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CASE REPORT

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Macro and mesoplastics at Joaquina Beach, southern Brazil: a case study

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ABSTRACT

Sandy beaches are ecologically important coastal ecosystems that are increasingly threatened by plastic pollution. This pollution disrupts their ecological balance and reduces their ability to provide ecosystem services. This study case at Joaquina Beach, Santa Catarina Island, southern Brazil, aimed to assess the spatiotemporal contamination by macro and mesoplastics concerning meteorological and anthropogenic variations, and to identify potential plastic sources for the region. Over 18 months (December 2018 to March 2020), monthly collections of macroplastics and mesoplastics were performed at 12 fixed sampling points. The amount of mesoplastics found was 216 items, with an average of 2.18 items m^{-2} (range: 0-17.33 items m^{-2}), a higher density than that of macroplastics, of which, 1069 items were found, at an average of 0.32 items m^{-2} (range: 0-2.2 items m^{-2}). Fragments were the predominant plastic type in both size categories. The region was assessed as ”very clean” only once during the monitoring, with the Clean-Coast Index classifying it as “clean” in 59% of the months. March 2019 had the highest macroplastic amount, followed by April 2019 and February 2020. Meanwhile, mesoplastic quantity was highest in April 2019, December 2018, and January 2019. For both categories, beach users were identified as the main possible source of plastic litter, with a smaller contribution from fishing activities. However, meteorological conditions, like wind direction, can also contribute to plastic accumulation in the area. The months with the highest concentration of macro and meso occurrences had a prevailing pattern of southern winds. This study contributes to the knowledge addressing macro and mesoplastics, providing useful information to bridge scientific and management gaps regarding the distribution of different plastic sizes.

Keywords: Coastal ecosystem, Marine debris, Seasonal winds, Fragmentation

INTRODUCTION

Beaches are important coastal ecosystems, one of their key functions being to absorb energy from storms or extreme events and thus provide coastal protection, especially when associated with mangrove or dune ecosystems (Asari et al., 2021; Jordan and Fröhle, 2022). Beaches also serve as nursery, spawning, and feeding areas for various organisms (Silva et al., 2004; McLachlan and Defeo, 2018) and contribute to human well-being via the ecosystem services offered, such as the cultural ones (Merlotto et al., 2019). However, plastic pollution has put the

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quality of this ecosystem at risk environmentally, economically, and socially (Sul and Costa, 2007; Oliveira et al., 2011; Silva-Cavalcanti et al., 2013; Chitaka and Blottnitz, 2019). Systematic data collection is, therefore, crucial to understand the extent and impact of plastic pollution in the marine environment. The Clean-Coast Index (CCI) is a well-established index used worldwide to assess beach cleanliness (Alkalay et al., 2007). The CCI can increase the comparability between ecosystems like beaches and mangroves (Duarte et al., 2023), identify contamination levels, and help in monitoring strategies (Souza Filho et al., 2023).

The characteristics of plastics—like durability, flexibility, lightness, and low production costs—make it indispensable across a wide range of sectors. Combined with inadequate solid waste management, this leads to a significant presence in the environment, particularly affecting coastal and marine ecosystems (Silva-Cavalcanti et al., 2013; Pawar et al., 2016). The dynamic distribution of plastics on sandy beaches depends on the characteristics of the beach itself, as well as environmental and anthropogenic factors (Lippiatt et al., 2013) such as wind and waves (Debrot et al., 2013; Ríos et al., 2018). These parameters may influence plastic amounts and types and may vary spatially and seasonally (Mheen et al., 2020). Wind can move light items, while waves can carry them to shore (Sebille et al., 2020). Beach morphology also matters, with sheltered areas tending to retain more plastic residue. Understanding how these conditions work together and interact with anthropogenic factors, like tourist and fishery seasons, is crucial.

Plastic items are commonly classified by size, which may range in length from microns to meters (Law, 2017). Macroplastics (25 mm to 1 m) mainly comprise single-use items such as food packaging, straws, bags, cigarette butts, and cups, among others (Xanthos and Walker, 2017). Due to their size, they may be detected and removed from the environment by hand or using machinery. Macroplastics may be classified according to their uses and possible sources. For example, items such as straws and plastic cups may be linked to beach users, whereas nets and styrofoam buoys may be associated with fishing activity (Silva-Cavalcanti et al., 2013). Mesoplastics (5 - 25 mm) are an intermediate category between microplastics and macroplastics. They are generally composed of fragments (secondary hard plastics) and represent a significant part of the plastic fragmentation process (Shi et al., 2023). However, mesoplastics studies are not common, thus being considered a knowledge gap in marine litter studies (Shi et al., 2023). Studies that link macro and mesoplastics in the environment aiming to better understand plastic fragmentation are even rarer (Lee et al., 2017). In this context, monitoring the beach environment for plastic pollution is a fundamental step to obtain necessary information on the pollution status and propose mitigation solutions (GESAMP, 2019). This study aimed to assess the spatio-temporal baseline for contamination of macro and mesoplastic litter on Joaquina Beach in southern Brazil (Santa Catarina Island). Additionally, we aimed to comprehend the influence of both natural and human-induced factors on litter contamination at the beach and identify potential plastic sources in the region. Furthermore, the Clean-Coast Index (CCI) was utilized as a metric to evaluate the cleanliness of the coastal area.

METHODS

Study area

Joaquina Beach is located in the eastern coast of Santa Catarina Island, southern Brazil (Figure 1). This beach stands out for its stunning natural beauty and ease of access, making it one of the most popular destinations on the island. Besides that, it is a very popular beach for surfing and surf culture. It encompasses a marine protected area (MPA) within its boundaries, Parque Municipal Dunas da Lagoa da Conceição (HORN, 2017). The whole region is preserved and protected because of the MPA. There are few structures and constructions on Joaquina beach and they serve primarily as tourism and surfing support, like hotels and restaurants. Joaquina is a sparsely urbanized beach with no new constructions since last decade (Teixeira, 2019).

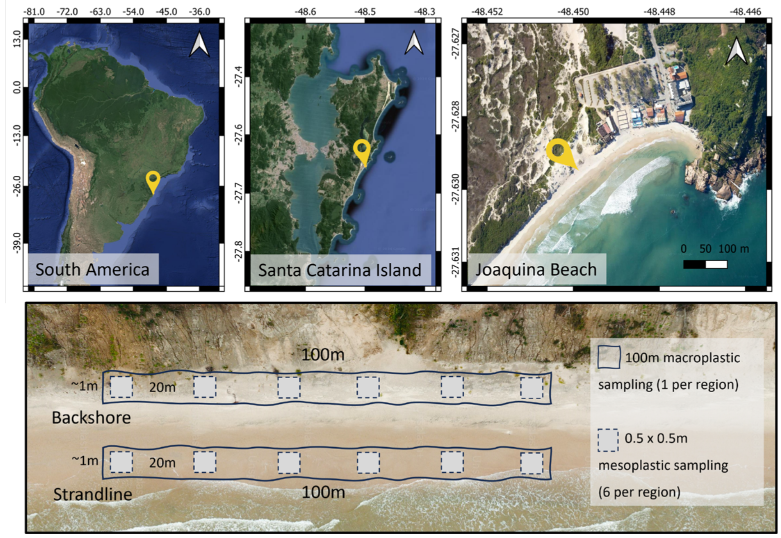

Figure 1. Joaquina Beach location and sampling area for macroplastics and mesoplastics.

It is an oceanic beach dominated by waves, classified as intermediate with longitudinal banks (Silveira et al., 2011). The region has a semi-diurnal microtidal regime, reaching a maximum amplitude of two meters (Garbossa et al., 2014). It has a distinct wind regime marked by seasonal variations. During winter, southerly winds predominate, causing water to pile up on the coast, while northerly winds predominate in the summer, decreasing the sea level (Möller et al., 2008). Because of the atmospheric circulation in this area, it is common to have an average of three to four cold fronts per month, heading from southeast to northeast, which may result in sea level changes (Rodrigues et al., 2004).

Non-fixed trash bins were distributed along the beach and the area also periodically receives manual cleaning services carried out using rakes (FLORIANÓPOLIS, 2019). The sampled section (initial point: −48.45058, −27.63025; final point: −48.45125, −27.63091) is located after the last construction at the beach, indicating that it is a less urbanized area (Figure 1).

Sampling and processing

Plastic litter was collected monthly from December 2018 to March 2020, always in the ebb of the spring tide. There was an extra collection in the quadrature tide in July (named as July extra 2019), after a storm that resulted in higher tide levels. The sampling stopped in 2020 due to the COVID-19 pandemic, when the lockdown was established.

Plastic litter monitoring was based on the Guidelines for the Monitoring and Assessment of Plastic Litter in the Ocean (GESAMP) (2019), with some adaptations. The sampling occurred in two transects parallel to the shoreline, one in the backshore and the other in the strandline (Figure 1). To sample macroplastics (25 mm to 1 m), a 100 m transect was delimited in each region (backshore and strandline). In March 2019 there was a storm, which prevented sampling in the strandline. All visible items one meter away, at maximum, from the center line along each transect were collected by hand and stored for further analysis.

To sample mesoplastics (5 - 25 mm), six sampling points were marked in each transect every 20 meters with PVC squares (0.5 X 0.5 m), in total 12 fixed sampling points. In each square, a visual inspection was carried out, and plastic items were removed and stored with the aid of metallic clamps. Then, using a metal spoon, approximately 1 cm of the entire surface sediment was sieved in the field using a 2 mm sieve over a 1 mm sieve, instead of a 5 mm sieve as suggested by GESAMP (2019). The items retained on the sieves were stored for later classification. The sampled items (macro and mesoplastics) were counted, measured, and photographed in the laboratory. Additionally, the items were classified according to material type, probable source, associated with item characteristics, activities and uses, such as: a) beach users (tourists, residents and sports practitioners), b) fishing and nautical activities, c) domestic use, and d) indeterminate (UNEP 2016, Ramos et al., 2021).

Meteorological factors

To understand the relationship between meteorological factors and plastic litter densities, data on wind (direction and intensity) and precipitation were obtained from the Santa Catarina Environmental Resources and Hydrometeorology Information Center (EPAGRI/CIRAM) database. All data were taken from a meteorological station located in the Itacorubi neighborhood, Florianópolis (−27.5814; −48.5072) 72 hours before each sampling. We chose to assess this time window considering the high energy and dynamics of Joaquina Beach (HORN, 2017). This decision aimed to observe the influence of cold fronts and their potential impact on other months. Currently, there is no existing study that combines meteorological data with litter analysis in the region. The decision to use a 72-hour window was based on observations and expert knowledge of the area. For future studies, it may be worthwhile to test alternative time intervals.

Data analysis

The total abundance and the concentration (items m^{-2}) were calculated for each plastic size (macroplastics and mesoplastics). To test the difference between size categories (macro and meso), a non-parametric Mann-Whitney test was performed (after performing the Shapiro-Wilk normality test) using the total concentration of each month (sum of backshore and strandline transects) for each category. We performed a permutational multivariate variance analysis (PERMANOVA) to evaluate significant differences in plastic abundance in the sampled beach regions (backshore and strandline). Furthermore, a principal component analysis (PCA) was conducted to assess overall plastic litter variation in Joaquina Beach. Target variables were plastic size concentration (for backshore and strandline), and explanatory variables included wind direction, average maximum wind speed, and precipitation (72 h sum).

Clean-coast index (CCI)

To assess the cleanliness of Joaquina Beach, the Clean-Coast Index (CCI) was calculated for each collection month. Proposed by Alkalay et al. (2007), this index allows for classifying a beach from very clean to extremely dirty, according to Equation 1, in which K is a constant with a value of 20. The equation is valid only for plastic items larger than 2 cm, so the present index was used only for the macroplastics class. According to the CCI, beaches may be classified as very clean (0 to 2), clean (2 to 5), moderately clean (5 to 10), dirty (10 to 20), and extremely dirty (over 20).

$$CCI = \frac{\Sigma\, litter\ items}{lenght\ (m).width\ (m)} K$$

RESULTS

Abundance and spatial temporal distribution

Out of the 1285 items collected at Joaquina Beach, 1069 items (0.32 items m^{-2}) were identified as macroplastics in 3300 m^{-2}, while 216 items (2.18 items m^{-2}) were classified as mesoplastics in 49.5 m^{-2}, indicating a higher density ($p < 0.05$) of mesoplastics compared to macroplastics in the total sampling. Most macroplastics were collected from the backshore (83%), where plastic density varied from 0.03 to 2.2 items m^{-2}. In turn, density ranged from 0 to 7.8 items m^{-2} in the strandline region. However, due to high data variability, it was not possible to identify significant differences between the two regions ($p > 0.05$).

Regarding mesoplastics, the backshore also presented more items (67%) than the strandline region, but the density variation in both regions was the same: 0 to 23.33 items m^{-2} and with no significant difference ($p > 0.05$). Since the macro and mesoplastic amounts were significantly different, their results will be presented separately. However, for each size, the litter collected on the backshore and strandline were grouped, since there were no significant differences.

Over the 18 months of sampling at Joaquina Beach, a variation in the density of macroplastics was observed, yet it was not seasonally related. The highest amount of macroplastics occurred in March 2019 (2.2 items m^{-2}), followed by April 2019 (1.06 items m^{-2}) and February 2020 (0.59 items m^{-2}). The lowest amount occurred in February 2019 (0.02 items m^{-2}) and September 2019 (0.05 items m^{-2}) (Figure 2). The highest density of mesoplastics (average of 12 quadrats) occurred in April 2019 (17.33 ± 16.56 items m^{-2}), December 2018 (13.33 ± 25.71 items m^{-2}), January 2019 (10.67 ± 20.35 items m^{-2}) and July 2019 (8.33±12.11 items m^{-2}). The lowest densities were observed in August, September and December 2019, and January, and March 2020, with an average of 0.33±2.39 items m^{-2} (Figure 2).

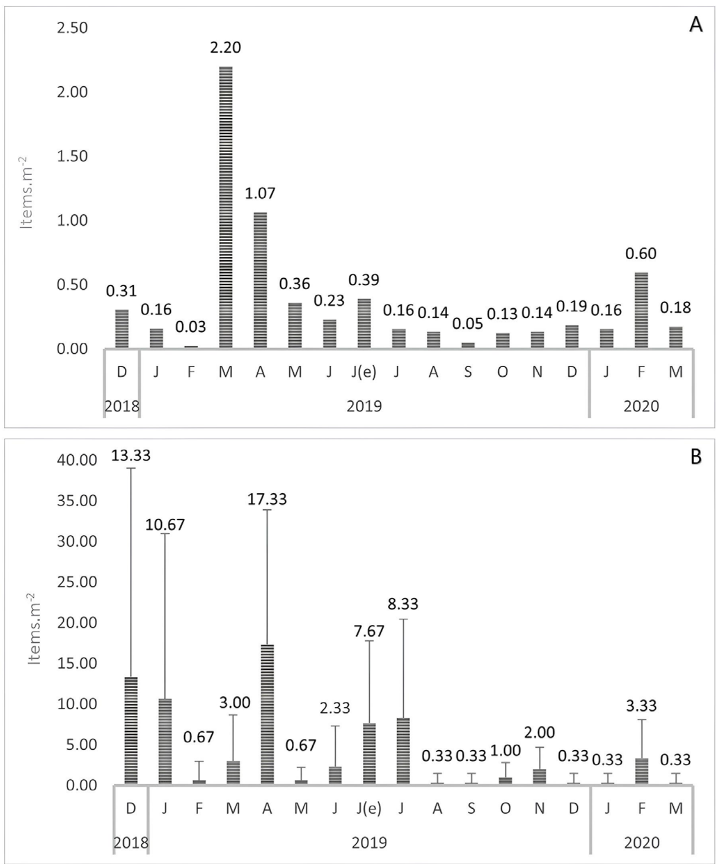

Figure 2. Monthly concentration of plastic litter in items m^{-2} during the sampling period from December 2018 to March 2020. J(E) represents July extra/19 sampling. (A) Macroplastics, sum of backshore and strandline transects. (B) Monthly average and standard deviation concentration of mesoplastics, calculated using an average of 12 quadrats—except in March/2019 (6 quadrats)—in items m^{-2} over the sampling period.

Plastic types and possible sources

The composition of macroplastics found on Joaquina Beach was classified into nine classes: cigarette butts (27%), fragments (18%), packaging (18%), bottle caps (6%), fishing ropes (5%), plastic foam (6%), lollipop sticks (5%), straws (3%) and others (16%) (Figure 3). According to this result, the main possible sources of marine litter were related to beach users (49%) and fishing (10%).

The class with more mesoplastic items was the fragment, which represented 70% of all items collected, followed by plastic foam (24%), fishing lines (2%), straws (1%), packaging (1%) and others (2%) (Figure 3). Since it was not possible to identify the possible source of fragments, their sources were classified as indeterminate. Tables 2 and 3 show the temporal distributions of macroplastic and mesoplastic compositions respectively, highlighting the months with higher values and item concentrations during the sampling period and months in which categories were absent.

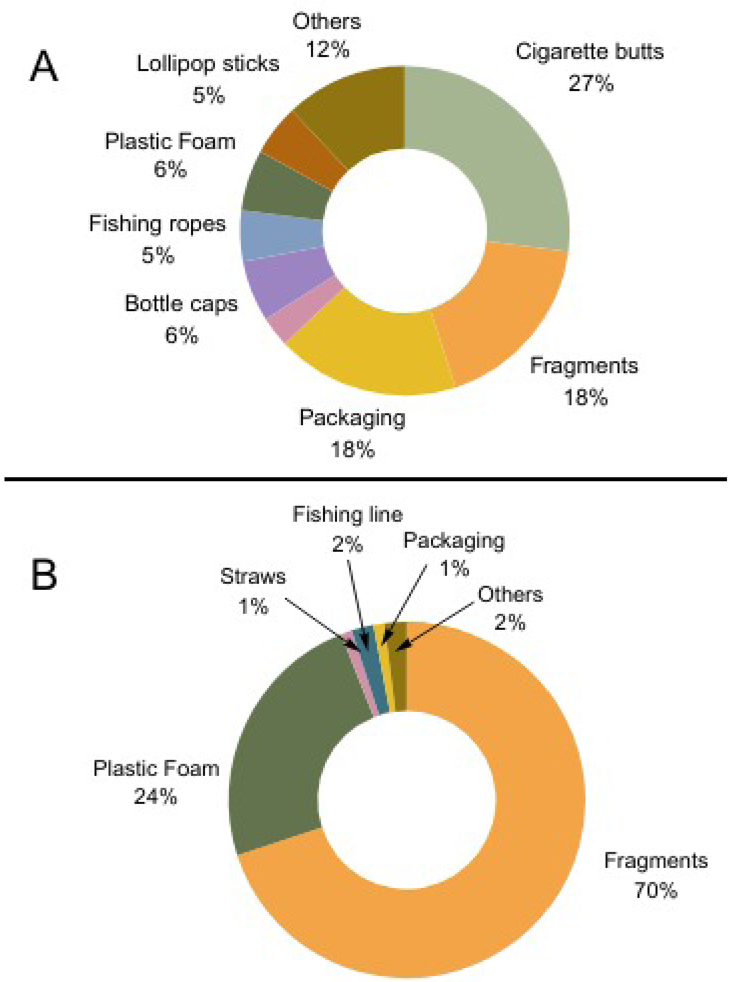

Figure 3. Percentage composition of the main categories observed at Joaquina beach during the sampling period from December 2018 to March 2020. (A) Macroplastic categories. (B) Mesoplastic categories.

Table 1. Classification of the possible source associated with each item category.

Possible Source	Categories
Beach users	Cigarette butts; packaging; bottle caps; plastic bottle seal; bags; glass; bottle; straw; lollipop sticks; plastic bags; lighter; cup; bottle; beach umbrella tip.
Domestic	Cotton swab; toothbrush
Fishing and nautical activities	Fishing rope; fishing line; plastic foam.
Indeterminate	Fragments; rubber; others.

Table 2. The months that had the highest occurrence of the main nine macroplastics categories (cigarette butts, fragments, packaging, bottle caps, fishing ropes, plastic foam, lollipop sticks, straws and others) collected at Joaquina Beach. The sampling period was from December 2018 to March 2020. The data are expressed as n=number of items and items m^{-2}.

Categories	Months of highestvalue	Values in other months	Absent
Cigarette butts	March/2019 (n=96; 0.96 items m^{-2}) February/2020 (n=52; 0.26 items m^{-2}) April/2019 (n=50; 0.25 items m^{-2})	n=<15; 0.07 items m^{-2}	-
Fragments	April/2019 (n=57; 0.29 items m^{-2}) March/2019 (n=22; 0.22 items m^{-2}) July extra/2019 (n=22; 0.11 items m^{-2}) May/2019 (n=21; 0.11 items m^{-2}) December/2018 (n=19; 0.10 items m^{-2}) February/2020 (n=14; 0.07 items m^{-2})	n=<10; 0.05 items m^{-2}	February/2019
Packaging	March /2019 (n=36; 0.36 items m^{-2}) April/2019 (n=31; 0.15 items m^{-2}) February/2020 (n=23; 0.11 items m^{-2}) December/2019 (n=11; 0.05 items m^{-2})	n=<10; 0.05 items m^{-2}	-
Bottle caps	March/2019 (n=13; 0.13 items m^{-2}) April/2019 (n=13; 0.06 items m^{-2}) July extra/2019 (n=12; 0.06 items m^{-2})	n=<5; 0.03 items m^{-2}	February/2019, June/2019, July/2019, October/2019, March/2020
Fishing ropes	March/2019 (n=6; 0.06 items m^{-2}) April/2019 (n=10; 0.05 items m^{-2}) December/2018, June/2019 (n=6; 0.03 items m^{-2})	n=<5; 0.03 items m^{-2}	February/2019
Plastic foam	March/2019 (n=11; 0.11 items m^{-2}) May/2019 (n=10; 0.05 items m^{-2}) July extra/2019 and February/2020 (n=7; 0.04 items m^{-2})	n=<5; 0.03 items m^{-2}	February/2019, August/2019, September/2019, November/2019,
Lollipop sticks	April/19 (n=14; 0.07 items m^{-2}) March/2019 (n=8; 0.08 items m^{-2}) December/2018 and June/2019 (n=7; 0.04 items m^{-2})	n=<5; 0.03 items m^{-2}	February/2019, September/2019 October/2019, December/2019, January/2020, March/2020
Straws	March/2019 (n=6; 0.06 items m^{-2}) February/20 (n=5; 0.03 items m^{-2}) April/19 (n=4; 0.02 items m^{-2})	n=<3; 0.02 items m^{-2}	February/2019, June/2019, July/2019, January/2020
Others	March/19 (n=28; 0.28 items m^{-2}) April/19 (n=34; 0.17 items m^{-2}) July extra/19 (n=17; 0.08 items m^{-2})	n=<15; 0.07 items m^{-2}	February/2019

Table 3. The months that had the highest occurrence of mesoplastic categories (fragments, plastic foam, packaging, fishing line, straw and others) collected at Joaquina Beach. The sampling period was from December 2018 to March 2020. The data are expressed as n=number of items and items m^{-2}.

Categories	Months of highest value	Values in other months	Absent
Fragments	April/2019 (n=51; 17 ± 15.6 items m^{-2}) December/2018 (n= 36; 12 ± 24.9 items m^{-2}) January/2019 (n=18; 6 ± 14.1 items m^{-2}) July/2019 (n=12; 4±5.9 items m^{-2}).	n=<10; 3.33items m^{-2}	September/2019, March/2020
Plastic foam	July extra/2019 (n=17; 5.7 ± 8.9 items m^{-2}), January/2019 (n=14; 4.7±6.9 items m^{-2}), and July/2019 (n=11; 3.7±6.8 items m^{-2})	n=<5; 1.67items m^{-2}	February/2019, April/2019, May/2019, August/2019, November/2019, December/2019, January/2020.
Packaging	November/2019 (n=2; 0.67 items m^{-2}) December/2018 (n=1; 0.33 items m^{-2})	-	January/2019, February/2019, March/2019, April/2019, May/2019, June/2019, July/2019, July extra/2019, August/2019, September/2019, October/2019, December/2019, January/2020, February/2020, March/2020.
Fishing line	March/2019, July/2019 and February/2020 (n=1; 0.33 items m^{-2})	-	December/2018, January/2019, February/2019, April/2019, May/2019, June/2019, July extra/2019, August/2019, September/2019, October/2019, November/2019 December/2019, January/2020, March/2020.
Straw	November/2019 (n=1; 0.33 items m^{-2})		December/2018, January/2019, February/2019, March/2019, April/2019, May/2019, June/2019, July/2019, July extra/2019, August/2019, September/2019, October/2019, December/2019, January/2020, February/2020, March/2020.
Others	December/2018 (n=2; 0.7±1.5 items m^{-2}) April/2019, July/2019 and February/2020 (n=1; 0.3±1.1 items m^{-2})	-	January/2019, February/2019, March/2019, May/2019, June/2019, July extra/2019, August/2019, September/2019, October/2019, November/2019, December/2019, January/2020, March/2020.

Meteorological variables

During the sampling period, the average annual rainfall was 130 mm, with February 2019 being the rainiest month (monthly sum of 288.4 mm), and August 2019, the dryest (monthly sum of 21.60 mm). The sum of the hourly precipitation in the 72 h before each collection was highest in February 2020 (43.86 mm), February 2019 (23.06 mm), January 2020 (20.66 mm), and May 2019 (19.85 mm).

Southerly winds were most frequent in the 72 h prior to sampling in December 2018, and January, February, March, April, May, and July (in both samplings) 2019. In turn, easterly winds were most frequent in June 2019, and January and February 2020 and northerly winds, in August, September, October, November and December (both samplings) 2019, and March 2020. The highest wind speed of the sampling period (> 4 m s^{-1}) occurred in December 2018, followed by March 2019 and April 2019 (> 3.9 m s^{-1}), September and December 2019 (> 3.8 m s^{-1}) and January 2020 (>3.6 m s^{-1}). The high intensity of winds from the south quadrant in such months is characteristic of cold fronts (Figure 4).

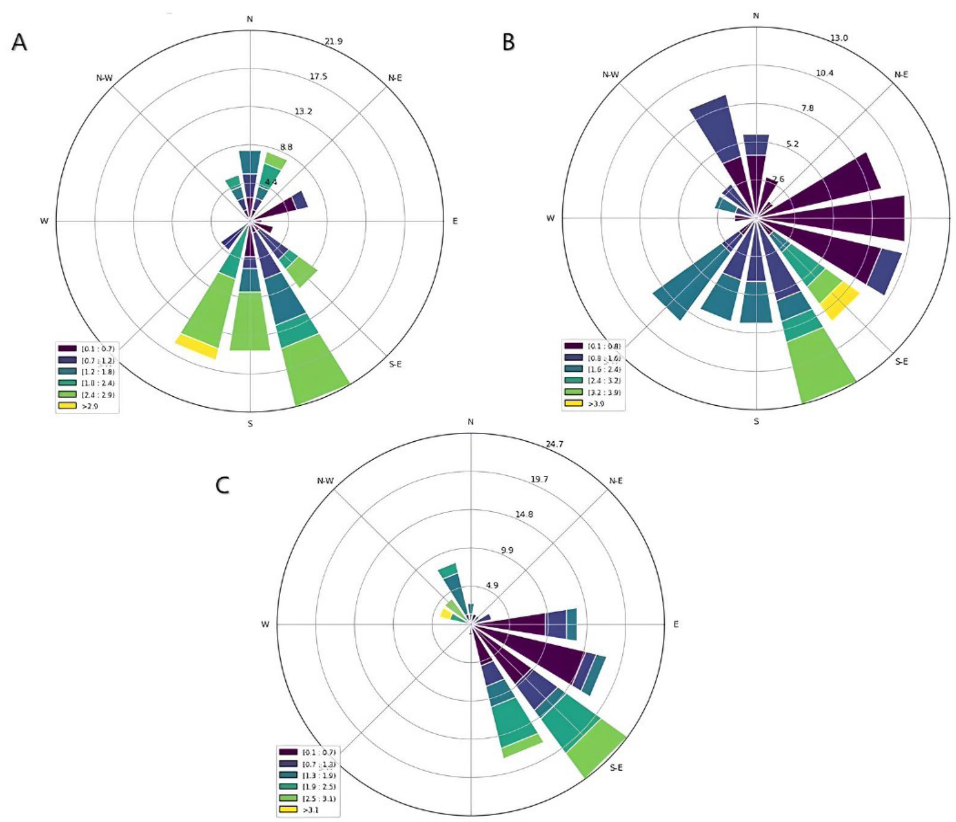

Figure 4. Wind direction and intensity (m s^{-1}) for the collection months during probable cold front periods and potential meteorological tide events: (A) March/19, a day with rough seas, high tide, possible occurrence of meteorological tide, (B) April/19, wind direction from southeast to northeast characterizes a cold front entering the region, (C) July extra/2019, following a storm that led to higher tide levels.

The PCA result provided a comprehensive view of the overall plastic litter variation in Joaquina Beach, but did not explicitly detail the impact of meteorological variables on plastic density (Figure 5). The two principal components explained 63.7% of the variability in macro and mesoplastics. A positive correlation between plastic sizes was observed. Wind intensity lacked correlations, while wind direction contributed to plastic densities. Precipitation weakly influenced (<10%) macro and mesoplastic densities on the beach.

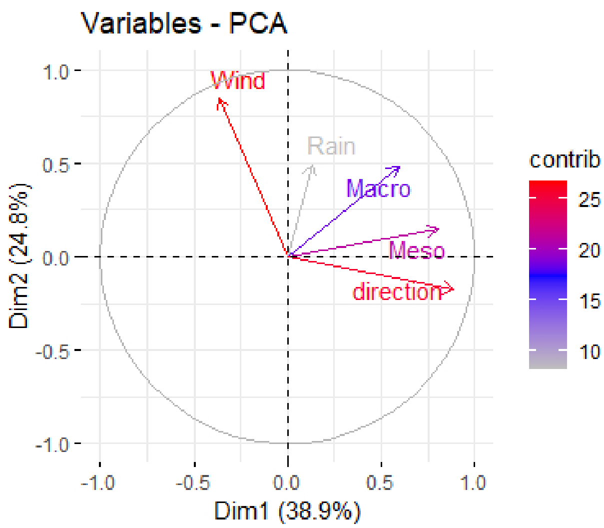

Figure 5. Principal component analysis (PCA) depicting the relationship between meso and macroplastic concentrations alongside meteorological factors —Direction = wind direction, wind = average maximum wind speed, rain= precipitation sum in the 72h before the sampling.

CCI

Even though Joaquina Beach has a periodic beach cleaning service, throughout the monitoring period it was only considered “very clean” once (February 2019), according to the Clean-Coast Index results (Figure 6). In 59% of the months, the CCI classified the beach as “clean”, and in approximately 18% of cases, the beach was classified as “dirty” and “extremely dirty”.

A

Sampling		CCI
2018	Dec	Moderate
2019	Jan	Clean
	Feb	Very clean
	Mar	Extremely dirty
	Apr	Extremely dirty
	May	Moderate
	June	Clean
	July Extra	Moderate
	July	Clean
	Aug	Clean
	Sept	Clean
	Oct	Clean
	Nov	Clean
	Dec	Clean
2020	Jan	Clean
	Feb	Dirty
	Mar	Clean

B

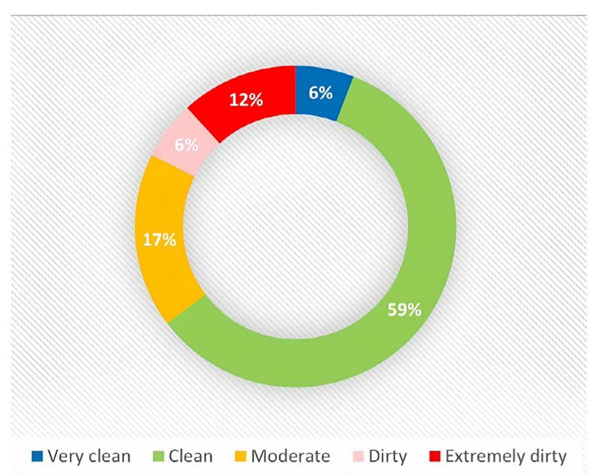

Figure 6. Principal Component Analysis (PCA) depicting the relationship between meso and macroplastic concentrations alongside meteorological factors—Direction = wind direction, wind = average maximum wind speed, rain= precipitation sum in the 72h before the sampling.

DISCUSSION

The abundance of macro and mesoplastics shows no statistical difference; however, they tend to concentrate on the backshore rather than in the strandline area. The strandline region has a more recent and variable deposition due to tide oscillation (Velander and Mocogni, 1999), whereas the backshore is near dunes or vegetation. This might allow the accumulation of debris, both natural and man-made, brought by tides, winds, and storms (Velander and Mocogni, 1999; Moreira et al., 2016). Nevertheless, the proximity between the backshore and strandline of Joaquina Beach, spanning approximately 15 m, facilitates connectivity and potential similarities between sampled regions. The relatively short beach width enhances the likelihood of interactions and shared characteristics concerning marine litter abundance and type in these areas.

Once in the environment, plastic litter tends to fragment due to its exposure to various degradation mechanisms, such as mechanical abrasion, photo-oxidation, thermo-oxidation, and wave action (Corcoran et al., 2009; Gewert et al., 2015). The fragmentation process is continuous and concomitant among distinct sizes; while macroplastic may be fragmented into mesoplastic, these may also be fragmented into smaller pieces, producing microplastics and nanoplastics (Costa et al., 2010; Lee et al., 2013; Gigault et al., 2016). Joaquina Beach presented higher densities of mesoplastics compared to macroplastics, suggesting that large items can break down into smaller pieces in the marine environment (*eg.* Andrady, 2022). However, it would be necessary to investigate the polymeric composition of both macro and mesoplastics to assess whether these materials have the same composition.

The fragmentation process also mischaracterizes the initial item, making it challenging to identify. In such cases, items are classified as fragments. Our findings corroborated the literature, showing that fragments were the most abundant type of mesoplastic (Ryan et al., 2018; Bancin et al., 2019; Rodríguez et al., 2020). Additionally, some studies have already reported fragments as an important fraction of macroplastic composition in sandy beaches (Fernandino et al., 2016; Ríos et al., 2018; Ramos et al., 2021), which was also a significant finding for Joaquina Beach. Thus, mesoplastics are an important fraction to be investigated, given that some studies have reported a direct relation between the quantity of mesoplastics and microplastics found on sandy beaches (Lee et al., 2017; Jeyasanta et al., 2020). The size of plastic litter is relevant, especially for beach cleaning processes. In this context, the smaller the size of the plastic, the more difficult it is to detect it and remove it.

Joaquina Beach undergoes year-round cleaning, but the focus is on manually removing large items using rakes and non-fixed trash bins. These techniques are efficient to remove macroplastics. They can be used as a strategy to prevent plastic fragmentation and further meso and microplastics contamination. However, they did not avoid particles that arrive from the ocean (Ryan and Schofield, 2020). The existing technologies for small item removal, e.g., eco-sifters, are limited and impractical for regular/periodic cleaning. The development of other alternative/technologies, such as a prototype of marine litter robot collectors, have been tested, but their widespread implementation is still experimental (Balasuthagar et al., 2020). Efforts are needed to continue to explore technologies for more effective and sustainable waste management on beaches.

The mesoplastics density found on Joaquina Beach (0 - 17.33 items m^{-2}) was low compared to the average of other beaches around the world, such as on the coast of Korea (13.2 items m^{-2}), ocean beaches in Uruguay (106 items m^{-2}), the southeast coast of India (9.37 items m^{-2}) and Taiwan (96.8 items m^{-2}) (Lee et al., 2017; Bancin et al., 2019; Jeyasanta et al., 2020; Rodríguez et al., 2020). When compared with work carried out on beaches on the Brazilian coast, the macroplastic density on Joaquina Beach was higher than that of Cassino Beach (RS) (0.15 items m^{-2}) (Ramos et al., 2021), but lower than the coast of Pernambuco (4.7 items m^{-2}) (Araújo et al., 2018).

Due to the seasonal use of Joaquina Beach by tourists, it was expected that more macroplastics would be found during the summer months (December to February) than in the winter (June to August). However, it was not possible to observe significant differences between months or seasons. One of the factors that may have contributed to the lack of significance could be the year-round beach cleaning, which intensifies during summer months. Beach cleaning has several benefits for scenic and sanitary quality, but it is not an efficient action for removing small items such as mesoplastics (Araújo and Costa, 2006; Williams et al., 2016; Lee et al., 2017), so this may have contributed to the differences between macro and mesoplastics quantities.

The highest density of macroplastics was found in March 2019 and April 2019. Meteorological events, such as wind intensification, may contribute to litter accumulation (Thiel et al., 2021). In March, stronger winds characterized the presence of a cold front in the region (Rodrigues et al., 2004), which may explain the higher values of macroplastics. March 2019 also presented higher quantities of cigarette butts, packaging, bottle caps, fishing ropes, plastic foam, straws, and other categories, when compared to the other sampled months. On the other hand, April 2019 showed higher quantities of lollipop sticks and fragments when compared to the other months.

Regarding mesoplastics, the variation in concentration and standard deviation did not enable establishing a clear pattern regarding higher or lower concentrations. The dynamic beach environment, wind speed and direction variations, and beach use patterns may have contributed to the high variability in the sampled mesoplastics. Even though more meteorological data is necessary to better understand the plastic contamination pattern, we propose that local authorities focus on monitoring marine litter every three months (seasonally) at Joaquina beach, with special attention after cold front events that result in storm lines on beaches, where more plastic would accumulate. Moreover, considering the lack of *in situ* meteorological data at Joaquina beach, the installation of a weather station would be beneficial to enhance the precision of future predictions and analyses.

Given the absence of large rivers in the region, Joaquina Beach does not receive relevant fluvial influence (Torronteguy, 2002), however, the beach is affected by precipitation runoff. Including the precipitation data in the analysis was an attempt to detect a pattern regarding precipitation and marine litter concentrations. The rainiest month (February 2019) had the lowest occurrence of both sizes of plastics, suggesting that the rainwater runoff may remove particles and reduce their residence time during rainy periods (Fanini and Bozzeda, 2018).

The PCA results indicated that meteo-oceanographic factors alone (wind intensity and rain) did not explain the abundance of marine litter on the beach but suggested an influence of wind direction on the abundance of macro and mesoplastics, with the highest density found in the southern quadrant. In this study area, such winds result in water piling up along the coast, contributing to the accumulation of marine litter (Möller et al., 2008). Additionally, Joaquina Beach is situated in the southeastern sector of Santa Catarina Island oceanic beaches tend to face greater exposure to winds and waves, making them more prone to the accumulation of marine litter (Corraini et al., 2018; Rodríguez et al., 2020). Therefore, other factors, such as beach and fishing activities, appear to have a greater influence on the arrival and accumulation of litter on Joaquina Beach. These same sources were identified by Widmer and Hennemann (2010) and Corraini et al. (2018) as the main sources of plastic on other beaches of Santa Catarina Island. However, the source and accumulation of fragments remains a gap in the study of plastic pollution on beaches (Shi et al., 2023).

Items associated with beach users comprise single-use plastics, such as cups, straws, bottle caps, plastic bottles, lollipop sticks, toothpick packaging, and plastic bottle seals, which make up 15% of the items collected on Joaquina Beach. Local regulations and environmental education are crucial to address the possible marine litter source.

Fishing is a significant activity in several locations around Santa Catarina Island (Bastos and Petrere, 2010). Mullet fishing is an important traditional, economic, social, and cultural activity in the region, which takes place from May to July. Even though our results did not show an increase in fishing items in these months, the kind of fishing ropes and lines found among macro and mesoplastics resemble those used in mullet fishing (beach seine). Additionally, recreational beach fishing should also be considered as a potential source of plastics in Joaquina beach.

According to the CCI, in three out of the 18 months sampled, Joaquina Beach was classified as "dirty" or "extremely dirty". The CCI is a beach cleaning index aimed at macroplastics, which are more visible, providing an assessment focused on the scenic quality of the location. These results indicate that even with fewer macroplastics than mesoplastics, the beach was still classified as "dirty" during some periods of the year. This is a warning and a gap concerning plastic pollution. Although the CCI ignores the mesoplastics in beach quality assessments, possibly underestimating the result, the beach was classified as dirty and extremely dirty (Marin et al., 2019).

According to Corraini et al. (2018), values in the order of 29 items 100m^{-2} are already sufficient to interfere with the scenic quality of beaches, resulting in high losses for tourism since a clean beach is among the main features required by visitors (Williams, 2011). Considering the tourist importance in Joaquina Beach, the marine litter quantity found (Figure 2) is a warning-sign that actions should be taken to prevent this problem from worsening and hindering this socioeconomic activity.

CONCLUSION

In this case study, the first monthly monitoring of macro and mesoplastics was conducted for over 18 months at Joaquina Beach, Santa Catarina Island, southern Brazil. It was observed that meteorological factors and beach use can be reflected in the marine litter found on the beach. Variations were observed over time, but they were not strongly correlated with the seasons. A higher density of mesoplastics was sampled compared to macroplastics, which showcases the probability of items breaking into smaller pieces, rendering their removal from the environment more challenging.

The composition analysis identified diverse types of macroplastics. Cigarette butts, fragments, and packaging were the most common, suggesting contributions from beach users and fishing activities. Mesoplastics were mainly composed of fragments, indicating challenges to identify specific sources. Meteorological variables, like rainfall and wind direction, showed some influence on plastic abundance, particularly during periods of high wind intensity associated with cold fronts. The Clean-Coast Index consistently categorized the beach as "clean" throughout the year, although specific meteorological events temporarily altered this status. This underscores the importance of ongoing monitoring of local environmental data, such as winds and currents, to better comprehend beach litter dynamics and accumulation patterns. Continuous monitoring, coupled with effective management strategies, is essential to mitigate plastic pollution.

Data availability statement

The python code for the simulations is available at: https://github.com/LaPoGeoMar/Proj_Modelagem_Pellet

Supplementary material

This article does not include any supplementary materials.

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Conflicts of interest

The authors declare no conflicts of interest.

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