found mostly at Ilha da Pombeba (55.9%).

A total of 32 items (56 items/km^2) were found in the subtidal benthic marine environments of Costa do Sol, in concentrations ranging from 10.61 items/km^2 (Prainha Beach, in Arraial do Cabo) to 19.46 items/km^2 (Ossos Beach, in Búzios). The highest diversity of litter was observed at the Ossos Beach station. Plastic was the most common item (59.4%), followed by pieces of modified wood (15.6%) (Table 1 and Figure 3).

The lowest concentrations of benthic marine litter were found in the Costa Verde region, ranging from 3.54 items/km^2 at Tarituba Beach, Paraty, to 17.69 items/km^2 at Abraão Beach, on Ilha Grande. Plastic (67.85%) followed by metals (17.85%) were the most collected litter items. No modified wood or glass was collected in this region (Table 1 and Figure 3).

The PERMANOVA test on the sample averages distinguished four regions (DF = 3, R2 = 0.70, p = 0.001, perm. = 999). The patterns of similarities in litter composition between sites are illustrated in the nMDS plot (Figure 4). Post-hoc testing suggests that litter compositions are similar among the groups of sites at Costa Verde vs Costa do Sol and Rio de Janeiro vs Niterói. Post-hoc paired test observed differences in Costa Verde vs Rio de Janeiro (R2 = 0.3695, p = 0.001), Costa Verde vs Niterói (R2 = 0.3003, p = 0.002), Rio de Janeiro vs Costa do Sol (R2 = 0.3783, p = 0.001) and Niterói vs Costa do Sol (R2 = 0.3206, p = 0.004).

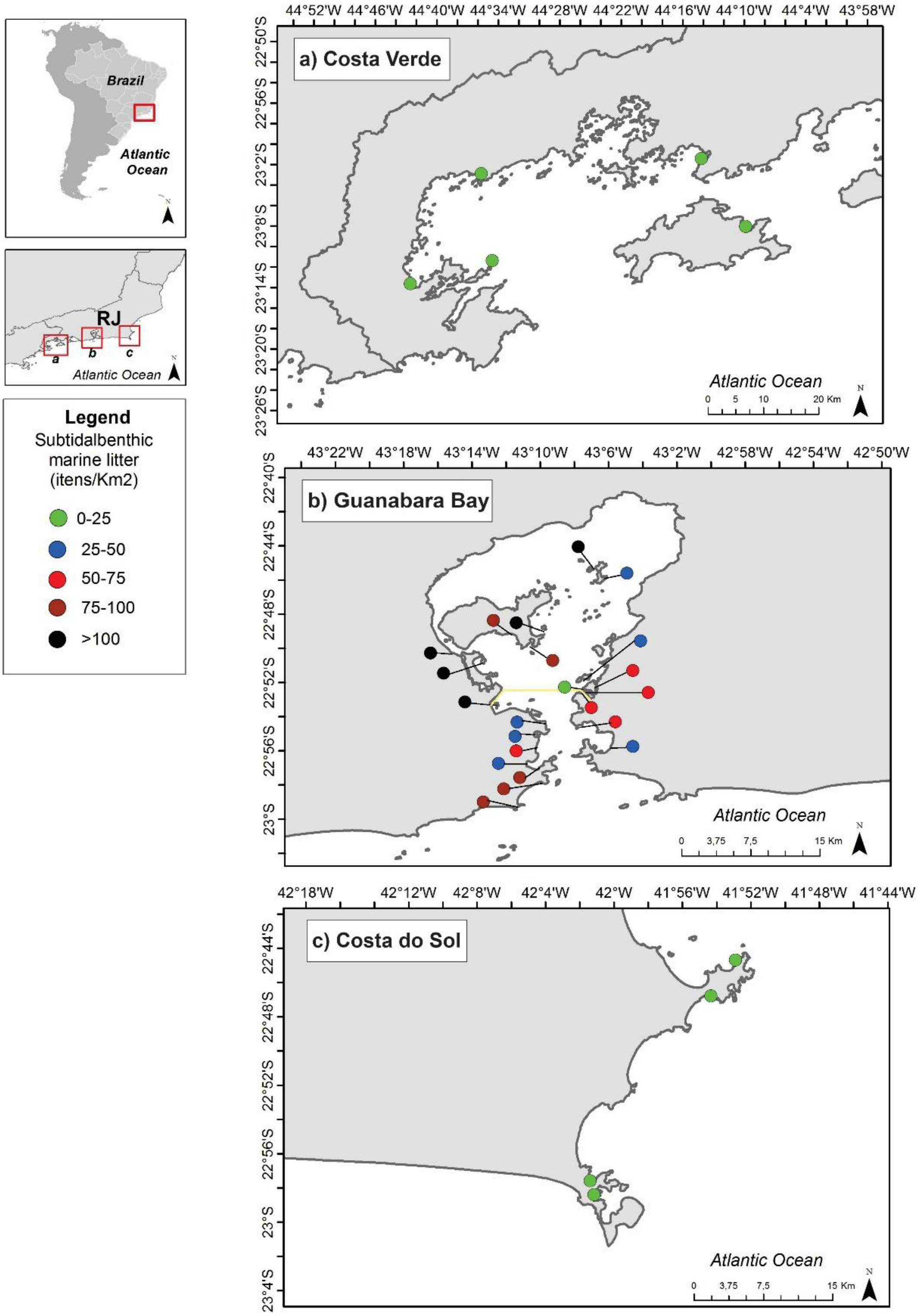

Figure 3. Subtidal benthic marine litter concentration (items/ km²) at the different sampled stations in a) Costa Verde, b) Guanabara Bay, c) Costa do Sol.

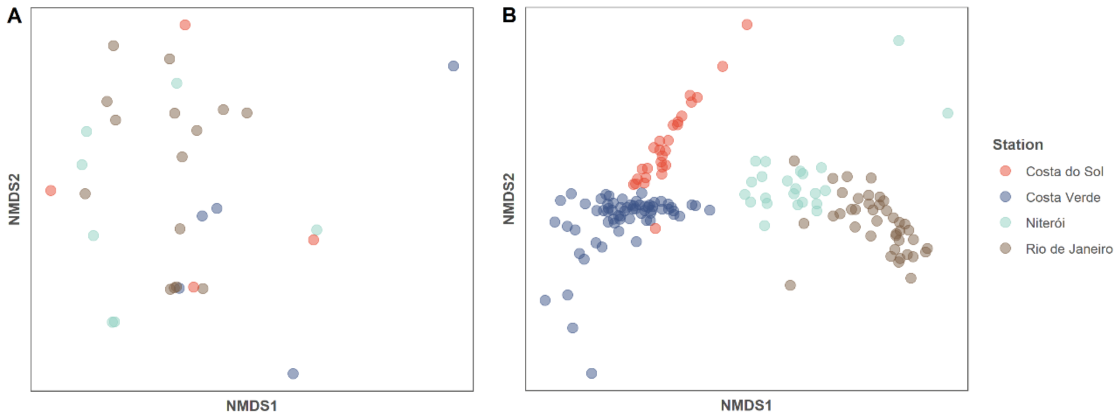

Figure 4. Patterns of similarities in litter composition between sites in the nMDS plots based on Bray-Curtis similarities. A) Metric MDS (mMDS) of the subtidal benthic marine litter collected (Table 1 data), and B) mMDS of resampling by simulation multivariate normal data based on correlation matrix, means, and sd´s.

Plastic followed by metals were the main categories which accounted for the difference between Guanabara Bay (Rio de Janeiro and Niterói) and the other regions (Figure 5b), mainly due to their high representation in these places (Figure 5a). The category "others" generally ranks third as a contributor to the difference between regions. The variations presented by modified wood and glass contribute less than the others to the difference between regions.

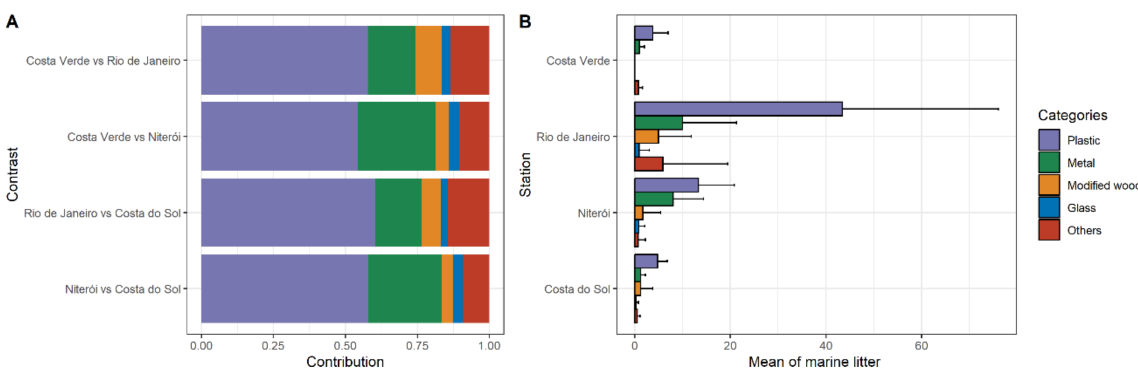

Figure 5. A. Results from marine litter contributions (SIMPER) to contrast between distinguished stations (PERMANOVA) of subtidal benthic marine litter collected at the stations located at Costa Verde, Guanabara Bay and Costa do Sol, RJ. B. Mean and standard deviation of the subtidal benthic marine litter (categories) collected.

DISCUSSION

Litter has been found in seas and oceans worldwide, and is mainly documented in coastal regions and in the water column, with a smaller number of studies conducted on the seabed, where about 70% of such litter is deposited (Chassignet et al., 2021)

In Brazil, for example, several studies have registered the presence of large amounts of marine litter in the waters and on the beaches of Guanabara Bay (Baptista Neto and Fonseca, 2011; Ferreira et al, 2011), Costa do Sol (Oigman-Pszczol and Creed, 2007; Silva et al., 2016; 2018) and Costa Verde (Macedo et al*.,* 2019). However, nothing has yet been published regarding the presence of macrolitter in the subtidal benthic environment of these areas. Knowledge on the extent of subtidal benthic marine litter allows us to understand the effects of its distribution and accumulation in these environments (Miyake et al., 2011; Mordecai et al., 2011).

Concentration of the subtidal benthic marine litter found is quite diverse (Table 2).

Table 2. Articles published on benthic litter in other countries

Local	Depth	Methodology	Type of marine litter found	Marine litter concentration	Reference
Eastern Mediterranean Sea	194-2,387 m	bottom trawl	Paint chips	NR	Galil et al, 1995
Northwest Mediterranean Sea	500-1,600 m	bottom trawl	plastic bags	0-78 . ha^{-1}	Galgani et al, 1996
Gulf of Patras and Echinadhes - Greece	247-360 m	bottom trawl	Plastic	240 items . km^{-2}	Stefatos et al, 1998
Kodiak Island – Alaska	0-488 m	bottom trawl	Plastic	31 items . km^{-2}	Hess et al, 1999
Coast of Europe	-	bottom trawl	Plastic	101,000 items . km^{-2}	Galgani et al, 2000
Coast of Greece – Mediterranean Sea	0-25 m	Scuba diving	Plastic	0-251 items . km^{-2}	Katsanevakis e Katsarou, 2004
East China Sea and South Korea	-	bottom trawl	Fishing material	109.8 Kg . km^{-2}	Lee et al, 2006
Gulfs of Greece – Mediterranean Sea	15-320 m	bottom trawl	Plastic	72-437 items . km^{-2}	Koutsodendris et al, 2008
Gulf of Aqaba – Red Sea	0-20 m	Scuba diving	Plastic	1-6 items . m^{-2}	Abu-Hilal e Al-Najjar, 2009
California Continental Shelf	20-365 m	submarine observation	Plastic	0-38 items . 100 m^{-1}	Watters et al, 2010
Coast of Japan	299-1,753 m	Video made with ROV	Plastic	NR	Miyaki et al, 2011
West Coast of Portugal	740-4,574 m	Video made with ROV	Plastic	6,600 items . km^{-2}	Mordecai et al, 2011
Antalya Bay – Mediterranean Sea	200-800 m	bottom trawl	Plastic	115-2,762 items . km^{-2}	Güven et al, 2013
Mediterranean Sea	900-3,000 m	bottom trawl	Plastic	3,264 kg . km^{-2}	Ramirez-Llodra et al, 2013
Belgium's Continental Shelf	0-800 m	bottom trawl	Plastic	6,429-6,767 items . 100 m^{-1}	Van Cauwenberghe et al, 2013
Maltese Island – Mediterranean Sea	48-713 m	bottom trawl	Plastic	78 items . km^{-2}	Mifsud et al, 2013
Monterrey Bay – California	25-3,971 m	Video made with ROV	Plastic	NR	Schlining et al, 2013
Eastern Mediterranean Sea	19-178 m	bottom trawl	Plastic	5.85 kg . ha^{-1}	Eryasar et al, 2014
Eastern Mediterranean and Black Sea	-	bottom trawl	Plastic	24 items . km^{-2}	Ioakeimidis et al, 2014
Tyrrhenian Sea – Mediterranean Sea	30-300 m	Remotely Operated Vehicle	Fishing material	0.09-0.12 items . m^{-2}	Angiolillo et al, 2015
Portuguese coast	90-349 m	bottom trawl	Plastic	178.9 items . km^{-2}	Neves et al, 2015
North and Central Adriatic Sea	8-100 m	bottom trawl	Plastic	171 kg . km^{-2}	Strafella et al, 2015
Northwest Mediterranean Sea	140-1,731 m	Remotely Operated Vehicle	Plastic	8,090 items . km^{-2}	Tubau et al, 2015
North and Central of Adriatic Sea	0-100 m	bottom trawl	Plastic	913 items . km^{-2}	Pasquini et al, 2016
Pass Faial-Pico – Azores	40-525 m	Remotely Operated Vehicle	Plastic	0.26 items . $100m^{-1}$	Rodríguez e Pham, 2017
Hausgarten Observatory - Arctic	0-2,500 m	Photographic register	Plastic	6,566 items . km^{-2}	Tekman et al, 2017
Sardinia Island – Mediterranean Sea	0-800 m	bottom trawl	Plastic	35.15 items . km^{-2}	Alvito et al, 2018
South of the Baltic Sea	19-110 m	bottom trawl	Plastic	0.20 items . ha^{-1}	Urban-Malinga et al, 2018

Legend : ROV = Remotely Operated Vehicle ; NR = not reported

Studies such as those by Abu-Hilal and Al-Najjar (2009) reported 2,800 items/km^2 at some of the collection points studied on the Jordan coast, in the Red Sea. Our findings showed great variation (3.54 to 306.08 items/km^2), as did those of Katsanevakis and Katsarou (2004) (0.45 to 251.25 items/km^2) in coastal areas of Greece. These variations can be explained by the proximity to urban centers, influence of marine currents, local geomorphology, proximity to river estuaries, and dumping activities (Corcoran, 2015).

Our results showed a great difference between the average concentration of subtidal benthic marine litter found in the Guanabara Bay (92.40 items/km^2) and that collected at Costa do Sol (14.15 items/km^2) and Costa Verde (9.91 items/km^2) areas of the state of Rio de Janeiro. A difference between these regions was also observed when analyzing the litter composition found (Figures 4 and 5). Guanabara Bay is located within the metropolitan region of Rio de Janeiro, with several densely populated municipalities in its surroundings, in addition to industries, ports, shipyards, and a large input from rivers, which provide a large amount of the most varied types of litter (Baptista Neto and Fonseca, 2011). These factors were also mentioned by Carvalho-Souza and Tinoco (2011) to explain the 132.2 items/km^2 found in Todos os Santos Bay, state of Bahia. The Costa do Sol and Costa Verde regions, on the other hand, are located in areas with a lower population density, having tourism as one of its major economic activities.

Katsanevakis and Katsarou (2004) argued that a higher concentration of subtidal benthic marine litter is usually found in bays compared to open coastal areas. According to Galgani et al. (2000), this is explained by the presence of stronger currents in oceanic areas, which might carry litter deposited in the sediment to other places, whereas the litter in bays is more likely to remain at the dumping sites. Together with a larger amount of potential litter sources, this explains the higher concentration of litter found in the Guanabara Bay and the lower concentrations observed in the Costa do Sol region, an open area with greater hydrodynamics. Conversely, the points sampled at Costa Verde, where the lowest litter concentrations were found, are also located within a bay — the Ilha Grande Bay, which presented a higher hydrodynamic than the Guanabara Bay and fewer potential sources of litter, explaining the lower concentrations found. Unlike Guanabara Bay, which has a narrow opening to the ocean (only 1.6 km), Ilha Grande Bay has a wide connection with the ocean (17.4 km between Ilha Grande and Paraty) and houses the island of Ilha Grande, its main barrier, located in the central portion. Another factor to be considered refers to the large number of existing conservation units at Costa Verde (INEA, 2015), which restricts certain uses at several locations along the coast.

Plastic was the most common litter item in all the studied areas (Table 1 and Figure 3), result that corroborates several studies conducted in other benthic environments around the world (Table 2) and in Brazil, in both beach environments (Neves et al., 2010; Oliveira et al., 2011; Tourinho and Fillmann, 2011; Bruno and Santos, 2012; Silva-Cavalcanti et al., 2013; Silva et al., 2015; Corrêa et al., 2019; Rangel et al., 2021; Rosa and Widmer, 2021), surface waters (Bernardino and Franz, 2016; Olivatto et al., 2019), and subtidal benthic environments (Soares et al., 2011; Farias et al., 2018; Carvalho et al., 2021). According to Jambeck et al. (2015), the increasing presence of plastic in the ocean is due to the continuous expansion of its production, resulting from its widespread use in various sectors and inadequate waste management practices. These authors reported that Brazil ranks 16th in the ranking of the main contributors to the input of plastic debris into the ocean, based on per capita production and poor waste management.

Metals, modified wood, glass, and other marine litter such as styrofoam, rubber, and fabrics were also observed at several collection points, varying in their amount (Table 1 and Figure 3). Their presence is commonly reported in other works on subtidal benthic marine litter, especially at locations close to urban centers (Stefatos et al., 1999; Backhurst and Cole, 2000; Moore and Allen, 2000). Regardless of the type of material found in this environment, however, high litter concentrations can cause changes in the structure of benthic communities (Katsanevakis et al., 2007).

Another type of material found in all the studied areas was fishing gear (hooks, lines, nets, sinkers and floats). This type of litter was common at Costa do Sol and Costa Verde, and found in large quantities in Guanabara Bay, corresponding to 12.5% of the total subtidal benthic marine litter found in the three studied areas (Table 1 and Figure 3). Several authors who investigated subtidal benthic marine litter have mentioned the presence of this category in their results (Hess et al., 1999; Lee et al., 2006; Angiolillo et al., 2015). The higher prevalence of fishing gear on the Costa do Sol and Costa Verde is probably because these regions have a rich marine fauna (Silva and Vianna, 2009), encouraging fishing activities. Although fishing occurs at some sites in Guanabara Bay, waste from urban activities is more relevant. Such lost, discarded, or abandoned fishing gear in the subtidal benthic environment presents high durability, maintaining its fishing ability and therefore results in the mortality of marine species in a process known as ghost fishing (Angiolillo et al., 2015). During its stay in the marine environment, this material continues to fragment into microplastics, which can be ingested by a diversity of marine animals at all trophic levels and life stages (including larvae, juveniles, and adults), causing ecological and economic damage (Videla and Araujo, 2021). Microplastics were found on several beaches at Ilha Grande by Macedo (2020), including Abraão Beach, which points to a variety of possible sources such as tourism, fishing activities and the intense marine traffic in the bay.

Although no differences between the types of litter found at sample stations on Costa do Sol were identified, we observed little variation in the subtidal benthic marine litter concentration, with all stations presenting values between 10 to 20 items/km^2 (Table 1 and Figure 3). These values are slightly lower than those found (~ 30 items/km^2) by Oigman-Pszczol and Creed (2007) in the only study performed on subtidal benthic environments in Rio de Janeiro, in the region of Búzios. Those authors collected litter during the summer, a period of high tourism activity, unlike our material collections, which took place in the winter when tourism was less intense. The lower values found, especially at Geribá Beach, can also be explained by the litter carried from these places by storm waves, which are more common during the winter (Bulhões et al., 2013). The highest concentrations at Costa do Sol were found respectively at Ossos Beach, in Búzios (19.46 items/km^2), and at Anjos Beach, in Arraial do Cabo (14.15 items/km^2), both of which have low hydrodynamics and are located where several boats usually dock. Values within this range were also observed at Abraão Beach and at Paraty pier (Table 1 and Figure 3), which also have intense boat traffic and low hydrodynamics. On the Greek coast, Katsanevakis and Katsarou (2004) observed higher concentrations of subtidal benthic marine litter in mooring places, suggesting that fishing is a major litter contributor to marine environments, confirming our results which recorded a high amount of fishing gear in regions of intense fishing activity. The presence of other materials at these stations, such as plastics, represented by disposable cups and metals (soda cans), show that tourism carried out by boats play an important role in generating subtidal benthic marine litter in these areas. In some areas, the concentration and types of subtidal benthic marine litter can be explained mainly by their main economic (Galgani et al., 1995; Corcoran, 2015), such as the presence of fishing gear at Ilha dos Meros, in Paraty, or at Geribá Beach, places where fishermen are frequently spotted. Similarly, the occurrence of disposable cups and soda cans at Prainha, in Arraial do Cabo, is explained by the high frequency of local food kiosks. These marine litter items were also reported by Silva et al (2018) on the sand of Prainha Beach. Importantly, the lowest concentration of subtidal benthic marine litter found in this study was from Tarituba Beach (3.54 items/km^2), where a fishing village is located, but no fishing gear was found. Besides Tarituba, Biscaia Beach and Ilha dos Meros, also located at Costa Verde, presented concentrations lower than 10 items/km^2 (Table 1 and Figure 3). These results contrast with the high concentration of solid waste found on some sheltered beaches at Costa Verde, such as Abraão, São Gonçalo, and Jabaquara by Macedo et al. (2020), as well as on Praia Grande and Biscaia during high season (summer) by Rangel et al. (2021). Tourism is also pointed out in these studies as the main factor influencing solid waste pollution, especially the plastic materials found on the sands. Collection during the low season (winter) and the action of local tidal currents may explain our values. The central and mainly western areas of Ilha Grande Bay have the least influence of tidal currents (Oliveira and Meyer, 2006; Duque et al., 2008) and storm waves (Godoy et al., 2011; Silva et al., 2011; Silva et al., 2008), pattern that may also influence the low concentration of subtidal benthic marine litter in these places.

Distribution of subtidal benthic marine litter in the Guanabara Bay region was heterogeneous, with values ranging from 35 to 100 items/km² (Table 1 and Figure 3). Except for Paquetá Station (PB), with values of 44.23 items/km², the other stations that presented concentrations within this range are located from mid-Guanabara Bay to its entrance. Conversely, the stations located from the middle region to the bay's southern and west side, had concentrations greater than 100 items/km² (Table 1 and Figure 3). This distribution pattern points to a decrease in benthic waste concomitant with an increase in wave and current dynamics, which increase in intensity towards the bay's entrance (Silva et al., 1999; Silva et al., 2016). In the areas close to the entrance and inside the Guanabara Bay, the waves vary from a few centimeters to about 1 meter in height (Silva et al., 1999). During stormy conditions, however, the waves can reach 1.5 meters or, more rarely, even greater heights (~5 m) (Silva et al., 2016). Storm events on this part of the coast occur mainly between March and August (Santos et al., 2004), which includes our study period.

According to Mayr et al. (1989), Guanabara Bay can be divided into five areas according to its hydrological characteristics, which directly reflect on their environmental quality. Most degraded areas are those located at the bay's bottom and west side due to the large input of rivers, low water circulation, and the presence of several landfills. The exception is the region of Ilha de Paquetá, which is still strongly influenced by the ocean waters that enter the channel area, due to the influence of the greater depth (10-15 meters near Paquetá) of the south-north central channel (Silva et al., 2019; Dias et al., 2021). Areas with better water quality are located from the middle to the bay's entrance due to the higher input of ocean waters and water circulation (Fistarol et al., 2015).

Located from the central portion to the innermost area of Guanabara Bay are Moreninha Beach (PM) and the Paquetá Ferry Station (PB), both located at Ilha de Paquetá; Ribeira (RB) and Bica (BI) beaches, both at Ilha do Governador and Ilha D'água (ID). Plastic was the predominant litter at almost all these sites (except for PM and ID) and the diversity of items found in this category (food packages, toys, and cleaning products, among others) suggests that the litter came from contributions of rivers located in the southern part of the bay (Ferreira et al., 2011; Carvalho et al., 2021).

Among these stations, only those located at Ilha de Paquetá Island (PM and PB) presented a large amount of fishing gear. Since this is an area of better water quality, this activity is largely carried out on this island, explaining the high concentration of subtidal benthic marine litter found at Moreninha Beach, composed of 50% fishing gear. At the Ilha D'água station, metals (51.72%) and modified wood (28.7%) predominated, showing the influence of litter coming from the southern part of the bay (modified wood) and the presence of an on-site waterway terminal (pieces of metals).

Ilha do Catalão, in Ramos Beach, and Ilha da Pombeba are located in the area with the lowest water circulation within Guanabara Bay and have a large amount of litter (Ferreira et al., 2011). These areas are highly polluted because they historically aggregate a set of activities related to occupation (houses without sanitation infrastructure, transport of goods (port), proximity to important roads, and intense maritime traffic). The rivers have been straightened out for decades and cut important roads with daily congestion. Urban surface runoff also contributes to the high quantity of residue at these sites. Ilha da Pombeba was created artificially in front of the Port of Rio de Janeiro, from dredging material. Although plastic litter predominates, different types of litter have been collected on different sides of the island (Medeiros et al., 2017). Additionally, the Canal do Mangue (Mangue Channel) acts as a major source of sewage discharge on the west face of the island, which explains higher concentration of marine litter at this site.

The other stations within Guanabara Bay, whether on the coast of the city of Rio de Janeiro or in the municipality of Niterói, presented a similar litter profile, with a predominance of plastics, followed by fishing gear. Thus, the presence of litter in the subtidal benthic environment of Guanabara Bay results both from inadequate waste disposal in the hydrographic basin and of activities carried out in these waters. This is also confirmed by the high amount of metal collected, which is characterized by large pieces of iron found at the Enave, Camorim, and Brasco stations, all of which are located in shipyard areas. Historically, numerous vessels (including large ships) have been abandoned in Guanabara Bay, with some being simply sunk and/or dismantled in its waters. This activity possibly contributes to the common occurrence of metals found in the bottom sediments of the bay.

Although the litter profile of all the stations is similar, small variations in their concentrations were observed. These variations and the consequent environmental quality of these stations can be explained by their proximity to polluting sources and by their location within Guanabara Bay, which directly interferes in the bay's inside dynamics (Silva et al., 2016). The amount of litter found at the Rio-Niterói bridge station (PP), the lowest within the Guanabara Bay, is similar to the values found at some stations at Costa Verde. Although located inside the bay and near the shipyard area, the low litter concentration in the area may be because fishing boats often trawl there, thus removing benthic underwater litter.

Influence of economic activity on the subtidal benthic marine litter composition is also observed at the Leme Beach and Copacabana Fort stations. Although located outside the bay, concentrations in these stations were similar to those found in the most polluted areas of Guanabara Bay (97.31 items/km^2 and 99.08 items/km^2 for Leme and Copacabana, respectively). Intense boat traffic and tourism, as well as amateur fishing activities can explain these values, since water bottles, disposable cups, plastic bags, and a plastic bucket were among the litter collected, along with a large amount of fishing gear.

Among the litter found in the various subtidal benthic environments studied, some was recent and in good condition but other items showed prolonged deposition, especially those observed in stations located at Ramos, Catalão, and Pombeba, confirming that lower water circulation in this region to marine litter remaining in this environment for a long time.

CONCLUSIONS

Our findings showed positive litter contamination of the subtidal benthic environment in several areas off the coast of Rio de Janeiro, including places away from urban centers such as Ilha dos Meros, in Paraty. However, its presence is greater in more densely populated and closed areas, such as Guanabara Bay, and consists of various types of litter, especially plastic. They also showed that ghost fishing, resulting from abandoned fishing gear in the marine environment, poses a potential risk for the great fauna diversity present in the regions of Costa do Sol and Costa Verde. In addition to waste from the lack of sanitation facilities, especially in Guanabara Bay, this litter also comes from local activities such as fishing, tourism, and shipping traffic.

Further studies on subtidal benthic marine litter are needed to better understand its distribution pattern and possible effects on marine diversity. Effectively implementing the actions foreseen in the Política Nacional de Resíduos Sólidos (National Solid Waste Policy –PNRS) (Brasil, 2010) would ensure a reduced generation, and reuse and correct disposal of solid waste to mitigate this problem. Environmental education actions with fishermen, tourists, and professionals working in the marine environment should be encouraged to stimulate their participation in the PNRS actions.

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AUTHOR CONTRIBUTIONS

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

E.S.V.: Formal Analysis, Investigation, Methodology, Validation, Writing – Original Draft, Writing – Review & Editing;

B.P.M; A.L.C.S.: Formal Analysis, Validation, Writing – Original Draft, Writing – Review & Editing.

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