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Recognizing microplastic deposits on sandy beaches by altimetric positioning, µ-Raman spectroscopy and multivariate statistical models

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ABSTRACT

Understanding the extent and implications of microplastic (MP) pollution along the São Paulo State coastline in southeastern Brazil is crucial, considering the significant environmental burden imposed by industrial and port activities in this region. This research aims to understand the complex dynamics of MP deposition on sandy beaches, which poses severe environmental risks to coastal ecosystems, marine organisms, and humans. Using a comprehensive five-step methodology—geodetic surveys, sediment collection, µ-RAMAN spectrometry for polymer identification, and multivariate statistical models—we analyzed the distribution of MPs across six coastal compartments (C1 to C6). The results (128 samples from 34 profiles) revealed relatively high MP concentrations in C3 and C2, which were likely influenced by local human activities. Various shape types of MPs, such as pellets, fragments, and fibers, present distinct distribution patterns based on their physical properties and emission sources. Fragments and foam were the most prevalent, accounting for 42 % and 35 %, respectively, of the 1026 MP items identified in total. Statistical analyses revealed significant correlations between MP types and beach morphometric features, with higher elevations correlating with increased MP concentrations, particularly for pellets and foam. Beaches with intermediate slopes ($0.05 < \tan\beta < 0.12$) and openings to the southern quadrant tended to accumulate more MPs. This research underscores the importance of tailored management strategies that consider the unique characteristics of each coastal region to mitigate the impacts of MP pollution. The findings contribute to the development of targeted monitoring and environmental remediation strategies, which are crucial for protecting marine life and maintaining the integrity of coastal environments.

1. Introduction

Microplastics (MPs), which are defined as plastic particles <5 mm in diameter (GESAMP, 2019), are increasingly recognized as widespread pollutants in marine environments. Global plastic production exceeded 4003 million tons in 2022, with a significant portion of fossil-originated plastic ending up in the ocean, contributing to the estimated 8 million tons of plastic waste entering marine ecosystems annually (Europe, 2023; Jambeck et al., 2015a, 2015b). As emerging pollutants on sandy beaches, MPs reduce the aesthetic value of these environments, affecting their visual appeal and recreational quality (Borriello, 2023; Corbau et al., 2023; Ghosh et al., 2023).

Studies have indicated that the presence of MPs on beaches not only diminishes their physical beauty and tourist appeal but also reflects

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issues in waste management and the public perception of the health of marine ecosystems (Amelia et al., 2021; Ghosh et al., 2023; Hartley et al., 2015; Oliveira et al., 2020). Moreover, this phenomenon raises concerns about the health and well-being of both local wildlife and humans (Botero et al., 2021; Costa et al., 2022; da Silva et al., 2022; Göktuğ, 2021).

The accumulation of MPs in coastal areas has generated significant concerns because of their persistence, ability to transport harmful chemicals, and potential to enter the food chain, impacting marine life and human health (Thompson et al., 2009). By altering the composition and characteristics of environments such as beaches, MPs have potential repercussions for coastal ecosystems and organisms that depend on these habitats for survival (Fries et al., 2013).

Residual MPs from UV radiation and/or mechanical abrasion (Harris, 2020) modify the porosity of sediments, impacting the drainage and moisture retention capacity of beach substrates, potentially releasing greenhouse gases such as methane and ethylene (Royer et al., 2018). These changes in the physical environment may influence temperature-dependent sex determination in certain species, such as crustaceans and sea turtles (Carson et al., 2011; Nelms et al., 2016).

At the chemical level, MPs can absorb and concentrate organochlorine contaminants, including polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloroethane (DDT), polycyclic aromatic hydrocarbons (PAHs), and mono-ethylhexyl phthalate (MEHP), a degraded form of diethylhexyl phthalate (DEHP) (Brighty et al., 2015; Hartley et al., 2015; Ogata et al., 2009; Teuten et al., 2009). These compounds can concentrate and transport contaminants to marine biota and, by extension, to humans through the food chain (Rochman et al., 2013a, 2013b; Smith et al., 2018).

Global concern over microplastic pollution has led to various international initiatives addressing this issue. The United Nations Sustainable Development Goal 14 aims to reduce marine pollution, including microplastics, by 2025 (Guterres, 2020; United Nations, 2020). Additionally, the G20 Osaka Blue Ocean Vision, adopted in 2019, seeks to eliminate additional marine plastic litter pollution by 2050 (Summit, 2019). These initiatives highlight the urgent need for studies that can inform policies and management strategies to mitigate the impact of MPs.

In Brazil, Escrobot et al. (2024) reviewed 102 studies on microplastics (MPs) in Brazilian coastal environments between 2018 and 2023. Most studies have focused on beaches and marine biota, with tourism, fishing, and river discharge being the primary sources of MPs. This review highlights the need to standardize research methods and deepen studies on the ecological impacts of MPs.

Southeastern Brazil, particularly the coastline in the state of São Paulo, represents a critical area for studying MP pollution because of its dense population, industrial activities, and significant port operations (Ferreira et al., 2021; Ivar do Sul and Costa, 2014). The Santos Estuary, encompassing the city of Santos, its port, and the industrial region of Cubatão, is known as a hotspot for MP pollution (Jong et al., 2022), especially pellets along the São Paulo coast (Ferreira et al., 2021).

Inadequate plastic waste management and failure in containment systems are the leading causes of the entry of this pollutant into the environment, especially during production, transportation, and transshipment processes in factories and port terminals (Geyer et al., 2017; Ivar do Sul and Costa, 2014; Jambeck et al., 2015a, 2015b). The impacts caused by this pollutant affect marine life through the ingestion of these particles by marine organisms, causing physical and chemical damage and reflecting the severity of the situation (Rochman et al., 2013a, 2013b, 2014).

Studies such as those by Turra et al. (2014) and Ferreira et al. (2021) have begun to elucidate the dynamics of MP pollution in this region, but there is still a need for more detailed and spatially extensive research. In this context, the combined analysis of geodetic, geomorphometric, and meter-oceanographic factors on a beach along the coast of São Paulo Ferreira et al. (2021) demonstrated that coastal currents and storm events can influence MP deposition patterns. Therefore, identifying the most suitable zones for MP accumulation and systematizing potential accumulation areas are critical considerations (Avio et al., 2017; Hidalgo et al., 2012; Kim et al., 2015; Van Cauwenberghe et al., 2015).

To this end, this study aims to comprehensively assess MP pollution along approximately 880 km of the São Paulo coastline. By integrating geodetic surveys, sediment collection, µ-Raman spectroscopy, and multivariate statistical models, we seek to understand the spatial distribution of MPs in different coastal compartments, focusing on identifying critical accumulation zones and the factors influencing MP deposition.

Our approach combines these techniques, allowing a more detailed understanding of how geomorphological, polymeric, and human activities interact to influence MP distribution and aiming to improve monitoring, remediation, and environmental management strategies adapted to the unique conditions of each coastal compartment. This aligns with global efforts to combat marine pollution and underscores the importance of localized studies in the development of effective environmental policies.

2. Methods

To indicate locations susceptible to MP deposition (MP hotspots), the data collection and analysis can be divided into three stages: 1) fieldwork, i.e., sediment sampling and beach morphometric parameters (aspect, slope, and altitude) via altimetry from the Global Navigation Satellite System (GNSS); 2) laboratory analysis, i.e., sieving (1–5 mm mesh) and µ-RAMAN spectrometry for the confirmation of polymeric properties; and 3) exploratory multivariate techniques, i.e., analytical hierarchy process-Gaussian (AHP-G) and correspondence analysis (CA) (Fig. 1).

2.1. Study area

The almost 880 km coastline of São Paulo State in southeastern Brazil is segmented into six distinct compartments: (C1) Ilha do Cardoso to Serra do Itatins; (C2) Peruíbe to Praia Grande; (C3) Santos to Bertioga; (C4) Bertioga to Toque-Toque; (C5) Toque-Toque to Tabatinga; and (C6) Tabatinga to Picinguaba (Fig. 2a), as outlined by Tessler et al. (2018). This coastline features diverse geomorphological characteristics, such as beaches, rocky shores, sandbars, and mangroves, shaped by a combination of geological, geomorphological, climatic, and human factors (Ferreira et al., 2023).

The southern part of the coastline is characterized by a flatter topography which includes critical ecological zones such as the Juréia-Itatins and Itinguçu State Park (Suguio and Tessler, 1984; Tessler et al., 2018). The Serra do Mar escarpment is situated farther from the shore (10 km to 70 km), allowing for a wide coastal plain that features long,

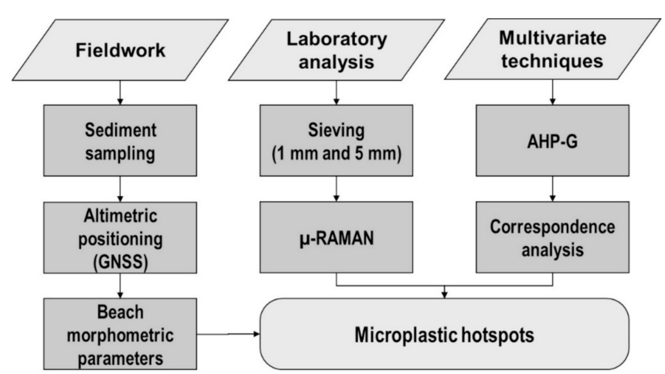

Fig. 1. Flowchart summarizing the methods used in this research. GNSS: Global Navigation Satellite System; µ-RAMAN: micro-Raman analysis; and AHP-G: analytical hierarchy process-Gaussian.

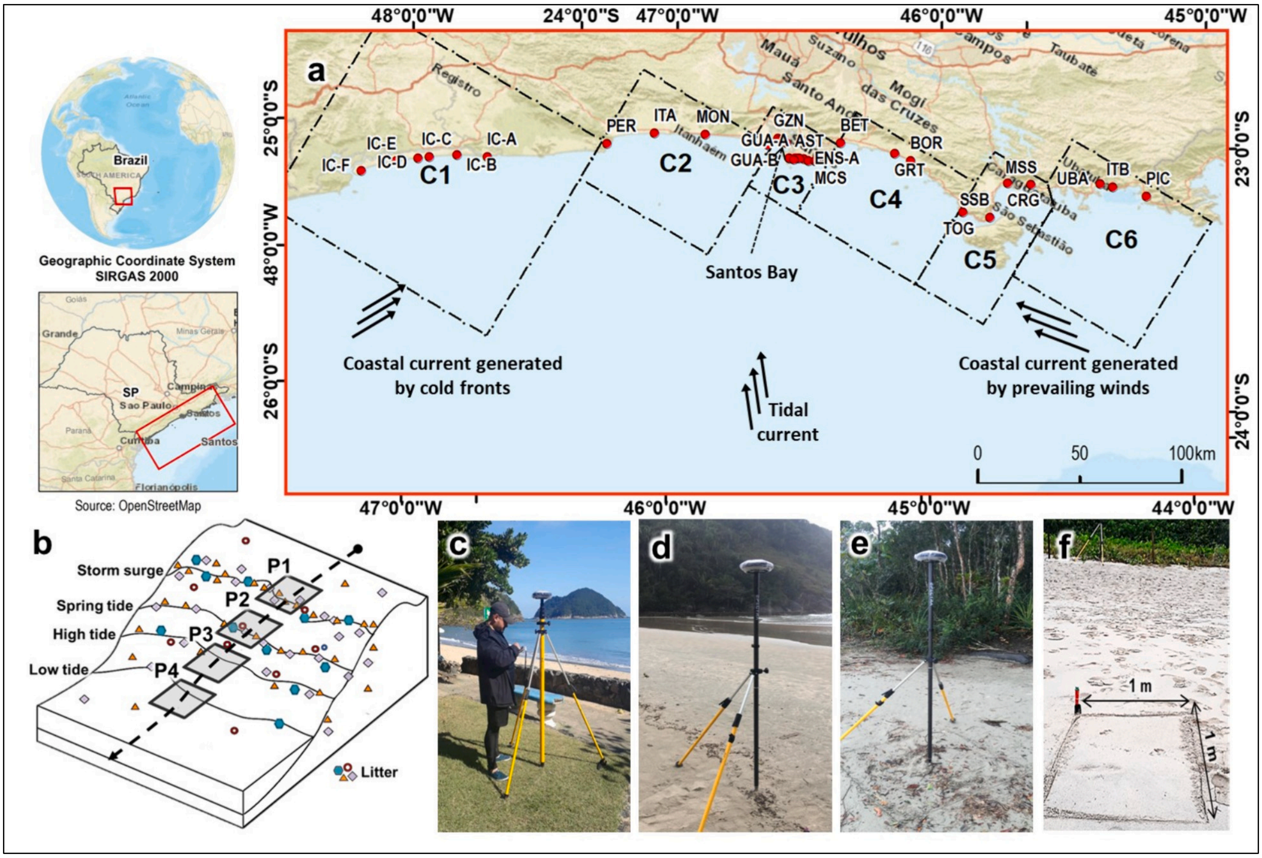

Fig. 2. (a) Red points are the sampling locations distributed within the six compartments on the São Paulo coast. (b) Sampling points by beach profile (P1, P2, P3, and P4), modified from GESAMP (2019); examples of GNSS base (c) and rover (d and e) surveys; and (f) area (1 m^2) of superficial sediment collection. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

uninterrupted beaches and several islands (Souza, 2012; Tessler et al., 2018). The central region hosts the largest port in Latin America (Reid et al., 2022) and significant industrial centers (i.e. Cubatão area).

From the central section moving northward, the Serra do Mar mountain range narrows the coastal plain, making the regional watershed (hydrographic basin) smaller compared to its southern counterpart one. The northern coastline is more topographically diverse, with numerous islands nearby (Suguio et al., 1985) and smaller secluded beaches pocket-shaped into coves and bordered by pre-Cambrian rocky promontories found at locations such as Itaguaré, Massaguaçu, and Praia Vermelha do Norte (Souza, 2012; Tessler et al., 2018).

The hydrodynamics along the Brazilian continental margin are governed primarily by the southward-flowing Brazil Current (BC) in deep waters and the Brazil Coastal Current (BCC), which travels from south–southeast to northeast along the continental shelf during spring and winter (Campos et al., 1995; De Souza and Robinson, 2004; Möller Jr et al., 2008). Predominant east–northeast winds create currents that run parallel to the northeast–southwest direction of the coastline. In winter, however, cold fronts influence the region, producing more intense south–southeast winds that generate stronger currents and waves from the southern quadrant (de Andrade et al., 2019; de Castro Filho et al., 1987; Ferreira et al., 2021; Harari et al., 2006; Pianca et al., 2010). Additionally, urban development and coastal infrastructure significantly alter coastal physiography and dynamics, potentially leading to erosion and progradation (Corrêa et al., 2021; Franzen et al., 2021).

2.2. Fieldwork samples and morphometric parameters

The field trips were conducted from April to September 2023, following the spring tide. During this period, cold fronts produced waves of up to 4 m and approached the coast from the southern and southeastern quadrants. This favored maximum sediment transport capacity, beach morphological changes, and the deposition and/or remobilization of microplastics (Ferreira et al., 2021). We opted for several varied beach profiles (34) that would proportionally cover the entire coast of São Paulo for each compartment, encompassing urban and rural beaches. Additionally, these locations were selected for their relatively easy accessibility by road, optimizing financial costs and time. Sediment samples and beach morphological parameters were obtained along beach profiles distributed across all six compartments of the São Paulo coastline, as shown in Table 1 and Fig. 2a.

The locations of sediment collection along each beach profile were

Table 1
List of sandy beach profiles per coastal compartment.

Compartment	Profiles ID	Number of profiles
C1 Ilha do Cardoso – Serra do Itatins	IC-A, IC-B, IC-C, IC-D, IC-E, IC-F	6
C2 Peruíbe – Praia Grande	PER, ITA, MON, PG	4
C3 Santos – Bertioga	GZN, ITR, GZG, GUA-A, GUA-B, TMB, AST, PIT-A, PIT—B, ENS-A, ENS-B, MCS, PEB	14
C4 Bertioga – Toque-Toque	BET, GRT, BOR	3
C5 Toque-Toque – Tabatinga	TOG, SSB, CRG, MSS	4
C6 Tabatinga – Picinguaba	UBA, ITB, PIC	3
Total		34

selected based on the environmental factors influencing litter dynamics on sandy beaches (GESAMP, 2019), particularly water levels (strandline altitudes), as noted by Ferreira et al. (2021). Sediment samples of approximately 1500 g of sediment were collected at each level of the beach profiles (Fig. 2b): storm strandline (P1), spring high tide (P2), neap high tide (P3), and low tide (P4). The collected sediments were subsequently homogenized and separated into 500 g aliquots to ensure consistency and repeatability of the sampling process, if necessary. This approach allowed the collection of samples from the top layer of sediment (~2 cm) within a 1 m^2 area (Fig. 2f) at each of the 128 sampling points, yielding 1026 items/pieces identified as large MPs ranging from 1 to 5 mm (GESAMP, 2019).

The morphometric parameters were divided into aspect, beach slope, and altitude. The first (aspect) is the beach-face orientation determined by the direction of the beach transect relative to geographic north as follows (Burrough et al., 1998): North – N (0°-22.5°), Northeast – NE (22.5°-67.5°), East – E (67.5°-112.5°), Southeast – SE (112.5°-157.5°), South – S (157.5°-202.5°), Southwest – SW (202.5°-247.5°), West – W (247.5°-292.5°), Northwest – NW (292.5°-337.5°), and North – N (337.5°-360°). The beach slope (tanβ) was derived from Eq. (1):

$$\tan\beta = \mathrm{atan}(VD/HD) \quad (1)$$

where VD and HD are the vertical and horizontal distances between sampling points P1 and P4, respectively (Fig. 2b). The slope can be used as a proxy of the beach morphodynamic stage (Bujan et al., 2019) and can be categorized as steep ($\tan\beta > 0.12$), intermediate ($0.05 < \tan\beta < 0.12$), or sloping ($\tan\beta < 0.05$) (Ferreira et al., 2023) to analyze the relationship between beach-face slope and sediment size and the correlation of slope parameters measured in situ with orbital images. The altitudes (*H*) of the sampling points were classified according to Ferreira et al. (2021) as follows: very low (VL; < 1.42 m), low (L; 1.42–1.57 m), mean (M; 1.58–1.89 m), high (H; 1.90–2.06 m), and very high (VH; > 2.06 m).

The altimetry of the sampling points (P1, P2, P3, and P4) was obtained via the GNSS, following the method described in Ferreira et al. (2021). Reference stations were established within <5 km of the markers distributed along the beach, and positions were received from the nearest active stations of the Brazilian Network for Continuous Monitoring via the SIRGAS2000 coordinate system. The coordinates and altitudes of the sampling points recorded by the mobile station were postprocessed relative to those of the reference station (Monico, 2008; Monico et al., 2009) via Survey Office software. The orthometric altitude (H) relative to the mean sea level of the Imbituba/SC datum of the Brazilian Geodetic System was obtained via Eq. (2) (Blitzkow et al., 2016):

$$H = h - N \quad (2)$$

where *h* is the geometric altitude obtained with the GNSS reference to the SIRGAS2000 ellipsoid and *N* is the geoidal height determined by the IBGE geoidal model, MAPGEO2015.

2.3. Microplastic analysis

MPs were extracted by sieving the samples through a 1–5 mm mesh. The retained MPs were visually separated from biological materials, such as shells, algae, and vegetation debris, and subsequently identified, counted, and categorized according to shape (Löder and Gerdts, 2015): pellets (spherical or smooth), foam, fibers or filaments, and plastic film.

The polymeric characterization of the MPs was undertaken in approximately 15 % of the total samples using μ-Raman spectroscopy (McCreery, 2005) in a labRAM HR Evolution (HORIBA) equipment, which works with laser wavelengths of 473 nm, 532 nm, 633 nm, 785 nm, and 1064 nm, and a long-range 50× objective numerical aperture (NA = 0.55). First, the laser's power is calibrated to obtain ideal spectra in the polymer identification region (approximately 1600 cm^{-1}) to prevent damage to the materials. The analysis subsequently extends to the spectral region from 200 cm^{-1} to 3200 cm^{-1}, focusing on identifying hydrocarbons (Araujo et al., 2018; Ferraro, 2003; Smith and Dent, 2019). Additionally, the limits and controls for adjusting the integration time, number of accumulations, and slit diameter are individually set for each sample to enhance the signal-to-noise ratio and prevent sensor saturation. A baseline is established for the acquired spectra, with subsequent noise filtering via a computational routine in MATLAB®. Finally, the spectra are compared with the Knowitall® software database to identify polymer types. Concurrently, images of the MP are captured by the Raman system microscope, complementing the database.

2.4. Unsupervised models

Given the heterogeneous nature of the data, which includes both quantitative and qualitative variables, we employed exploratory multivariate techniques such as the analytical hierarchy process-Gaussian (AHP-G) and correspondence analysis (CA). These algorithms were chosen based on their simplicity and effectiveness for exploratory analyses. Specifically, the AHP-G was utilized to analyze quantitative data and perform rankings, as it effectively represents these types of data. Conversely, correspondence analysis was selected to examine qualitative variables, also known as latent or categorical variables, which cannot be directly measured but can only be categorized or counted (dos Santos et al., 2023; Fávero and Belfiore, 2017).

The AHP-G incorporates the Gaussian distribution to quantify and assess, through distributions, uncertainties in evaluations and probabilistic decision-making while maintaining the classic hierarchical structure of Saaty's (2008) AHP without arbitrary weighting (Dos Santos et al., 2021, 2023). The results generate a ranking of MP abundance, which is subsequently standardized (Eq. (3)) and transformed into a Likert scale (Table 2). This allows an assessment of the associations between these rankings and beach morphometric parameters through CA.

The CA examines associations between variables of interest via the chi-square test (X^2; *p* value <0.05). The adjusted standardized residuals (ASRs) check for dependence relationships between each variable based on the reference critical value (+1.96 ≤) of the standard normal curve at the 5 % significance level. Thus, if the value of the ASR in a cell is greater than or equal to 1.96, significant dependence relationships exist (Fávero and Belfiore, 2017; Haberman, 1978; Johnson and Wichern, 1992). All the statistical analyses were performed using Python in Anaconda/Spyder software.

$$Standardization = \frac{(observed\ value) - (minimum\ value)}{(maximum\ value) - (minimum\ value)} \quad (3)$$

3. Results

3.1. Geographic distribution of microplastics

The 34 profiles perpendicular to the coastline had an average width of 37.57 m, with minimum and maximum values of 5.52 m and 182.48 m, respectively. The beach faces had an average orientation of 158° (SE), with values varying from 43° (N) to 259° (W). The slopes of these

Table 2
Standardized qualitative data based on the total number of polymers.

Ranking	Qualitative data
0.80–1.00	Very high (VH)
0.60–0.79	High (H)
0.40–0.59	Moderate (M)
0.20–0.39	Low (L)
0.00–0.19	Very low (VL)

faces were predominantly intermediate. Table 3 shows that fragments, foam, and pellets appeared in greater quantities, compared to fibers and films. The same table also shows that the highest proportions of this material were found mainly in P1 (highest points of the beach profile), gradually decreasing to P4 (close to the waterline) (Table 3).

Among the 128 collection points, the majority of the 1026 MP items found consisted of fragments (42 %) and foam (35 %), with pellets, fibers, and film representing 20 %, 3 %, and 0.3 %, respectively. Fig. 3 shows the distribution of the standardized MP rankings across the study area. Low (L) and very low (VL) MP concentrations were detected on beaches across all coastal compartments. In contrast, very high (VH) concentrations were predominantly found on beaches located in compartments C2 and C3 (PIT-B and ITA), with high (H) and moderate (M) concentrations identified in C4 and C1 (BOR and IC-D), respectively.

The X^2 statistical test indicated statistically significant associations ($p < 0.05$) between the presence of all types of MPs and the specific compartments in which they were found, except for film ($p = 0.6885$). The CA revealed a clear dependency relationship (ASR ≥1.96) between high (H) and very high (VH) MP concentrations and compartments C2 and C4, respectively. On the other hand, moderate (M), low (L), and very low (VL) concentrations were observed in C1, C4, C3, and C5, respectively (Fig. 4a). No significant relationship was found between the MP concentration and C6.

The concentration of pellets significantly varied between the compartments. Very high (VH) concentrations of pellets were significantly associated with beaches in C2 and C3 (Fig. 4b). Significant associations were found between high (H) and very low (VL) concentrations of pellets at C1 beaches, with VL also found at C5. Moderate (M) concentrations were associated with beaches in C3 and C4, whereas low concentrations were significantly associated only with beaches in C6 (Fig. 4b). Considering fragments, no significant association was found for VH concentrations, whereas H concentrations showed a significant relationship only with beaches in C3 (Fig. 4c). Moderate concentrations of fragments were significantly related to beaches in C2 and C4, with low concentrations associated with C3. Very low (VL) concentrations were significantly related to C1, C5, and C6. The presence of fibers was not significantly related to beaches in C5 or C6. Moreover, the VH and VL concentrations were associated with beaches in C2 and C3, respectively, and moderate (M) concentrations were associated with beaches in C1 and C4 (Fig. 4d). Similar to fibers, the presence of foam had no significant relationship with C5 or C6. Significant associations were found between VH foam concentration in C4, M in C2 and C3, and VL in C1 (Fig. 4e). The film concentration did not display significant dependency relationships with any compartment, although C3 presented the highest ARS values (Fig. 4f).

3.2. Associations between morphometric variables and microplastics

The X^2 test revealed statistically significant associations between beach slope (tanβ $p = 2.2239E\text{-}07$), aspect ($p = 1.1805E\text{-}06$), altitude ($p = 0.0016$), and MP concentration. Dependency relationships were identified between high MP concentrations and a southerly beach aspect (the slope faces the S quadrant). In contrast, low MP concentrations (L) were associated with an easterly beach aspect (Fig. 5a). Very high and moderate MP concentrations were significantly related to beach slopes classified as intermediate (0.05 < tanβ <0.12), with low concentrations associated with gentler beach slopes (tanβ <0.05), as illustrated in Fig. 5b.

Table 3
Absolute and percentage values of items sampled collectively for each corresponding position across all collection points.

Point	Pellet	Fragment	Fiber	Foam	Film	Total	%
P1	70	105	9	167	0	351	34
P2	59	133	7	69	2	270	26
P3	51	86	3	80	0	220	22
P4	26	103	7	48	1	185	18

The analysis of ASR values indicated that very high MP counts along the beach profile were significantly related to high and very high altitudes (Fig. 5c), reflecting strandlines along the upper parts of the beach profile (2.06 m to 2.62 m above mean sea level). Conversely, very low MP concentrations were associated with very low altitudes (<1.90 m), suggesting strandlines along the lower part of the beach profile.

The results from the X^2 tests revealed that different MP types were more likely to be found at specific beach elevations, with significant associations ($p < 0.05$) found between altitude levels and pellets ($p = 1.6604E\text{-}10$), fragments ($p = 0.0003$), fibers ($p = 0.03677$), foam ($p = 5.69E\text{-}08$), and film ($p = 0.04353$). Very high pellet concentrations were associated with very high altitudes (the upper beach), whereas low and moderate concentrations were significantly more prevalent at low and moderate altitudes (Fig. 6a). High and very high concentrations of fragments were significantly associated with moderate altitudes (Fig. 6b), with concentrations decreasing at higher and lower beach elevations. The concentrations of fragments were very low at the lowest beach elevations, low at both high and low beach levels, and moderate at high and very high altitudes (Fig. 6b). The accumulation of fibers was significantly related only to moderate concentrations and very low altitudes (Fig. 6c). Like fragments, very low concentrations of foam were significantly associated with very low altitudes, and low concentrations were associated with high altitudes (Fig. 6d). However, high and very high foam concentrations were found at the highest parts of the beach rather than at moderate altitudes, as shown for fragments. Finally, very high film concentrations were associated with low altitudes, the only significant relationship found between this type of MP and altitude (Fig. 6e).

3.3. μ-Raman analysis

At the sites where the highest MP concentrations were observed (beach profiles IC-D in C1, ITA in C2, PIT-B in C3, and BOR in C4, Fig. 3), the μ-Raman analyses indicated that most pellets found on the upper beach were primarily polymers derived from high-HDPE and low-density polyethylene (LDPE), along with other copolymers (Table 4). They were typically found in the form of small spherical or cylindrical granules, with HDPE exhibiting significant Raman peaks at approximately 1130 cm^{-1}, 1295 cm^{-1}, and 1460 cm^{-1} and a density range between 0.941 and 0.965 g/cm^3. LDPE showed Raman peaks similar to those of HDPE, maintaining the same characteristic peaks at 1130 cm^{-1}, 1295 cm^{-1}, and 1460 cm^{-1}, but with subtle differences in the spectral profile and a lower density range (0.910 to 0.940 g/cm^3).

The fragments and fibers predominantly found at moderate altitudes in the beach profile presented the greatest diversity of polymeric material. As they are derived from already industrialized products, these products are commonly found in the form of polymers such as high- and low-density polyethylenes (HDPE and LDPE, respectively), which are identical to the pellets in the Supplementary Files (Raman spectroscopy analysis data), as well as polypropylene (PP) and other copolymers, including ethylene-polypropylene, poly(ethylene-*co*-vinyl acetate), poly (propylene-ethylene-acrylic acids), and high-ethylene random copolymer (RCP) (Table 1). PP was identified in the Raman spectrum by its distinctive peaks at 841 cm^{-1}, 973 cm^{-1}, and 1160 cm^{-1}, with densities ranging between 0.855 and 0.946 g/cm^3.

Like fragments, foam also stood out for its diversity of compounds. These polymers were predominantly identified and classified as polystyrene, polyurethane, and styrene/allyl alcohol copolymers with low molecular weights (Table 2). Moreover, the film primarily featured materials derived from polyethylene (Table 2). Styrene, a base monomer for polystyrene production, exhibited peaks in the Raman spectrum at 1000 cm^{-1}, 1030 cm^{-1}, and 1600 cm^{-1}. The density of polystyrene, a styrene derivative, is approximately 0.91 g/cm^3.

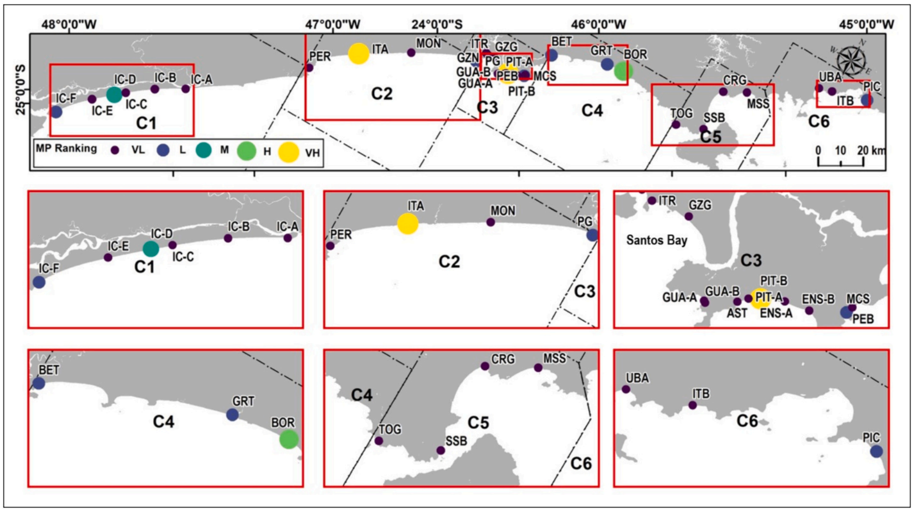

Fig. 3. The AHP-G method generated an MP ranking for the entire coast of São Paulo, emphasizing compartments C1, C2, C3, C4, C5, and C6. The map features circles of varying sizes that represent very high (VH), high (H), moderate (M), low (L), and very low (VL).

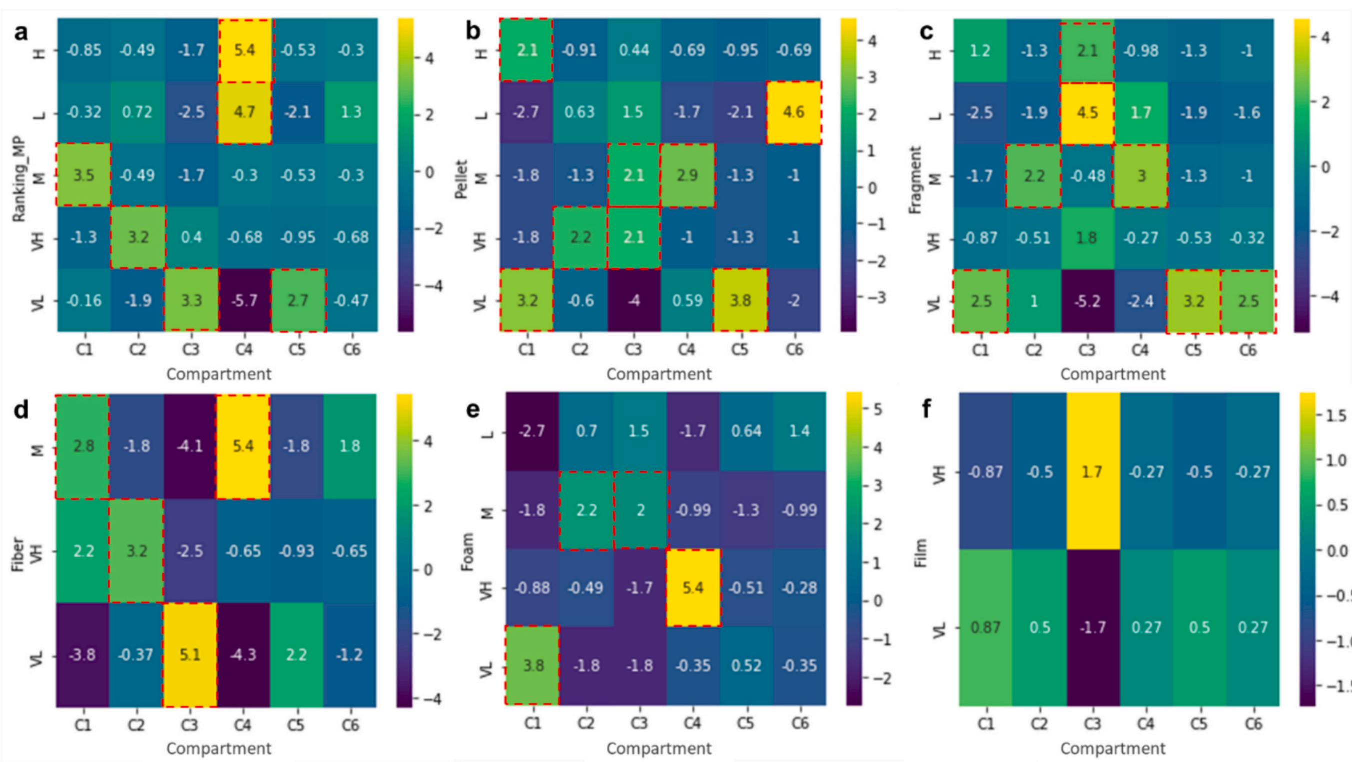

Fig. 4. Matrices showing the adjusted standardized residual (ASR) values between the concentration rankings for MPs (a), pellets (b), fragments (c), fibers (d), foam (e), and film (f) for each compartment (C1, C2, C3, C4, C5, and C6). The dashed red contours indicate variables exhibiting significant dependency relationships (ASR ≥ 1.96). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

4.1. Factors responsible for MP distribution and accumulation along the coast

The MP ranking revealed a distribution starting from the Santos Estuary and Mar Pequeno (São Vicente), initially depositing on beaches near these channels (e.g., sectors C3 and C2) and progressively accumulating as it moved toward the SSW, the same direction as the predominant coastal current in the region (NE-SW) (Tessler et al., 2018) on beaches such as Itanhaém (ITA) and those located on Ilha Comprida (IC-D), in sectors C2 and C1, respectively. Conversely, beaches in sectors C4, C5, and C6 presented the lowest values in the ranking. This suggests that beaches near Santos Bay are the first to be impacted by their proximity to the primary sources of this pollutant, resulting from cities with relatively high population densities, such as Santos and São Vicente, in addition to the Port of Santos and the petrochemical industries in Cubatão. The last two are responsible for the reception and processing of this material (Balthazar-Silva et al., 2020; Ferreira et al., 2021; Turra et al., 2014).

The high population density and industrial concentration, combined with intense port activity, make this region a hub for the dispersion of

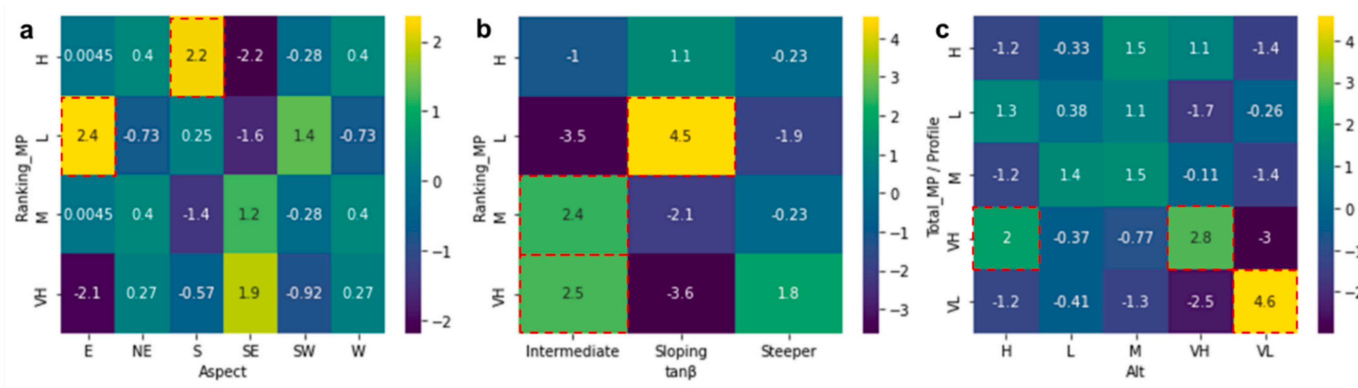

Fig. 5. Matrices showing the adjusted standardized residual (ASR) values between the MP rankings and the orientation of the beach face (aspect) (a), beach slope (tanβ) (b), total MP count per profile and altitude (Alt) (c). The dashed red contours indicate significant relationships (ASR ≥ 1.96). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

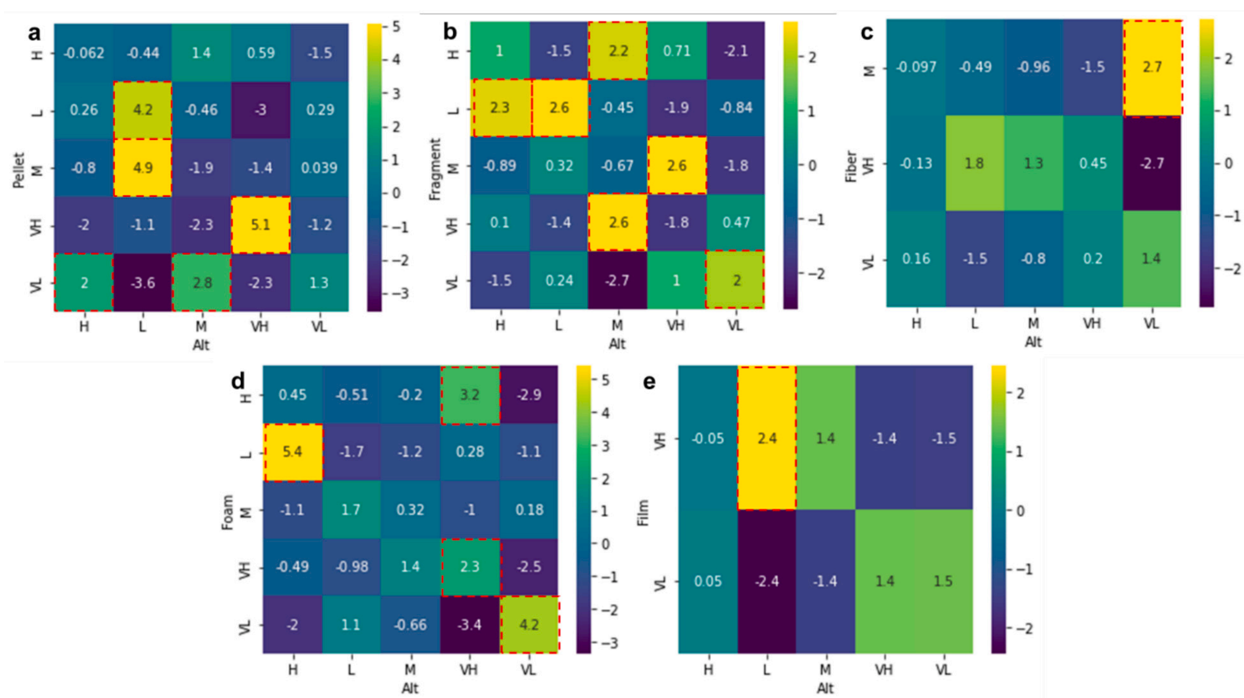

Fig. 6. Matrices of the adjusted standardized residual (ASR) values between altitude (Alt) and the total count of pellets (a), fragments (b), fibers (c), foam (d), and film (e) per profile. The dashed red contours indicate significant relationships (ASR ≥ 1.96). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Main polymers identified by micro-Raman spectrometry at different beach elevations (IC-D, ITA, PI-B, and BOR).

Pellet	Fragment	Fiber	Foam	Film
High- and low-density polyethylene	High- and low-density polyethylene	High- and low-density polyethylene	Styrene	Polyethylene
Poly(ethylene), p-(ethylene-*co*-acrilyc-acid)	Polypropylene		Polystyrene	
	Ethylene-polypropylene Poly(ethylene-co-vinyl acetate)		Polyurethane Styrene/allyl alcohol copolymer low molecular weight	
	Poly(propylene-ethylene-acrylic acids)			

MPs (Jong et al., 2022). Ivar do Sul and Costa (2014) noted that on Brazilian beaches, a high concentration of MPs is correlated with the intensity of port and industrial activities, especially in the Southeast Region. The impacts caused by this pollutant affect, among other factors, marine life through the ingestion of these particles by marine organisms, causing physical and chemical damage, reflecting the severity of the situation (Rochman et al., 2013a, 2013b, 2014).

The results of the analysis of the distribution of MPs across different compartments of the São Paulo coast provide a comprehensive overview of the environmental impact of this pollutant. The applications of AHP-G, the χ^2 test, and CA provided a robust statistical understanding of the distribution of these materials (Ferreira et al., 2023; Pereira et al., 2023; Dos Santos et al., 2021). Although a significant relationship was found between high concentrations of film and low altitudes, indicating that they are commonly found in the lowest portion of the beach or near the waterline, the other analyses did not reveal significant relationships between film and the other studied parameters (aspect, beach slope–tanβ, and altitude). This suggests a possibly distinct distribution of dynamic or emission sources for this type of MP compared with other types of MPs. This observation aligns with research indicating variations in the sources and environmental persistence of these materials (Tiwari et al., 2023).

Pellet and fragment analysis indicated significant dependence on specific compartments, indicating potential point sources of pollution or specific transport and deposition processes for these materials (Barnes et al., 2009; Lebreton et al., 2017). The high concentration of these materials in specific compartments (C3 and C2) underscores the need for more competent handling, transport, and manufacturing management (Tian et al., 2023). For fibers, the observed distribution suggests wide dispersion across different compartments, aligning with studies indicating their release from various sources, including the wear of synthetic fabrics and fishing nets (de Oliveira et al., 2023; Zhang et al., 2022).

The foam results show a high dependency relationship with compartment C4. This observation may be attributed to the specific characteristics or sources of this material near this compartment. On beaches, foam is commonly associated with waste from fishing materials or insulated containers for storing beverages and/or food, which are typically used by merchants and/or beachgoers. When coming from fishing materials, these residues, which are light and bulky, are easily transported by water, especially by waves, and tend to be deposited in the lowest parts of the beach profiles, where the wave energy is insufficient to take them to higher areas (Chen et al., 2022; Zeng, 2023; Ziani et al., 2023). However, although compartment C4 is not as densely populated as C2 and C3 are, the beaches receive many visitors on weekends and holidays. These beaches do not frequently undergo mechanical cleaning. As a result, waste from insulating containers for storing beverages and/or food tends to accumulate in the higher portions of beaches, which are commonly used by visitors (da Silva et al., 2022, 2018, 2015; Zamora et al., 2021).

With respect to morphometric variables, the results of the analysis and their relationships with MP concentrations on beaches provide a relevant understanding of the distribution of this pollutant on the São Paulo coast and in coastal environments. The χ^2 test and ASR analysis revealed statistically significant associations between the physical characteristics of the beaches and the presence of MPs, which aligns with previous studies that highlighted the influence of geomorphological factors on the accumulation of marine debris (Ferreira et al., 2021; Hidalgo-Ruz and Thiel, 2013).

The relationship between beach slope (tanβ) and the concentration of MPs suggests that beaches with intermediate slope profiles are generally more prone to accumulate higher concentrations of MPs. This may be due to sediment and debris transport and deposition dynamics on these profiles (Andrady, 2011; Ferreira et al., 2021). Beaches with a dissipative trend (tanβ <0.05) have lower concentrations. The flatter and lower profiles favor beach washing during high tides and, consequently, the fluctuation of MPs back into the coastal current (Cooper and McLaughlin, 1998; Ferreira et al., 2021). The orientation of beaches (aspect) is also significantly related to the concentration of MPs (Vito et al., 2022). Beaches facing the southern quadrant exhibit relatively high concentrations in the same direction as the high-energy storm waves (Ferreira et al., 2021; Young and Elliott, 2018) from this direction. According to Ferreira et al. (2023), beaches with this orientation on the São Paulo coast naturally accumulate sediments and marine litter.

With respect to altitude, the observed association between higher altitudes and higher MP concentrations can be attributed to the deposition of debris caused by high-tide processes combined with storm events, which deposit material in higher areas of the beach (Álvarez-Hernández et al., 2019; Ferreira et al., 2021; Lavers and Bond, 2017; Schmuck et al., 2017; Young and Elliott, 2018). The distributions of pellets, fragments, fibers, foam, and film with respect to altitude reinforce the idea that different types of MPs have distinct distribution dynamics, possibly influenced by their physical characteristics and sources of origin (Hidalgo et al., 2012).

Based on the analyzed parameters (aspect, tanβ, and altitude), it is possible to state that intermediate beach profiles facing South and locations with higher coastline stability and/or accretion are more susceptible to MP accumulation, therefore representing potential hotspots. This is due to the ~90° angle between storm waves formed by cold fronts coming from the South, resulting in small longshore sediment transport rates, favoring the accumulation of sediments and anthropogenic debris, including MPs (Ferreira et al., 2023, 2021; Harris, 2020; Jong et al., 2022; Laurino et al., 2023; Stein and Siegle, 2019). This indicates that the relative stability at some beaches can favor such deposition (Veerasingam et al., 2020), as observed in those associated with slow accretion processes, such as sandy spits and areas protected by tombolos in compartments C1 and C3, respectively (Ferreira et al., 2023; de Mahiques et al., 2016; Mascagni et al., 2018; Silva et al., 2021).

Owing to the configuration of the São Paulo coastline (SW-NE), beaches facing SE are more susceptible to erosive processes, as the acute angle (~45°) of incidence of storm waves (South) can reach up to 4.0 m (de Andrade et al., 2019; Ferreira et al., 2023, 2021; Stein and Siegle, 2020, 2019) during the austral autumn and winter (April to September), favoring maximum sediment transport capacity (Lavenère-Wanderley and Siegle, 2019; Pianca et al., 2010; Sousa et al., 2013; Stein and Siegle, 2020, 2019). On erosive beaches, sand removal can expose buried layers containing MPs, increasing their availability in the marine environment (Ranjani et al., 2022; Sun et al., 2021; Wang et al., 2021).

In this context, the seasonal incidence of storms and extreme events (increasingly frequent) on the São Paulo coast (Gramcianinov et al., 2023; Nunes et al., 2018) may alter MP dynamics. During storms, the resuspension and redistribution of sediments can increase the mobility of this pollutant (Cheung and Not, 2023). Harris et al. (2021) and Lebreton et al. (2017) emphasized that estuaries are significant vectors for transporting MPs to the sea and are influenced by urbanization and human activities. Thus, areas near river mouths and estuarine channels, such as those in Santos, São Vicente, and Bertioga, are critical points for the entry of MPs into the ocean.

4.2. Polymer diversity and microplastic accumulation

The diversity of polymers found in fragments and fibers, including PE, PP, and various copolymers, suggests a variety of pollution sources. These materials are often derived from already industrialized and discarded products, reflecting the widespread use of plastics in modern society and the inadequacy of waste management systems (Gao et al., 2022; Geyer et al., 2017). The identified foam and film, which are composed mainly of styrene and other polymers, such as polystyrene and polyurethane, are consistent with the literature, highlighting the presence of these materials in marine environments. The former (styrene and polystyrene) are commonly used in packaging and thermal insulation applications because of their lightness and resistance. Polyethylene, which is widely used as the primary material in the manufacture of plastic bags and packaging, represents one of the most significant sources of MP pollution in the marine environment (Gao et al., 2023; Gunawan et al., 2022; Katsara et al., 2022).

The accumulation of pellets in the higher portions of beach profiles is a phenomenon that can be attributed to a combination of physical and geomorphological factors (Ferreira et al., 2021). The spherical or cylindrical shape and relatively low density (0.910 and 0.965 g/cm^3, respectively) of these pellets play crucial roles in their deposition and distribution on beaches. This enhances the transport of these microplastics by ocean currents and, specifically, their mobilization by high-energy waves and winds. When high-energy waves strike beaches, particularly during high tides and storm events, these microplastics are driven to the upper sections of the beach profiles. Moreover, the spherical or cylindrical shape of the pellets reduces friction with the sand and other beach materials, facilitating wind transport through rolling and/or saltation. Once in the higher areas of the beach profile, these MPs tend to be retained due to the decreased energy of these factors (waves, winds, and tides), where they end up depositing and accumulating (Alvarez-Zeferino et al., 2020; Ferreira et al., 2021; Ryan et al., 2009).

In contrast to pellets, fragments and fibers often exhibit faceted or irregular shapes, influencing their transport dynamics and deposition on beaches. These irregular shapes increase resistance to movement in this environment, limiting their ability to be transported to higher beach areas, especially under the influence of less intense winds and waves (de Oliveira et al., 2023; Lefebvre et al., 2023; Zhang et al., 2022). Furthermore, the density of these MPs, which is generally greater than that of pellets, also contributes to their accumulation in the middle regions (P2 and P3) of the beach profile. Fragments and fibers tend to settle where wave and current energy diminish, but is still sufficient to mobilize them. This intermediate zone of the beach profile typically corresponds to a balance between areas reached by high tides and the extent of significant aeolian transport (Andrady, 2011; Ferreira et al., 2021; Jambeck et al., 2015a, 2015b).

The accumulation of expanded foam and plastic film at relatively high concentrations in the lower parts of the beach profiles (P4, primarily, and P3) can be attributed to the specific characteristics of these materials and the environmental dynamics of beaches. Foam, which is commonly composed of polystyrene and polyurethane, has a cellular structure that endows it with low density and high buoyancy (Auta et al., 2017; Gao et al., 2023). This low density allows foam to be easily transported by water, particularly by waves. However, its voluminous structure and lightness contribute to these materials being deposited in the lower parts of beach profiles, where wave energy is insufficient to carry them to higher areas. In contrast, plastic film is generally thin and flexible, facilitating its movement by wind and wave action. Nevertheless, its flat shape and larger surface area relative to its weight mean that it is easily trapped in the lower beach areas (P4), where the wind and wave energy are lower. Additionally, plastic film can become entangled with natural debris or adhere to moist sand, reducing mobility (Andrady, 2011; Barnes et al., 2009; Browne et al., 2011; Martin et al., 2017; Rochman et al., 2013a, 2013b; Thompson et al., 2004).

5. Conclusions

This study provides a comprehensive examination of the distributions of various types of MPs (categories: pellets, fragments, fibers, foam, and film) along the São Paulo coastline, considering morphometric characteristics (beach-face orientation, aspect, slope, tanβ, and altitude) and meteo-oceanographic conditions. We revealed a complex pattern in the dispersion and accumulation of MPs. Robust statistical analyses, including AHP-G, the X^2 test, and correspondence analysis (CA), identified statistically significant associations between MP presence and specific geographic compartments and morphometric variables of the beaches.

Notably, the highest concentrations of MPs were found predominantly on beaches in compartments C3 and C2, suggesting a direct influence of proximity to urban and industrial sources, such as the Santos Estuary and Mar Pequeno. Different types of MPs, including pellets, fragments, fibers, and foam, exhibit distinct patterns of dependency on these compartments, reflecting potential differences in emission sources, transport, and deposition processes. The relationships between environmental characteristics and MP accumulation dynamics were comprehensively understood. Higher altitudes were associated with elevated MP concentrations, indicating a significant role of high tide processes and storm surges in depositing debris in higher beach areas.

μ-Raman spectroscopy showed a predominance of polymers such as polyethylene (PE) in high- and low-density forms, polypropylene (PP), and styrene, underscoring the significant contribution of industrialized and consumer products to MP pollution. This study identified locations susceptible to MP accumulation (hotspots) along the coastline via remote sensing data and morphometric analyses. These hotspots are often associated with intermediate beach profiles facing the southern quadrant and areas with greater stability or shoreline accretion, where aggradation processes favor the accumulation of anthropogenic debris, including MPs.

These findings highlight the complexity of MP dynamics in coastal environments and emphasize the importance of considering the physical characteristics of beaches, MP diversity, and local human activities to understand and manage this type of emergent pollution. For example, the variability in MPs and their relationships with different beach shapes highlight the need for differentiated management approaches tailored to the specific characteristics of each coastal compartment and pollutant type. Therefore, identifying areas prone to MP accumulation is crucial for developing specific monitoring and environmental remediation strategies.

However, this study has its limitations. The samples were collected only once over six months during the cold-front period, not accounting for temporal variability due to seasonal changes, sediment composition, sedimentary processes, or human activities, which could provide new interpretations of the data. Additionally, the sampling depth was limited to the top ~2 cm of a 1 m^2 area, potentially not reflecting the entire topographic profile of the beach and the more stable, deeper sediment layers. The absence of detailed information on human activities, urbanization, and industrialization also limits understanding of the direct impact on MP distribution.

Future studies linking these results with data derived from orbital remote sensing could generate models capable of predicting and synoptically expanding all these aspects. Understanding all these distribution patterns is essential for correct coastal management concerning this matter along the São Paulo coast and other similar coastal regions. Nevertheless, the present work contributed to achieving Sustainable Development Goal 14 (Life Below Water), specifically targeting Goal 14.1 — to prevent and significantly reduce marine pollution, particularly from land-based activities, including marine debris (Indicator 14.1.1 — density of plastic debris) by 2025 — and Goal 14.a, which seeks to enhance scientific knowledge, develop research capacities, and transfer technology to improve ocean health (https://sdgs.un.org/goals/goal14).

CRediT authorship contribution statement

Anderson Targino da Silva Ferreira: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Niklaus Ursus Wetter:** Writing – review & editing, Writing – original draft, Validation, Software, Resources, Methodology, Funding acquisition, Formal analysis. **Maria Carolina Hernandez Ribeiro:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Formal analysis, Conceptualization. **Luciana Slomp Esteves:** Writing – review & editing, Writing – original draft, Supervision, Methodology. **António José Guerner Dias:** Writing – review & editing, Writing – original draft, Validation. **Carlos Henrique Grohmann:** Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Formal analysis. **Maria Kuznetsova:** Writing – review & editing, Writing – original draft, Formal analysis. **Anderson Freitas:** Funding acquisition. **Regina Célia de Oliveira:** Writing – review &

editing, Writing – original draft, Visualization, Resources. **Eduardo Siegle:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, Conceptualization.

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 table <https://doi.org/10.5281/zenodo.12193104>
- Raman spectroscopy analysis <https://doi.org/10.5281/zenodo.12193201>.

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