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Meso- and microplastic composition, distribution patterns and drivers: A snapshot of plastic pollution on Brazilian beaches

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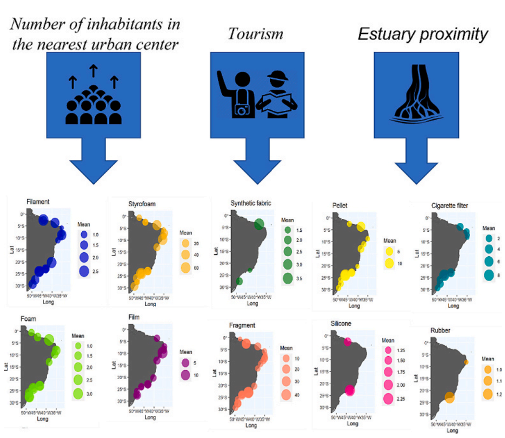
HIGHLIGHTS

- First plastic waste assessment by standardized protocol along Brazilian sandy beaches
- More than half of the items collected were microplastics.
- Styrofoam and fragments were the predominant type of plastic found in the beaches.
- PE and PP were the main polymers in plastic composition according FTIR analyses.
- Estuary distance, tourism and population in urban center ruled plastic distribution.

GRAPHICAL ABSTRACT



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ABSTRACT

Pollution by plastics is a worldwide problem on par with climatic change and biological invasions. In coastal sediments, plastic particles tend to accumulate and persist over the long term. We assessed the plastic pollution using a standardized surface sediment sampling protocol on 22 sandy beaches along >4600 km of the Brazilian coast. The abundance, size, color, type, and polymeric composition of all meso- and microplastic items found in the surveys were processed to disclose spatial patterns of distribution and pollution associated drivers. A General

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Riverine pollution
Tourism
FTIR

Linear Model (GLM) was run to investigate how the predictor variables influenced overall beach plastic amounts and by plastic type and size class. Overall, 3114 plastic items were found, with microplastics comprising just over half of all items (54 %). Most items were either white (60 %) or blue (13 %), while polystyrene foam (45 %) and fragments (39 %) comprised the most abundant plastic types. The principal polymers were Polyethylene (40 %) and Polypropylene (32 %). The analyses indicated that the distribution of plastic litter along beaches is determined by three predictive variables: the distance to the nearest estuary (−), tourism (+), and the number of inhabitants in the nearest urban center (+). Tourist (highly-visited) beaches and those near estuarine runoffs or urban centers presented the highest plastic pollution rates. The unveiling of plastic pollution patterns through a large-scale systematic survey is essential for future management guidance and science-based decisions for mitigating and solving the plastic pollution crisis.

1. Introduction

Globally, the annual production of plastic is approximately 360 million tons, of which 50 % are single-use plastics (PlasticEurope, 2019; PlasticOceans, 2020). Because of its lightweight, low cost, and durability, plastics are widely used in our daily lives and, when inadequately disposed, may fragment and accumulate in terrestrial and aquatic environments (Kako et al., 2014; Lebreton et al., 2019). Pollution by plastics is a worldwide concern, as problematic as climate change and invasive species (UNEP, 2014). Plastic pollution is ubiquitous in aquatic environments, ranging from shallow rivers to the deepest ocean basins (Chiba et al., 2018; Singh et al., 2021).

Plastics are synthetic polymers derived mainly from petroleum (UNEP, 2018), which a wide range of polymers and polymer mixes are

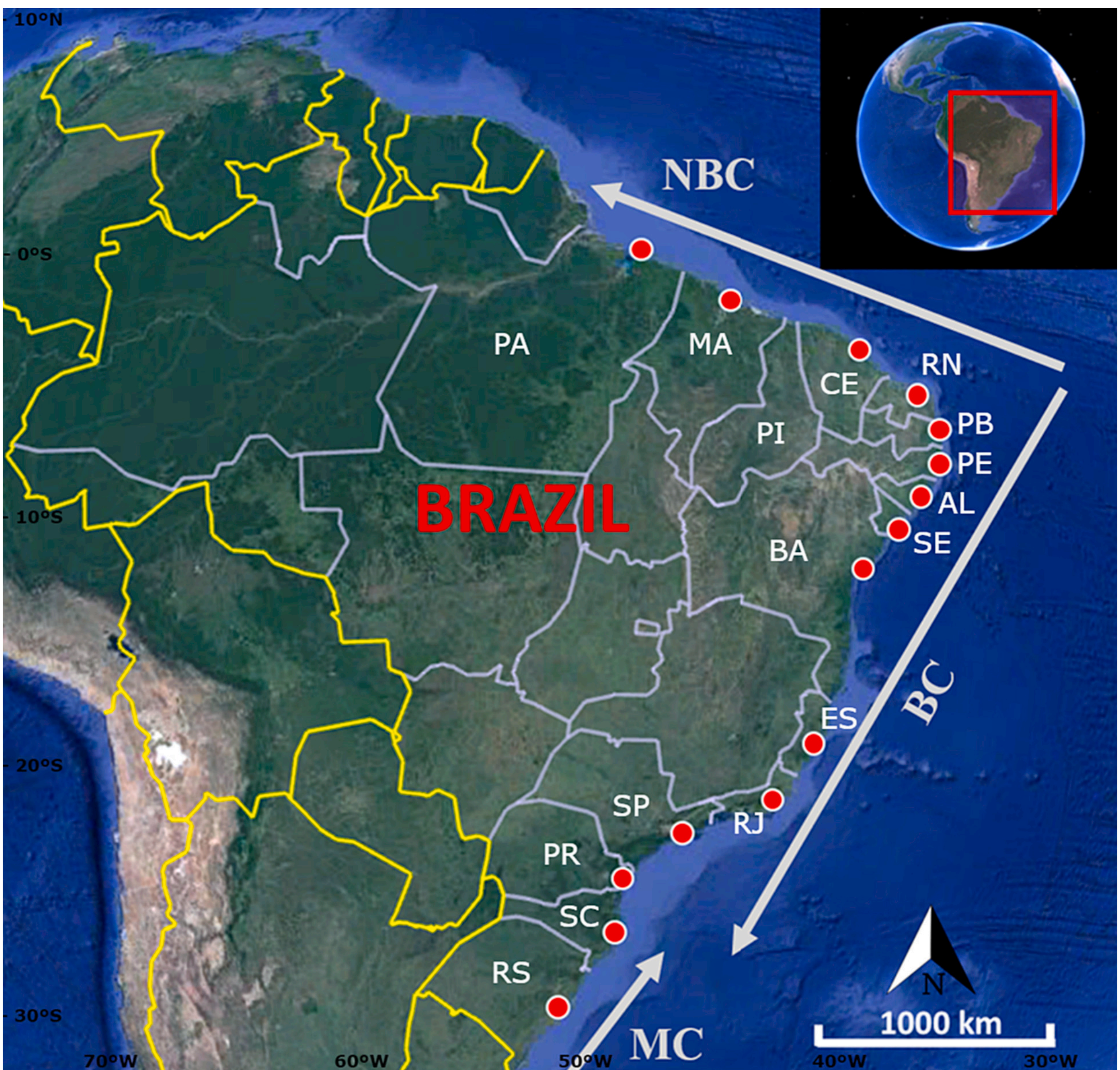

Fig. 1. Location of the 22 sampling beach sites (red spots, 6 replicates in each) along the Brazilian coast. Arrows denotes North Brazilian Current (NBC), Brazilian Current (BC) and Malvinas Current (MC) directions.

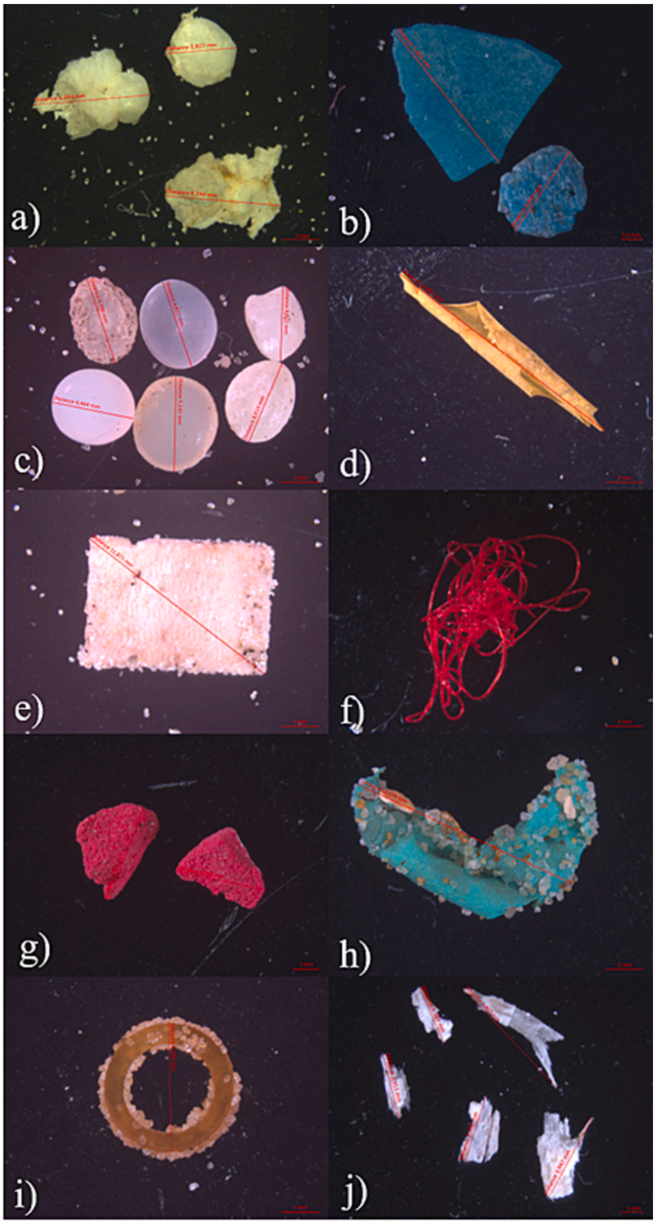

Fig. 2. Meso- and microplastics of Brazilian beaches. a) Polystyrene foam; b) Fragment; c) Pellet; d) Film; e) Cigarette filter; f) Filament; g) Foam; h) Rubber; i) Silicone; and j) Synthetic fabric.

produced commercially. These, 80 % are composed of high- (HDPE) or low-density polyethylene (LDPE), polypropylene (PP), polyvinyl chloride (PVC), polyurethane (PU), polystyrene (PS), and polyethylene terephthalate (PET). Not surprisingly, these polymers are the most common among marine pollution litter items (GESAMP, 2019).

Besides polymer composition, plastic litter can also be classified according to its size. Four categories are considered – mega- (> 1000 mm), macro- (25–1000 mm), meso- (1–25 mm), and microplastics (< 5 mm). Furthermore, microplastics can be classified according to their origin, being divided into primary microplastics, those plastics produced in the form of micro-particles for a specific function (e.g., micro-beads used in cosmetics or resin pellets), and secondary microplastics, those derived from the degradation of larger objects, including synthetic textiles (GESAMP, 2015). Given their minute diameter (1 μm–5 mm; Frias and Nash, 2019), microplastics are easily incorporated into aquatic food webs through their ingestion by a wide range of organisms (Provencher et al., 2019; Setälä et al., 2018). Once ingested, microplastics may act as a vector for toxic metals or persistent organic pollutants, which are often added during their manufacturing or are adsorbed from the surrounding environment (Acosta-Coley et al., 2019; Pannetier et al., 2019).

Coastal ecosystems, such as mangroves and sandy beaches, may also often act as sinks for plastic litter (Lebreton et al., 2019; Martin et al., 2020), which is generated by human activities, both inland and on the open ocean (Jambeck et al., 2015; Karthik et al., 2018). The combination of high temperatures, intense solar radiation, strong winds and waves makes sandy beaches a suitable environment for the degradation of larger plastic items into smaller pieces, which leads to an increase in microplastic amounts in the marine environment (Browne et al., 2007; Corcoran, 2021). By comparison, it is more difficult to trace the source of microplastic items than larger plastic litter. This is especially true regarding secondary microplastics, which are difficult to infer about their source material (Browne et al., 2015; Andrady, 2017). This means that the identification of the origin of beach microplastics depends on the understanding of their spatial relationships with potential sources on the land-sea interface, such as urban centers, local tourism (e.g., highly-visited beaches), and riverine inputs (Robin et al., 2020; Vetrimurugan et al., 2020).

The presence of microplastics in the beach sediments can disrupt key ecological processes and dynamics of meio- and macrofauna that are essential to guarantee ecosystem services and other benefits for human society, such as the rework of sediment particles, nutrient cycling and the coastal food-chain by serving as food for other organisms (Browne et al., 2015; Tosetto et al., 2016; Carrasco et al., 2019; Afghan et al., 2020; Kristensen et al., 2012). Pollution by plastics may also reduce the cultural and economic value of a beach, therefore impacting local economies (Krelling et al., 2017).

Unfortunately, plastic pollution is widespread on sandy beaches worldwide, including Europe (Urban-Malinga et al., 2020), Asia (Chen and Chen, 2020), Oceania (Bridson et al., 2020), Africa (Vetrimurugan et al., 2020), and the Americas (Dodson et al., 2020, De-La-Torre et al., 2020), as well as in remote areas of Antarctica (Kelly et al., 2020). However, comparisons at regional or global scales are limited by the lack of standardization of sampling or laboratorial procedures (Löder and Gerdts, 2015). In Brazil, this scenario is not different. A couple of studies approach plastic pollution in beach environments, though they were developed in restricted environments such highly urbanized regions, with low sample coverage and different methodologies strategies (e.g., De Carvalho and Baptista-Neto, 2016, Moreira et al., 2016a, b, Fisner et al., 2017, Carvalho et al., 2021).

A large-scale database with standardized protocols for plastic litter is important to provide a baseline of pollution levels and comparable scientific basis to future monitoring activities and decisions (Blumenröder et al., 2017; Peng et al., 2017). In this context, the present study provides the first systematic and standardized assessment of the pollution of Brazilian beaches by meso- and microplastics. This study focused on the characteristics of the plastic particles (shape, size, color, and polymeric composition), as well the spatial distribution patterns and potential drivers of plastic pollution along an extensive coastline (>4600 km).

2. Material and methods

2.1. Study area

The Brazilian coast (Fig. 1) varies considerably in its climatic, geomorphological, oceanographic, and ecological characteristics, including a diversity of intertidal ecosystems, including mangroves, reefs, and sandy beaches (Schaeffer-Novelli et al., 2000; Amaral et al., 2016; Andrades et al., 2018). Brazil has one of the world's most complex coastlines, extending approximately 9000 km between latitudes 4°N and 34°S, with 4000 km of open coast and bay beach environments (Short and Klein, 2016). The study area is dominated by semi-diurnal tides with tidal amplitudes exceeding 4 m in the extreme north, decreasing to <1 m southwards (Dominguez, 2009).

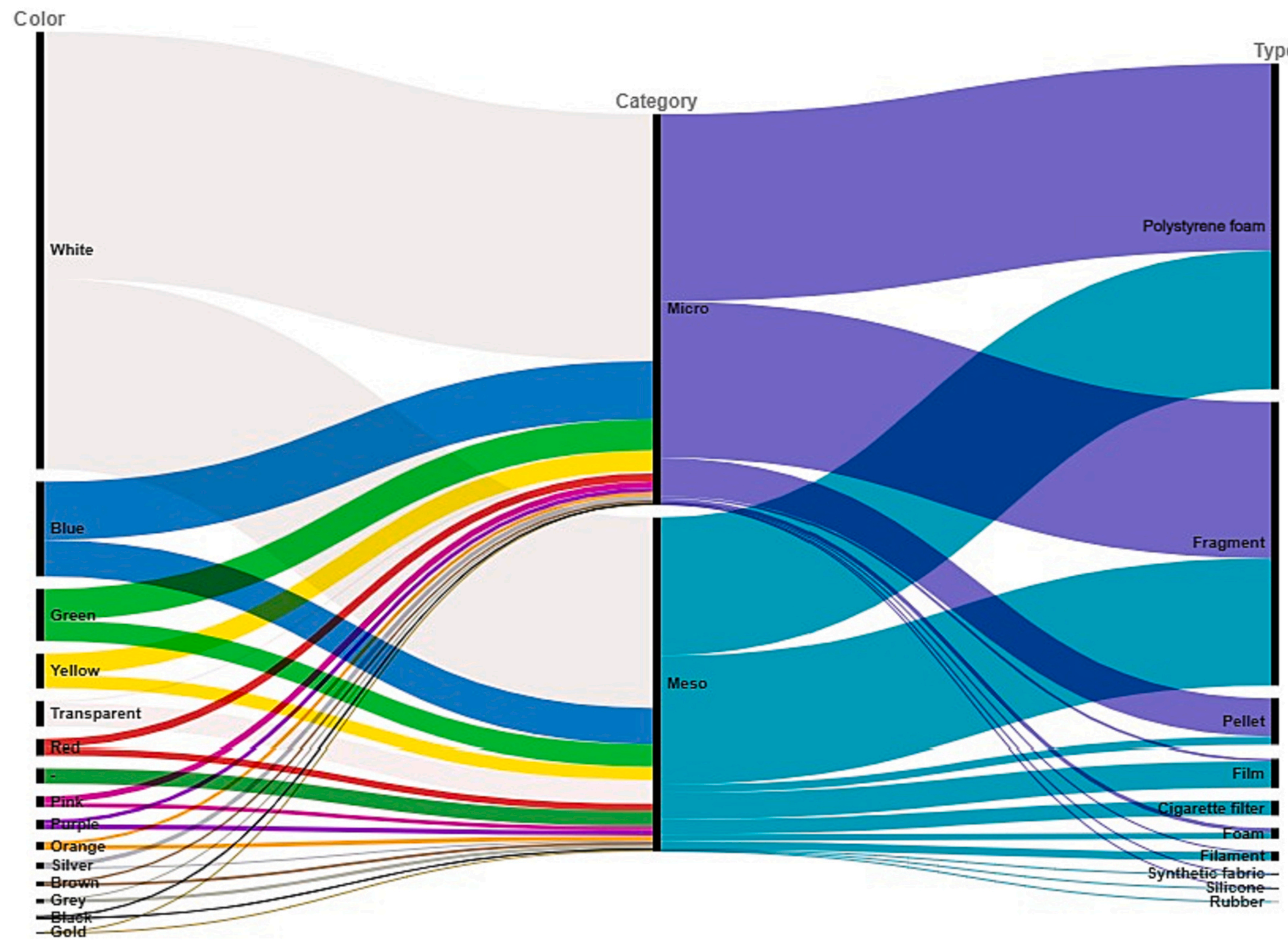

Fig. 3. Chord diagram showing the flows and relationships of the colors of meso-and microplastics of Brazilian beaches and the litter types.

2.2. Sampling methods and beach plastic processing

A total of 132 sediment samples were collected from 22 sandy beaches following a protocol adapted from Palatinus et al. (2015). The beaches were surveyed along the Brazilian coast between December 2017 and January 2018. We highlight that sampling was not carried out right after New Year's Eve to avoid influence of the holiday. The number of beaches is representative and covers 21 of the 23 Brazilian federal states (the only exceptions are Amapá and Piauí state). All beaches were near urban centers, to avoid logistic timing constrains to accessing remote locations.

Six quadrants (20 × 20 cm) were randomly placed at the upper limit of hightide mark, and the top sediment layer (to depth of 3 cm) was taken with the aid of stainless-steel spoon, totalizing approximately 1 kg of sediment each sample. All samples were stored in unused aluminum trays and taken to the laboratory for processing.

In the laboratory, the sediment samples were dried in a stove at 60 °C before being weighed on a digital scale (0.01 g precision) to determine the dry weight (g). Our investigation was focused on extract meso- (5–25 mm) and larger microplastics (0.1–5 mm) (International Organization for Standardization (ISO), 2020). To achieve this goal, we used a stereomicroscope (Opton Tim-2b) for the visual separation at magnifications of 6.5× to 50×. The plastic particles were separated from the sediment using tweezers and then placed in Petri dishes. Then, the plastic items were counted and classified by type (cigarette filter, filament, film, foam, fragment, pellet, rubber, silicone, polystyrene foam, synthetic fabric) and color (black, blue, brown, gray, green, gold, orange, pink, purple, red, silver, transparent, white, and yellow) according to Monteiro et al. (2022). Posteriorly, each item was measured (greatest dimension with a precision of 0.001 mm) and photographed under a Zeiss SteREO Discovery V12 microscope equipped with the Zen software (blue edition, v2.0, Zeiss, Oberkochen, Germany).

All steps of plastic processing and analyses were conducted following the directions regarding avoidance of cross contamination as described in Lu et al. (2021). Procedures of QA/QC were adopted, as 1) all laboratory staff used cotton coats, 2) equipment's were rinsed and cleaned before and after use and covered up when the work end, 3) the samples were processed under a fume hood in a room with restricted access, 4) plastic tools were avoided, such as petri dishes and sampling containers. Also, blank Petri dishes were placed in the workspaces, however, no plastic particles in the interval of millimeters target in our study were found.

A single sample of each meso- and microplastic shape category identified in the present study was selected randomly for polymeric identification in Department of Chemistry "Ugo Schiff", University of Florence (UniFI). The mesoplastic particles were analyzed by Attenuated Total Reflectance-Fourier Transformed Infrared Spectroscopy (ATR-FTIR), using a Cary 620–670 FTIR microscope, equipped with an ATR Ge crystal, to acquire 128 scans with a spectral resolution of 8 cm^{-1}, in the 4000–450 cm^{-1} spectral range. A single-element MCT detector was used in this case. Instead, the microplastic samples were analyzed via 2D FTIR Imaging with the same microscope, but using a Focal Plane Array (FPA, Agilent Technologies) detector with an array of 128 × 128 photosensitive elements (pixels). The spectra were recorded directly on the

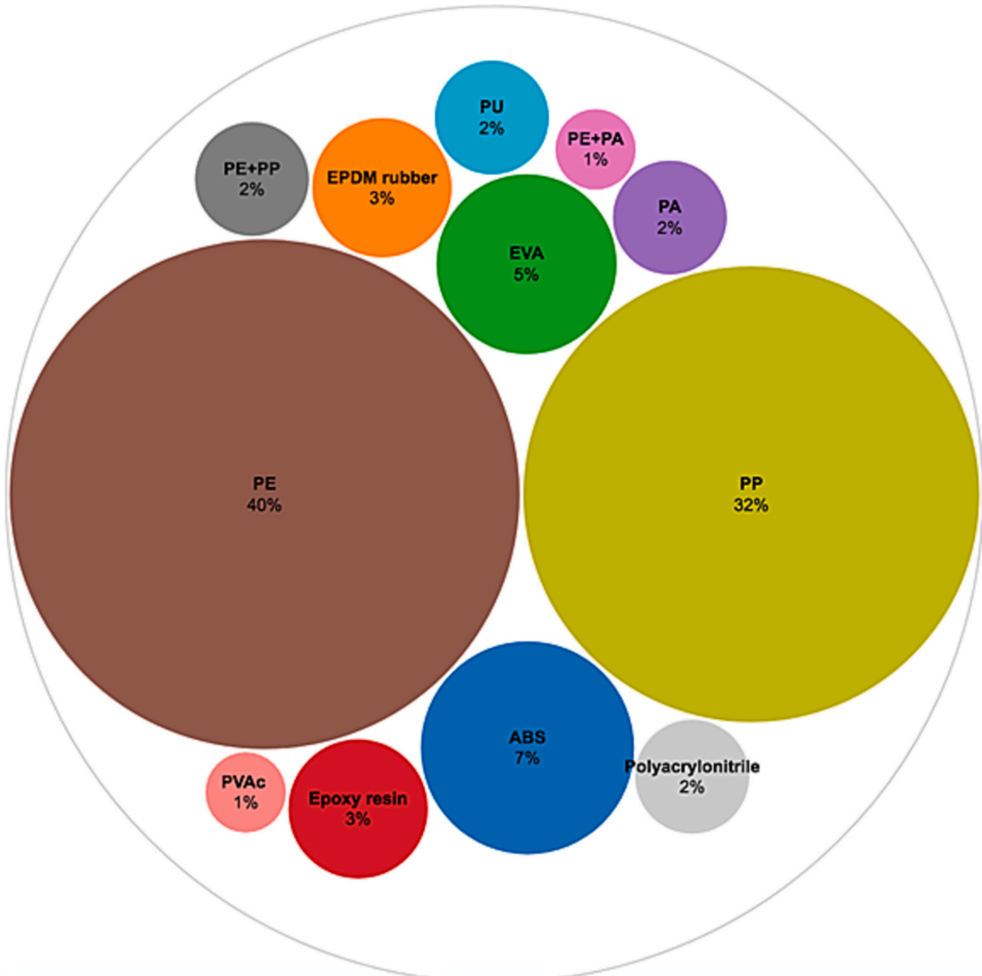

Fig. 4. Circle packing chart of the proportions of the different polymers identified in the particles collected from Brazilian coastal beaches by ATR-FTIR spectroscopy. ABS = Acrylonitrile Butadiene Styrene; EPDM = Ethylene Propylene Diene Monomer rubber; EVA = Ethylene Vinyl Acetate; PA = Polyamide; PE = Polyethylene; PP = Polypropylene; PU = Polyurethane; PVAc = Polyvinyl Acetate; PE + PP = Polyethylene and Polypropylene blend; PE + PA = Polyethylene and Polyamide blend.

surface of the samples (or of the Au background) in reflectance mode, using an open aperture, a spectral resolution of 8 cm^{-1}, and acquiring 128 scans for each pixel. The “single-tile” analysis yields a map of ca. 700 × 700 μm^2, with each pixel providing an independent spectrum over an area of 5.5 × 5.5 μm^2. This experimental set up thus allows collecting non-invasively a large number of independent spectra on plastic fibers and fragments (Pegado et al., 2021).

2.3. Data analysis

A Generalized Linear Model (GLM) was fitted to each category of plastic particle using the mean density of the plastic recorded at each site, with a Gaussian distribution, by the equation:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \beta_8 X_8 + \beta_9 X_9 + \beta_{10} X_{10} + \beta_{11} X_{11} + \varepsilon$$

where:

Y represents the response variable (mean density of plastic recorded at each site for a specific category of plastic particle); β_0 is the intercept term; β_1 to β_{11} are the coefficients for the predictor variables X_1 to X_{11}, respectively; X_1 is the number of inhabitants of the city where the beach was situated; X_2 is the number of inhabitants of the nearest urban center (i.e., the nearest city with >10,000 inhabitants); X_3 is the distance to the nearest urban center; X_4 is the distance to the nearest estuarine runoff; X_5 is the mean river discharge of the nearest estuarine runoff; X_6 is the beach tidal range; X_7 is the extension of the sampled beach; X_8 is the distance to the nearest petrochemical complex; X_9 is the Human Development Index (HDI); X_{10} is the Gross domestic product (GDP); X_{11} is the Tourism (total income collected from touristic activities by a city; IBGE, 2012); and ε represents the error term, accounting for the variability not explained by the model. The predictor variables (Table S1) were chosen based on literature that indicate urbanization, harbor activities, river and estuarine inputs, and tourism as the mainly drivers for litter distribution on coasts (Andrades et al., 2020; Robin et al., 2020; Vetrimurugan et al., 2020).

The distance to the nearest urban center and estuary, the extension of the beach, and the distance to the nearest petrochemical complex (when applicable) were taken from Google Earth (Google, 2018), the tidal range and mean river discharge were obtained from the Brazilian Waters Agency (SNIRH, 2018). The number of inhabitants of the city or village where beach is located, number of inhabitants of the nearest urban center, HDI and GDP were obtained from Brazilian Institute of Geography and Statistics (IBGE). A forward stepwise procedure was used to determine which factors generate the most parsimonious models in each case, using the Akaike Information Criterion (AIC) as a measure of the goodness of fit (Akaike, 1974). The adjusted r-squared coefficient was also used to estimate the performance of the model in explaining the observed variance. The model residuals were examined for the assumption of normality using Shapiro and Wilk's (1965) test and for homoscedasticity based on Breusch and Pagan's (1979) test. Scatter plots of the residual and predicted values were used to check for linearity. Multicollinearity was also verified using the Variation Inflation Factor, VIF (Kutner et al. 2004). All analyses were performed through the R software (R Development Core Team, 2021). The GLM models, the goodness of fit comparison, and the normality test were fit using the R base package. The homoscedasticity test was performed using the package 'lmtest' (Zeileis and Hothorn, 2002) and the VIF using the package 'caret' (Fox and Sanford, 2019).

3. Results and discussion

Plastic litter was present in all 22 studied sandy beaches. Overall, 3114 plastic items were found in sediment samples, which 1682 (54 %) being microplastic items and 1432 (46.0 %) mesoplastic items. The mean size of items was 6.5 mm (SD ± 1.5 mm), ranging from 0.19 mm to 24.6 mm (Table S2). Specifically, microplastic items ranged in size from 0.1 to 4.9 mm, with mean of 3.4 mm (SD ± 0.5 mm), while mesoplastic items varied from 5 mm to 24.6 mm, with mean of 9.7 mm (SD ± 1.2 mm).

A total of 10 different types of plastic litter were identified, with polystyrene foam (n = 1402, 45 %) being the most common item, followed by fragments (n = 1223; 39 %), pellets (n = 199; 6 %), film (n = 125; 4 %), cigarette filters (n = 65; 2 %), filaments (n = 39, 1 %), foam (n = 46; 1 %), and rubber, silicone, and synthetic fabric, with <1 % of the total amount (Fig. 2 and Table S3). While the most of items (60 %) were white, colors varied considerably, including blue (13 %), green (7 %), yellow (4 %), transparent (3 %), red (2 %), pink (1 %), purple (1 %), and orange (1 %), with silver, brown, gray, black, and gold each referring to <1 % of the collected items (Fig. 3 and Table S4). Cigarette filters were specifically classified as "no color" (2 %) because they presented variations in tone, probably due to the time they were exposed to the environment.

A predominance of polystyrene foam was also observed in other studies on beach and surface water plastic pollution (e.g., Lee et al., 2015, 2017; Cordova and Nurhati, 2019), which reinforces polystyrene foam as one of the principal pollutants in marine environments. In this sense, the governments of some Caribbean countries are already implementing controls on the use of polystyrene foam, including the regulation of imports, manufacturing, and sale (Clayton et al., 2021). Although the Brazilian National Plan for Marine Litter (Plano Nacional de Combate ao Lixo no Mar in Portuguese; MMA, 2019) recognizes that polystyrene foam is among the most common litter types on Brazilian beaches, no target initiatives are planned to address the problem.

The overall mean density of plastic litter recorded in the present study was 28.7 items/kg (SD ± 5.8 items/kg) ranging from 1.2 items/kg (± 2) in Maçarico beach (Pará state) to 71.9 (± 15.6) items/kg in Iracema beach (Ceará state). Mean litter density was lower comparing with others Atlantic beaches, such as in Colombia (1109 items/kg) (Rangel-Buitrago et al., 2021), in Lesser Antilles (261 ± 6 items/kg) (Bosker et al., 2018) and also in Hong Kong and Maldives beaches (188 ± 2 items/kg and 277.9 ± 24.9, respectively) (Lo et al., 2020; Patti et al., 2020). On the other hand, mean litter density in our study is higher than those reported in New Zealand (6 items/kg), Spanish (10.7 items/kg) and Argentinian beaches (13 ± 16 items/kg) (Bridson et al., 2020; Expósito et al., 2021; Truchet et al., 2021) and similar to observed densities in Guatemalan and Caspian beaches (30 items/kg and 19.8 ± 12.8 item/kg, respectively) (Ghayebzadeh et al., 2020; Mazariegos-Ortíz et al., 2020). However, we need to be cautious with direct comparisons of mean litter densities given to a variety of collection methods, sampling seasonality, and processing protocols used in different studies.

The polymeric composition of a subset of 151 items was identified through the FTIR analysis. A total of 12 polymers were identified in the analysis (Fig. 4), Polyethylene (40 %) and Polypropylene (32 %) were prevalent. The most frequent polymers can be seen in Figs. S1, S2 and S3. A recent review of MP studies in Latin America showed that the majority of studies reported PE (40 %), PP (17 %), and PET (15 %) as the

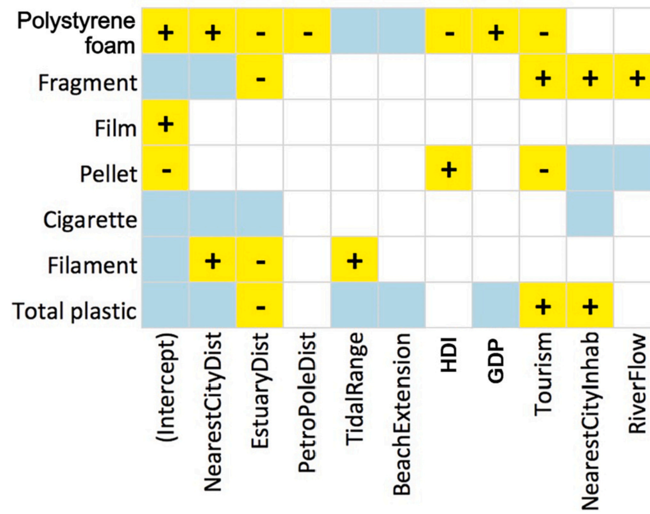

Fig. 5. Summary of the Generalized Linear Models regarding the potential drivers of each plastic item types on Brazilian beaches. NearestCityDist = distance to nearest urban center; EstuaryDist = distance to nearest estuary; PetroPoleDist = distance to nearest petrochemical complex; HDI = Human Development Index; GDP = Gross Domestic Product; NearestCityInhab = number of inhabitants in nearest urban center). Positive and negative significant relationships are displayed in yellow with positive (+) and negative (−) signals, respectively. In yellow and blue colors are highlighted the factors that generated the most parsimonious models.

dominant polymer types across environmental compartments and species (Kutralam-Muniasamy et al., 2020), which is in agreement with our findings.

Four (foam, rubber, silicone, and synthetic fabric) of the 10 plastic types did not generate an adequate GLM due to their reduced abundance and occurrence at only a few of the studied sandy beaches (Figs. 5 and 6). The total amounts of plastic on the Brazilian beaches appear to be determined by three predictive variables (Fig. 5 and Table S5), the distance to the nearest estuary (negatively), tourism and the number of inhabitants in the nearest urban center (both the latter positively). Indeed, urbanized and tourist beaches are usually more polluted than rural beaches (Rios-Mendoza et al., 2021). Proximity to estuarine run-off appears to influence the accumulation of the principal types of microplastic (filaments, fragments, and polystyrene foam), as well as the overall pollution by microplastics in the present study (see Fig. 5). In tropical countries with major river basins, such as Brazil, the input of estuaries into coastal environments can be a main driver of coastal pollution by macro-, meso- and microplastics (Andrades et al., 2020; this study), with local tourism, urbanization, and population density also acting as drivers of beach pollution.

These same three factors are also associated with the accumulation patterns of specific types of microplastic (Fig. 5). However, the tidal range had a positive effect on filament density, as Human Development Index on pellets, and riverine flow on fragments (Fig. 5). Filaments are common in coastal environments (Alomar et al., 2016). They are often classified as lines (derived from fishing activities) or textile fibers, found mainly in municipal wastewaters (Li et al., 2016; GESAMP, 2019). In the present study, however, we did not divide the filaments into these two categories, given that most of these items were derived from the fragmentation of ropes, lines, and nets (Fig. 2f). Although not in greater amounts in our study, pellets were concentrated primarily in the Brazilian richer regions (southeast Brazilian coast) and were not associated with tourism. Pellets of plastic resin are the raw material to produce many types of plastic objects that are common in the daily life (Andrady, 2011). The low density recorded in the present study may thus be the result of the sampling method, given pellets tend to accumulate below the top sediment layer, at depths below 10 cm (Turra et al., 2014). In

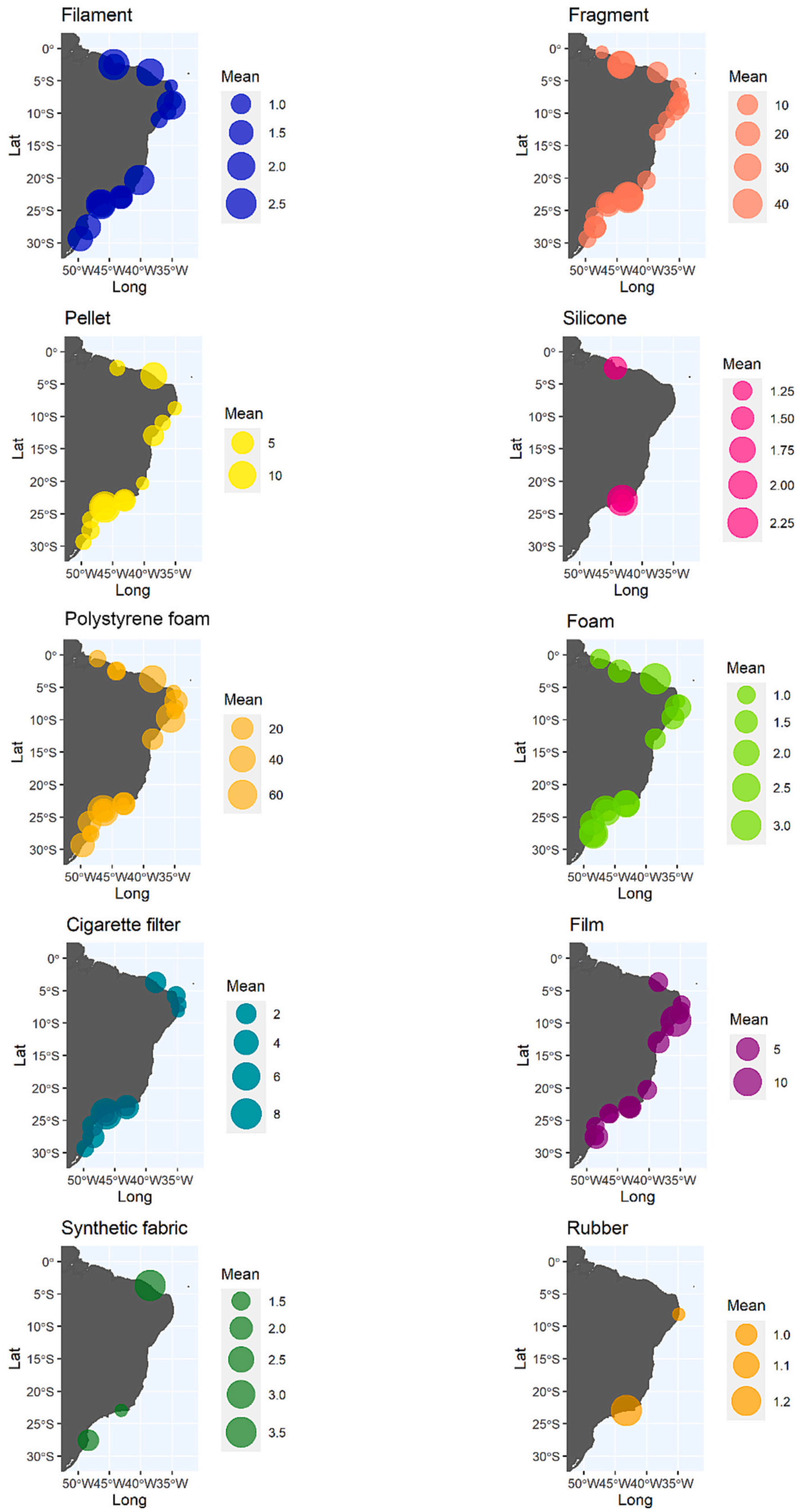

Fig. 6. Density (items/kg) of meso- and microplastic particles collected from sandy beaches on the Brazilian coast.

Guanabara Bay, southeastern Brazil, Castro et al. (2020) found pellets primarily on beaches, rather than in the water surface or bottom sediments. Carvalho and Baptista-Neto (2016) concluded that the high number of pellets amount on Guanabara Bay beaches was related to the presence of >12 thousand local industries around the bay, including oil refineries, ports, and shipyards. This is in line with the negative relationship found between pellet densities and tourism, and the positive relationship with high HDI reported in our study.

Pollution by polystyrene foam was associated negatively with the distance from the nearest estuary and petrochemical complex, HDI, and tourism, and positively with the distance from the nearest city and the GDP. As mentioned earlier, polystyrene foam is a major pollutant in marine environments worldwide. In the present study, the proximity of estuarine runoff and urban centers was associated closely with the polystyrene foam amounts. Polystyrene foam fragments are easily transported and deposited along the shoreline by natural forces, such as river flow, surface currents, and waves. River discharge in tropical regions, mainly during the rainy season, is responsible for the high transportation and accumulation rates of lightweight items, such as polystyrene foam, on beaches and in the shallow waters of estuarine and coastal environments (Cordova and Nurhati, 2019). Even so, the polystyrene foam pollution recorded here appeared to be influenced by a myriad of variables in the model, which is probably a result of the inherent high dispersal capacity of this low-density material. Given this, polystyrene foam tends to accumulate on almost any beach, regardless of the factors that may be driving its dispersal and, with rare exceptions, it is virtually polluting all Brazilian shoreline habitats.

Developing countries, such as Brazil, exhibit varying levels of solid waste treatment, characterized by low recycling rates and significant illegal disposal (Alpizar et al., 2020). Moreover, these countries contribute substantially to the deposition of marine plastic waste in our oceans (Jambeck et al., 2015). While international treaties and global initiatives are essential for addressing the current plastic pollution crisis (Borrelle et al., 2017; Lau et al., 2020; Simon et al., 2021), it's equally crucial to implement local-scale strategies that boost environmental awareness (Ogunola, Onada, and Falaye, 2018).

Nevertheless, to formulate effective local and regional strategies, we must first identify the categories of plastics that accumulate in significant quantities and their possible sources (e.g., Kataržytė et al., 2020; Arias et al., 2022). Furthermore, it is imperative to measure progress and assess the effectiveness of any management plan using monitoring and research data to ensure the success of these actions (Sivadas et al., 2022).

4. Conclusions

The present study has significant importance as it represents the first systematic and standardized assessment of plastic pollution along the extensive Brazilian coast, spanning over 4600 km. Hence, providing an essential foundation for future studies. In the present survey, plastic was found at all beaches, with mean density of 28.7 items/kg, and microplastics comprised the majority of plastic litter with size ranging from 0.1 to 4.9 mm. Ten categories and variety colors were identified, being polystyrene foam, fragments, and white, the most common type, plastic category, and color, respectively. Our data based on a large-scale standardized data suggest that beaches close to estuarine discharges and populated areas are prone to receive great amounts of meso- and microplastics items. Also, tourist beaches recorded high litter densities. We recommend the replication of our plastic surveys in a short- (seasonal) and long-term (annual) period to address potential seasonal shifts of plastic pollution trends on Brazilian beaches. More surveys with the same methodology used here will improve the understanding and strengthen decision power in favor to best science-based solutions for plastic pollution in Brazil.

CRediT authorship contribution statement

Tamyris Pegado: Data curation, Writing – original draft, Writing – review & editing. **Ryan Andrades:** Visualization, Writing – original draft, Writing – review & editing. **Eurico Noleto-Filho:** Formal analysis, Methodology, Writing – review & editing. **Simone Franceschini:** Data curation, Formal analysis, Writing – review & editing. **Marcelo Soares:** Writing – review & editing. **David Chelazzi:** Methodology, Writing – review & editing. **Tommaso Russo:** Writing – review & editing. **Tania Martellini:** Methodology, Writing – review & editing. **Angelica Barone:** Methodology, Writing – review & editing. **Alessandra Cincinelli:** Methodology, Writing – review & editing. **Tommaso Giarrizzo:** Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.167769.

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