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Baseline

A multidriver assessment of beach litter accumulation rates

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A R T I C L E I N F O

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A B S T R A C T

Anthropogenic marine litter poses ecological and economic risks to coastal environments, and its accumulation dynamics remain poorly understood at precise spatial and temporal scales. Most studies lack high-frequency data and rarely consider variations between beach use zones. Therefore, we investigate how social and environmental factors influence the daily accumulation rates of anthropogenic marine debris in different use zones of a tourist beach in Jericoacoara National Park, a conservation unit in Brazil's northeast. Sampling was conducted for one full week each month, from July 2022 to June 2023, across three distinct user zones. Two hierarchical generalized additive models (HGAMs) were applied to test the influence of monthly rainfall and number of monthly tourists on zonal daily litter accumulation rates. A total of 22,375 litter items were recovered, with average daily accumulation rates (1.77 items.m^{-1}.day^{-1}) peaking during the tourist season. The accumulation varied notably between zones, with the most impacted site reaching nearly triple the rates of the other sites. Cigarette butts emerged as the most abundant item (average = 0.95 items.m^{-1}.day^{-1}), followed by metals (0.24 items.m^{-1}.day^{-1}), paper (0.20 items.m^{-1}.day^{-1}), hard plastics (0.16 items.m^{-1}.day^{-1}) and flexible plastics (0.13 items.m^{-1}.day^{-1}). Modeling revealed that litter accumulation patterns were significantly shaped by temporal dynamics, followed by zonation, the number of visitors, and rainfall regimes. These findings highlight the interplay between human activity and environmental factors in driving litter accumulation on urban beaches, offering key insights for targeted coastal management strategies.

Beaches are environments that provide many ecosystem services, supporting diverse biological communities (Harris and Defeo, 2022). They also provide many benefits to society, such as recreation and economic activities (Rangel-Buitrago et al., 2020). However, beaches are subjected to human pressures, including urban development, population growth, poor waste management and tourism, and global climate changes (Bettim et al., 2021). The management of beaches is a theme of concern around the world, mainly in terms of anthropogenic pollution.

Marine anthropogenic litter (MAL) can be defined as any solid material discarded or disposed of in marine and coastal environments (UNEP, 2009). In addition, persistent materials such as plastics accumulate unevenly across coastal areas as a function of human pressure, land-based inputs, and hydrodynamic conditions, reinforcing spatial

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heterogeneity in ecological risk (Özşeker et al., 2024, 2025) MAL generates many ecological impacts on marine ecosystems altering ecological function structures, smoother benthic communities, modify food-web dynamics, and can release toxic substances, thereby, impacting negatively ecosystem functioning (Erüz et al., 2022). Litter also poses direct hazards to wildlife through entanglement, ingestion, and physical obstruction, contributing to biodiversity loss and long-term ecological degradation (Costa et al., 2022). Economic expenditures with cleaning efforts are also factors of negative impact (Cruz et al., 2020). Additionally, beaches may act as sinks for MAL, accumulating large amounts of litter in the backshore zone derived from marine-based activities, such as fishing and commercial ships, and land-based activities, such as tourism and freshwater discharges (Garcés-Ordóñez et al., 2020; Olivelli et al., 2020; Adam, 2021; Chassignet et al., 2021; Ryan, 2023; Brabo et al., 2024).

Although MAL is ubiquitous on sandy shores worldwide, most studies have a limited temporal scope and often focus on single beach zones (Serra-Gonçalves et al., 2019; Guerrero-Meseguer et al., 2020). Coastal litter management depends on indicators capable of linking land-use patterns and beach usage with litter accumulation (Baccar Chaabane et al., 2024). In Brazil, Ribeiro et al. (2026), applied the clean coast index - CCI (Alkalay et al., 2007) on three different zones of a remote beach classifying the area as *clean* during all study period, except in one zone, which was rated as *moderate* in autumn and summer, concluding that the origin debris is likely allochthonous influenced by wind and waves dynamics, pointing out that the coastal management must take into account upstream sources, environmental factors, and local socioeconomic activities. Yet, litter abundance and composition are highly dynamic, vary strongly across short temporal scales and between distinct beach-use zones. This spatiotemporal complexity is not captured by infrequent or generalized surveys (Burlat and Thorsteinsson, 2022; Soliveres et al., 2024).

When monitoring ignores spatial and temporal heterogeneity, management actions, such as cleaning frequency, bin placement, or awareness campaigns, are often mistimed or misplaced (Lange et al., 2020; UNEP, 2021). As a result, resources are wasted and conservation goals are weakened, especially in heavily visited tourist beaches.

As a result, methodological constraints combined with the high costs of sustained monitoring make it difficult to evaluate the effectiveness of measures aimed at mitigating the negative impacts of MAL (Smith and Markic, 2013; Galgani et al., 2015). To address these challenges, Thiel et al. (2021) recommended the implementation of daily litter surveys, which allow for the determination of arrival rates with high temporal resolution. Consequently, when the goal is to infer trends in coastal litter accumulation or to assess the performance of management strategies, ensuring consistency in sampling frequency is essential (Ryan et al., 2014).

These shortcomings also have policy implications. Ongoing negotiations of the Global Plastics Treaty (UNEP, 2025) and integrated coastal zone management strategies highlight the need for high-resolution, site-specific data to guide decision-making. Linking daily accumulation patterns with local drivers therefore provides evidence that is directly relevant for both coastal managers and international frameworks.

In this context, our research is guided by the following question: What is the relative influence of environmental and social drivers on the spatiotemporal dynamics of daily marine litter accumulation in distinct beach-use zones? To answer this, we assessed the spatial and temporal patterns of daily MAL accumulation on a resort beach type (Micallef and Williams, 2004; Micallef and Williams, 2009) located inside the Jericoacoara National Park (Brazil). As the country's third most visited park, with more than 1.4 million visitors in 2024 (Agência Gov, 2025), it offers a highly relevant setting for researching the interaction between intense tourism and coastal conservation. To achieve this, we applied hierarchical generalized additive models (HGAMs) to estimate the effects of environmental and social factors, and their interactions, on litter accumulation dynamics.

The surveys were conducted in Jericoacoara National Park (Fig. 1), a conservation unit in the northeast region of Brazil. Created in 2002, the park covers approximately 8850 ha of a coastal landscape recognized for its ecological and aesthetic value. The rainfall regime in the region is tropical semiarid, with the rainy season concentrated in the first half of the year (90 % of the annual rainfall) (Meireles, 2011). The present study was conducted on the principal beach of the park, which is located in Jericoacoara village and attracts the greatest number of tourists visiting the park.

To investigate the variations in litter accumulation rates on beaches with different types of tourist activity, we divided the main beaches of Jericoacoara village into three zones on the basis of their use (Fig. 1): (Z1) an area popular for sports, such as windsurfing and surfing; (Z2) a section concentrated with restaurants, beach stalls, and carts serving freshly made drinks; and (Z3) a quieter zone frequented only by pedestrians and beachgoers. Each zone was 50 m wide, and the sampling occurred from the waterline to the highest strandline, which was the vegetation line or restaurant in the backshore zone. The sampling was conducted once a month for a full week over 12 months, from July 2022 to June 2023, beginning on a Sunday and ending the following Sunday. The first sample of each week was excluded to avoid atypical initial variations and ensure consistency throughout the week; therefore, valid samples were collected from Monday to Sunday. To prevent variability associated with tidal height, we performed all monthly surveys during the same moon phase, and these collections took place in the late afternoon (between 4:00 pm and 5:00 pm) to ensure efficiency and punctuality. The same collection and sorting team, previously trained, carried out the campaigns throughout the study period and was composed of employees from the Chico Mendes Institute for Biodiversity Conservation (ICMBio), which manages the park. All macrolitter, items larger than 2.5 cm in diameter (Garcés-Ordóñez et al., 2025), were collected and placed in bags. In the laboratory, each item was weighed and classified by material type (plastic, glass, manufactured wood, metal, etc.); however, some types with specific uses and compositions, such as cigarette butts, polystyrene, latex, rubber, nylon and ropes, were classified individually to avoid misinterpretation and to better represent their environmental relevance.

The daily accumulation rates of the litter were calculated in items. $m^{-1}.day^{-1}$ for the beach, beach zones and litter types (Thiel et al., 2021). Each sample corresponded to a 50 m transect collected in one day. Thus, for every sampling event, the accumulation rate was obtained by dividing the number of items recorded in the transect by its length (50 m):

$$\text{Accumulation rate} = \frac{N}{50}$$

where N is the number of items collected in each transect. Beach, zone and types of litter values represent the arithmetic mean of the transect rates across study period.

Hierarchical generalized additive models (HGAMs) were applied to assess the influence of multiple factors on daily accumulation rates. The models incorporated (i) environmental variables, such as *monthly rainfall* data obtained from the Ceará Foundation of Meteorology and Water Resources (http://www.funceme.br/); (ii) socioeconomic variables related to tourism in the park, including the *monthly number of visitors* provided by the Finance Department of the Municipality of Jijoca de Jericoacoara; (iii) spatial variables, represented by *beach-use zones*; and (iv) temporal variables, such as *month and week*. Two primary HGAMs were developed, in both, sampling zones and litter type were included as independent random effects. They were not specified as nested or orthogonal; instead, they were modeled as crossed random effects, because each observation belongs simultaneously to a sampling zone and a litter type. The first term the *interaction model*, which includes a smooth tensor product (representing an interaction between months and weekdays) as a fixed effect, with the sampling zone and litter type

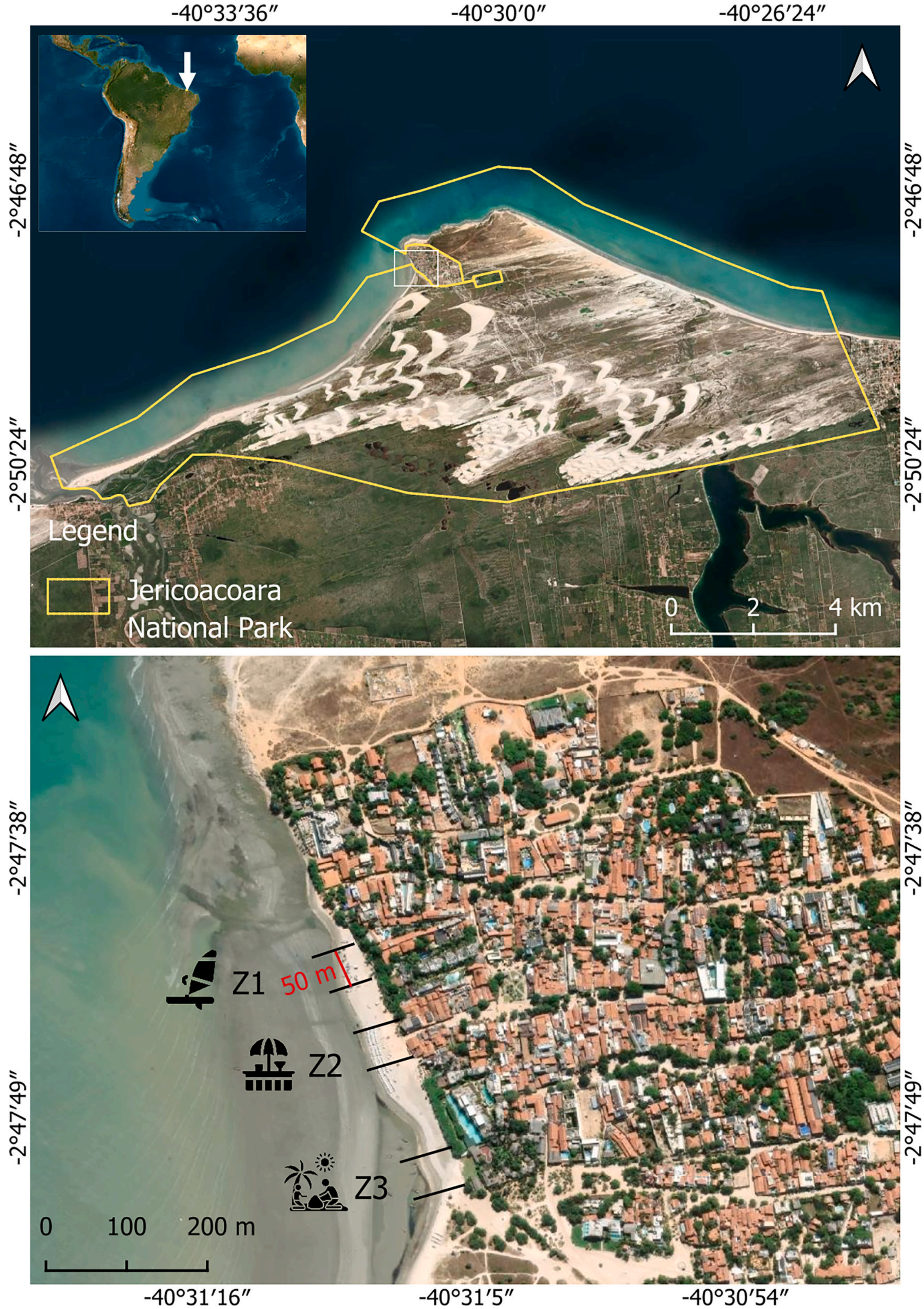

Fig. 1. Jericoacoara National Park (upper panel) with its main beach (highlighted in yellow). The three studied zones (lower panel): Z1 – an area popular for sports such as windsurfing and surfing; Z2 – a section concentrated with restaurants, beach stalls, and carts serving freshly made drinks; and Z3 – a quieter zone frequented only by pedestrians and beachgoers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

included as random effects. This model was designed to detect temporal patterns and potential seasonal–weekly interactions. The second model, referred to as the *mechanistic model*, retained the same random effect structure but replaced the interaction term with separate smooth functions for rainfall, visitors, and weekdays. This allowed for the disentanglement of individual environmental drivers influencing litter accumulation. Both models were also applied to the five most abundant litter categories to evaluate whether different materials respond differently to the modeled factors. In these category-specific models, the random effect for litter type was omitted. In all cases, the daily accumulation rates were log-transformed, and a Gaussian distribution was assumed. Thin plate regression splines (TPRS) were used as a smoothing basis, with the number of basic functions (k) set to three for continuous variables. All analyses were conducted in R (R Core Team, 2024) via the mgcv package (Wood, 2012) for HGAM implementation.

A total of 22,375 MAL items, weighing 82.22 kg, were collected throughout the sampling year. The annual mean daily accumulation rate was 1.77 items.m^{-1}.day^{-1}, with a minimum value of 0.02 and a maximum of 11.26 items.m^{-1}.day^{-1}. Finally, Z2 presented an average accumulation rate of 3.46 items.m^{-1}.day^{-1} greater than that of Zone Z1, with 1.22 items.m^{-1}.day$^{-1,}$ and that of Zone Z3, with 0.64 items.m^{-1}.day^{-1}.

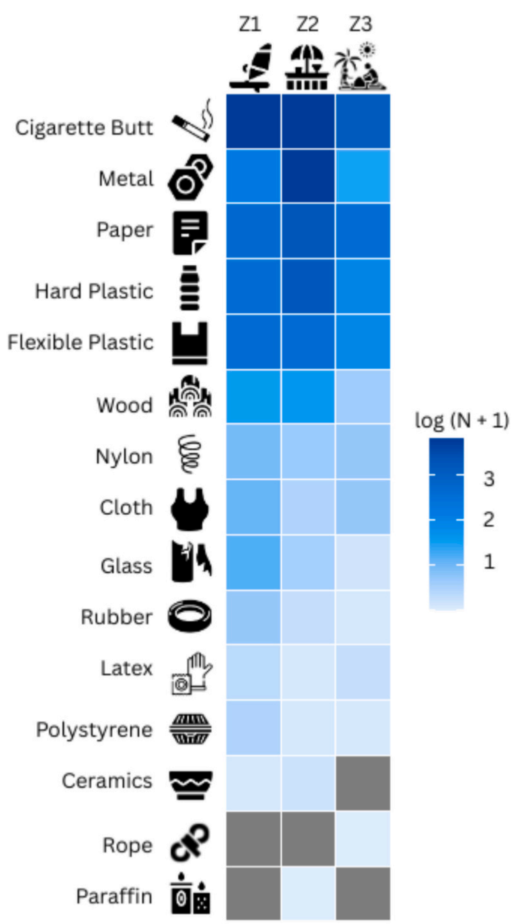

Fig. 2. Graphical representation of marine litter composition by type in each sampling zone (Z1; Z2; Z3). The color composition of the squares is proportional to the logarithm of the number of items recorded (N): log(N). By adding 1 to N, we ensure that the minimum value to be transformed is log(0 + 1) = log (1) = 0. This allows zero counts to be mapped to a finite value (zero), which is represented in the graph by the gray color (type do not sampling in that zone) on the log(N + 1) scale, allowing the absence of the type of litter that was not sampling in that zone. This transformation is applied to reduce the range of values across different litter types, allowing better visualization of the relative differences between categories even in the face of very unequal contributions.

A wide variety of MAL were recorded daily during the study period (Fig. 2). The majority of items appear to have a local origin, most likely from land-based sources, as the prevailing winds on the studied beach winds blow offshore (0–180° relative to the coastline), which reduces the likelihood of marine litter being transported from the ocean to the beach (Turrell, 2018; Forsberg et al., 2020; Brabo et al., 2022). Cigarette butts were the most abundant item, with an average accumulation rate of 0.95 items.m^{-1}.day^{-1} (range: 0.02–7.00 items.m^{-1}.day^{-1}), followed by metals with 0.24 items.m^{-1}.day^{-1} (range: 0.02–1.82 items.m^{-1}.day^{-1}), which were predominantly composed of crown caps (80 %) and beverage cans (9.4 %). Paper items accounted for 0.20 items.m^{-1}.day^{-1} (range: 0.02–1.48 items.m^{-1}.day^{-1}), with paper straws representing 51.5 % of this category. Less abundant, hard plastics accumulated at a rate of 0.16 items.m^{-1}.day^{-1} (range: 0.02–1.08 items.m^{-1}.day^{-1}), mainly represented by bottle caps (57.1 %), whereas flexible plastics accounted for 0.13 items.m^{-1}.day^{-1} (range: 0.02–0.96 items.m^{-1}.day^{-1}), with disposable food packaging comprising 45.5 % of this group. Other materials, such as glass, wood, polystyrene, rubber, rope, ceramics, paraffin, cloth, and nylon, presented lower occurrence rates, each contributing less than 0.02 items.m^{-1}.day^{-1} throughout the study.

The interaction model considering total MAL and the five most common MAL types revealed that daily accumulation rates were significantly influenced by nonlinear interactions between days and months (effective degrees of freedom – edf = 6.12; $p < 0.05$). Lower accumulation rates occurred predominantly during the early months of the year, whereas higher rates were observed from the middle to late months of the year. Minor changes were observed across weekdays (Fig. 3). In this way, the mechanistic model indicated that the effects of different zones were also significant for total litter ($p < 0.05$, Fig. 4). Nonlinear and linear effects were observed for visitors (edf = 1.98; $p < 0.05$; Fig. 5) and rainfall (edf = 1; $p < 0.05$; Fig. 6), respectively. On the other hand, weekdays presented marginal significance with a slightly nonlinear effect in this study (edf = 1.28; $p = 0.0951$). (See Table 1.)

The accumulation rates differed among the litter types, with clear seasonal, weekly, and spatial patterns (Fig. 3). Cigarette butts presented lower rates between February and May and higher rates from October onward, with little variation across weekdays ($p = 0.0514$). However, the mechanistic model indicated a strong effect of the beach zone (Fig. 4) and a significant nonlinear influence of the number of visitors (edf = 1.65; Fig. 5). Metals presented lower daily rates from March to June, especially during the middle of the week, and greater accumulation between September and November, mainly on early weekdays (Fig. 3). These factors were also significantly affected by the beach zone (Fig. 4) and by the nonlinear effect of visitors (Fig. 5). Papers showed more pronounced seasonal variation than weekly variation, with rates steadily increasing from April to October (Fig. 3). Significant effects were detected for the beach zone (edf = 1.82, $p < 0.05$; Fig. 4), number of visitors (edf = 1.92, $p < 0.05$; Fig. 5), and precipitation (edf = 1.44, $p = 0.014$; Fig. 6), all with nonlinear effects, indicating complex relationships across gradients. Hard and flexible plastics displayed strong monthly fluctuations and more stable values across weekdays (Fig. 3). The flexible plastics presented smoother patterns between June and November (edf = 2.29), whereas the hard plastics presented greater temporal complexity between August and January (edf = 4.39). For both categories, beach zone had a highly significant effect ($p < 0.05$; Fig. 4), visitor numbers showed a smoothed nonlinear response (edf ≈ 1.9; Fig. 5), and rainfall had a positive, approximately linear effect (edf ≈ 1; Fig. 6).

Daily accumulation studies provide a useful indication of the daily load of MAL reaching beaches, offering insights into local pollution dynamics (Ryan et al., 2014; Ryan, 2020). The values recorded show a wide range, falling within the wide range of daily accumulation rates reported by other studies on continental and island beaches around the world, ranging from nearly zero to over 30 items.m^{-1}.day^{-1} (Fig. 7). Although this variability reflects differences in the intensity of coastal use, extensive studies by beach typology (e.g., urban, remote, village)

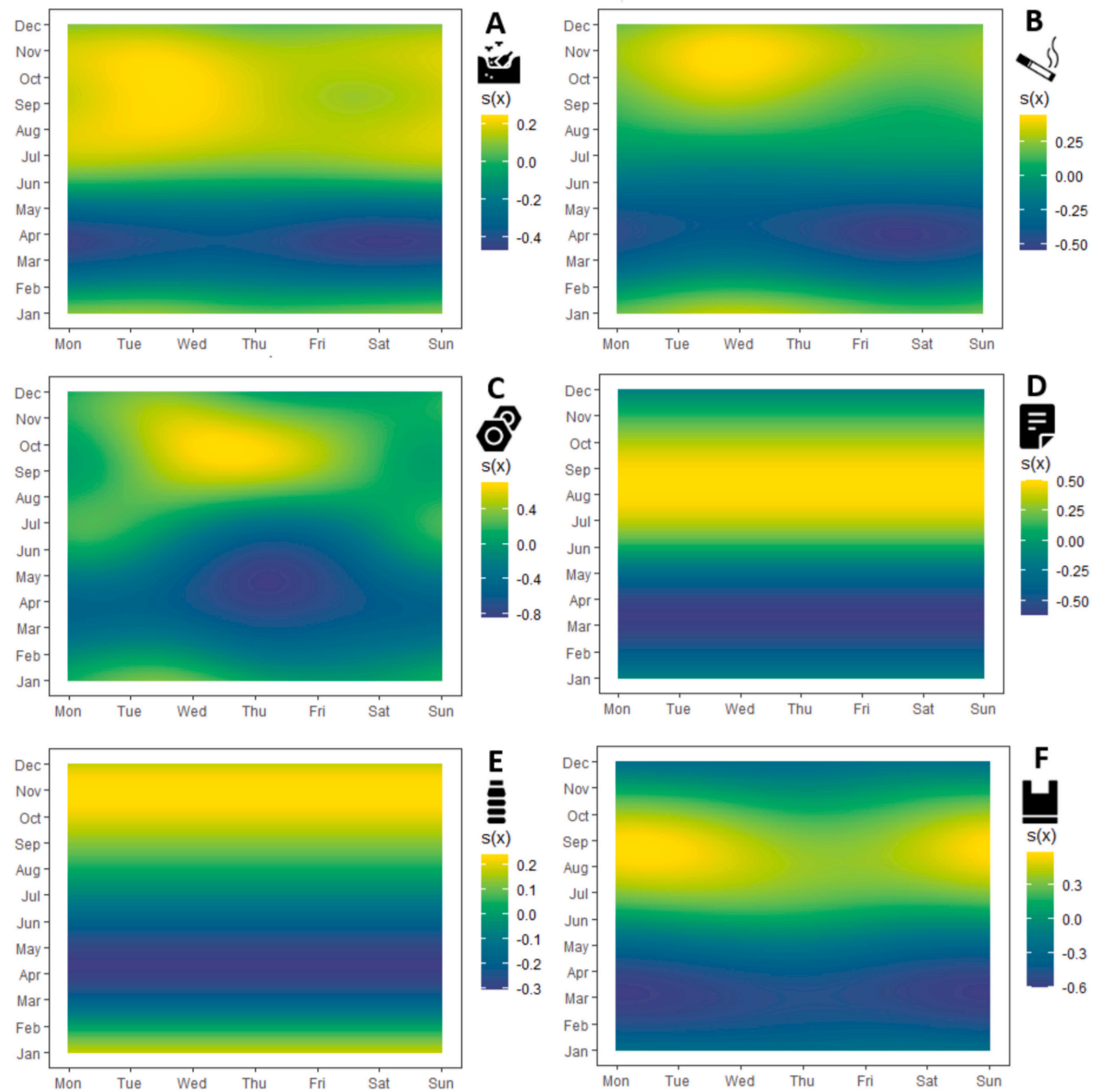

Fig. 3. Effect of interaction between day of the week and month on the daily accumulation rates for the most abundant anthropogenic marine found on the beaches studied: (A) total litter; (B) cigarette butts; (C) metals; (D) paper; (E) hard plastic; and (F) flexible plastic. Values represent s(x), the smooth function estimated by the HGAM, which describes the non-linear effect of the interaction (month × weekday) on the predicted daily accumulation rate. Positive values of s(x) indicate periods with higher-than-average predicted accumulation, while negative values indicate lower-than-average predicted accumulation.

should be developed to obtain the real values of accumulation rates between these locations around world.

Among continental beaches, the highest accumulation was reported in the South Atlantic Ocean at Cape town, South Africa (Chitaka and von Blottnitz, 2019), with a maximum of 26.6 items·m^{-1}·day^{-1}, mainly after increasing number of rain events. Our local maximum daily accumulation suggests that peak accumulation events are linked to the high tourism season and the use of beaches and rainfall, as confirmed by our HGAM models. Island beaches also showed notable variation. The highest rates were observed on Mediterranean islands (Grelaud and Ziveri, 2020), reaching 32.9 items.m^{-1}.day^{-1}, likely due to intense recreational tourism activities. In contrast, remote Heard and Maquire islands in the Austral Ocean (Eriksson et al., 2013) recorded near-zero values, underscoring the role of long-range oceanic transport in isolated areas.

Understanding the drivers behind daily MAL accumulation is key to identifying the relative influence of environmental and anthropogenic factors (Galgani et al., 2015; Willis et al., 2018; Soliveres et al., 2024). The modeling results highlight that temporal patterns and local environmental and anthropogenic factors influence daily litter accumulation

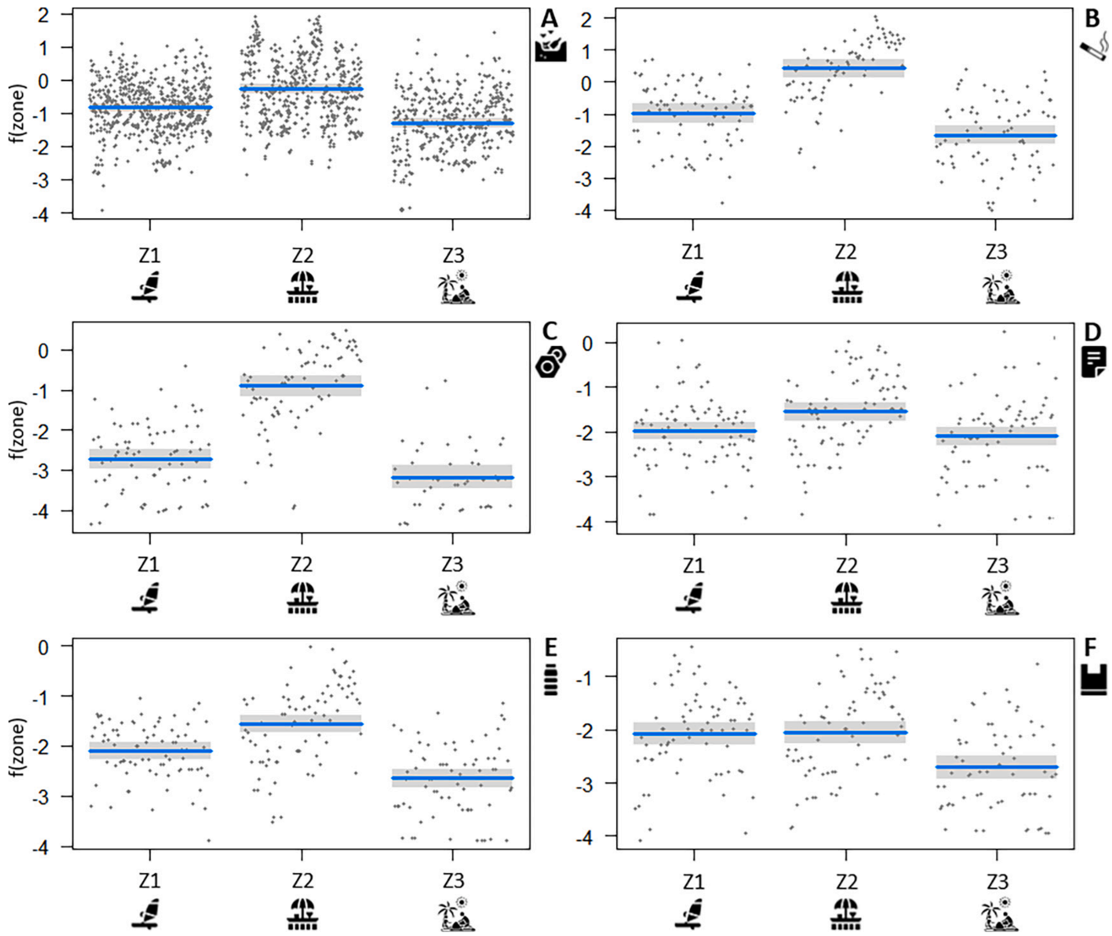

Fig. 4. Partial effect of zones on daily accumulation rates, estimated via HGAMs for total (A) all types of litter; (B) cigarette butts; (C) metals; (D) paper; (E) hard plastic; and (F) flexible plastic. The x-axis shows the monitored beach sectors (Z1, Z2, Z3), whereas the y-axis indicates the smooth function estimate f(zone). The dots represent partial residuals, the blue lines represent the estimated effect, and the shaded areas correspond to 95 % confidence intervals. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

on beaches. While the interaction between weekday and month was significant across all litter categories, the mechanistic models provided a clearer understanding of the specific drivers shaping accumulation dynamics. However, the marginal effects observed for the day-of-the-week interaction with litter and cigarette butt counts indicate that our models were limited using aggregated monthly data for both precipitation and visitor numbers. Consequently, future work would benefit from employing daily precipitation records and a more precise metric for daily beach visitation.

Rainfall seasonality is one of the factors most explored in studies about MAL, and its influence on runoff and remobilization of debris is widely recognized (Guerrero-Meseguer et al., 2020; Orthodoxou et al., 2022; Xu et al., 2024; Berto et al., 2025). The rainy season in our study area extended from December to April, peaking in April with an average rainfall of 276 mm. The significance of this factor for paper, flexible plastics, and rigid plastics is likely due to their propensity to float and be remobilized by rainfall (van Emmerik, 2024). In contrast, cigarette butts are more directly linked to being discarded by tourists than to hydrological processes (Brabo et al., 2022). Similarly, metal objects like bottle caps and cans were unaffected by rainfall, as their weight causes them to remain stable during surface runoff (Valero et al., 2024).

However, the specific uses of beach zones was also a key factor in explaining litter loads. Zone 2 accumulated almost three times more MAL than Z1 and five times more than Z3. The concentration of restaurants, stalls, and services linked to tourism in this zone explains the predominance of items such as cigarette butts, beverage cans, bottle caps, and disposable food packaging. Similar associations between tourism intensity and litter composition have been reported in Jericoacoara (Brabo et al., 2022) and along the Colombian Caribbean (Garcés-Ordóñez et al., 2020).

Cigarette butts presented high daily accumulation rates during the study. It is one of the most common types of anthropogenic litter found in coastal environments and poses an environmental challenge because of its hazardous compounds (Araújo and Costa, 2019a; Araújo et al., 2022). When discarded, cigarette butts can release more than 40 toxic compounds, including polycyclic aromatic hydrocarbons (PAHs), nicotine, phthalates, volatile organic compounds, metals and metalloids (Araújo and Costa, 2019b; Green et al., 2022). Additionally, cigarette butts are considered a potential source of microplastics (MPs), which are estimated to constitute approximately 300,000 tons of plastic microfibers of cellulose acetate and have the potential to enter the aquatic environment annually (Shen et al., 2021; Lian et al., 2024). The improper disposal of butts reflects a general lack of environmental awareness among beachgoers. While effective clean-up efforts play an important role in reducing their presence, they alone cannot fully address the problem (Zielinski et al., 2019). Educational campaigns and regulations on use are important for raising awareness among beachgoers of the health and environmental damage caused by cigarettes (Araújo and Costa, 2021; Mghili et al., 2023).

Plastic items are recognized as the main environmental threat to managing litter pollution in the marine environment (Thushari and Senevirathna, 2020). In the recent discussion of the Global Plastics Treaty to combat plastic pollution through a circular economy where all plastics are responsibly managed during production, use, and disposal

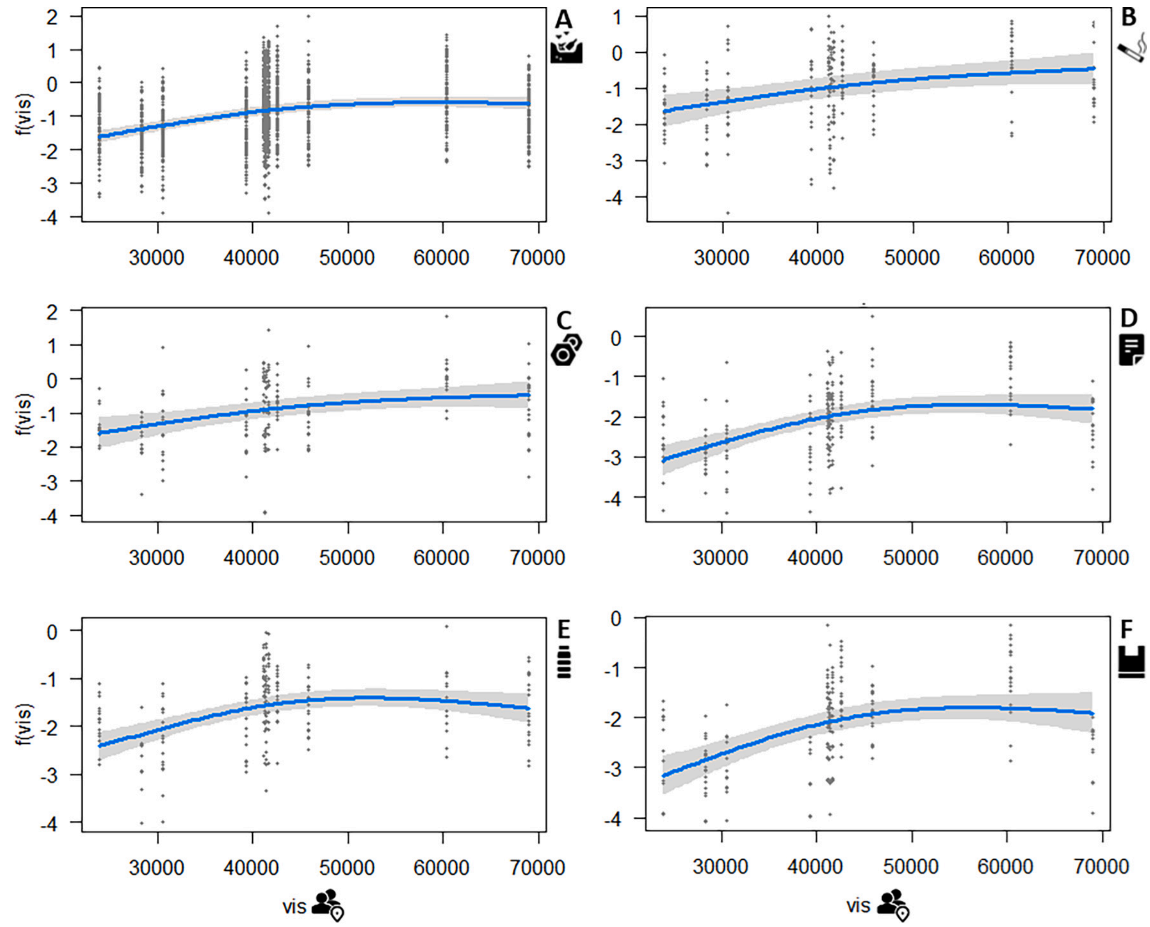

Fig. 5. Partial effect of the number of visitors per month on the daily litter accumulation rate across beaches, based on HGAM models. The plots show estimated smooth functions f (vis) for (A) all types of litter; (B) cigarette butts; (C) metals; (D) paper; (E) hard plastic; and (F) flexible plastic.

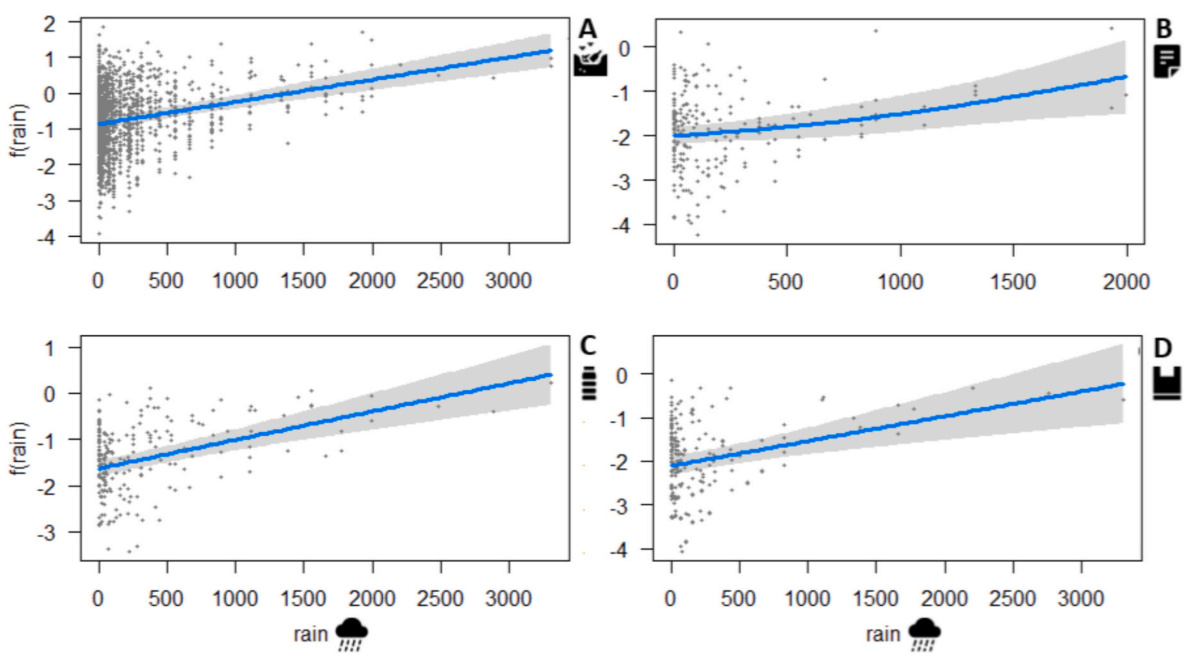

Fig. 6. Partial effect of rain (mm) on the daily litter accumulation rate across beaches, as determined via HGAM models. The plots show smooth functions f(rain) that were statistically significant (P values < 0.05) for (A) all types of litter; (B) Paper; (C) Hard Plastics; (D) flexible plastic.

Table 1
Summary of results from hierarchical generalized additive models (HGAMs) for different types of litter. The average daily accumulation rates column presents the mean daily accumulation rates (items·m^{-1}·day^{-1}). The "Interaction model" section indicates the *p* value for the interaction term between the day of the week and month and the adjusted R^2 of the model. The "Mechanistic Model" section shows the p value for the effects of the explanatory variables (beach zones, rain, day of the week, and number of visitors) and the adjusted R^2 of the full model. *P* values < 0.05 were considered statistically significant.

Litter types	Average daily accumulation rates	Interaction model		Mechanistic model				
		day x month	r^2 adj	zone	rain	days	visitors	r^2 adj
Total litter	1.77	2 e^{-16}	0.526	2 e^{-16}	2 e^{-16}	0.0951	2 e^{-16}	0.544
Cigarette butts	0.95	0.0002	0.452	2 e^{-16}	0.1359	0.0514	0.0001	0.457
Metals	0.24	8.9e^{-6}	0.606	2 e^{-16}	0.1536	0.2623	0.0001	0.568
Papers	0.20	2 e^{-16}	0.231	4.9e^{-5}	0.0139	0.4808	2 e^{-16}	0.216
Hard plastics	0.16	0.0005	0.318	2 e^{-16}	2 e^{-16}	0.5100	2 e^{-16}	0.339
Flexible plastics	0.13	2 e^{-16}	0.289	9.56e^{-7}	0.0001	0.3062	2 e^{-16}	0.248

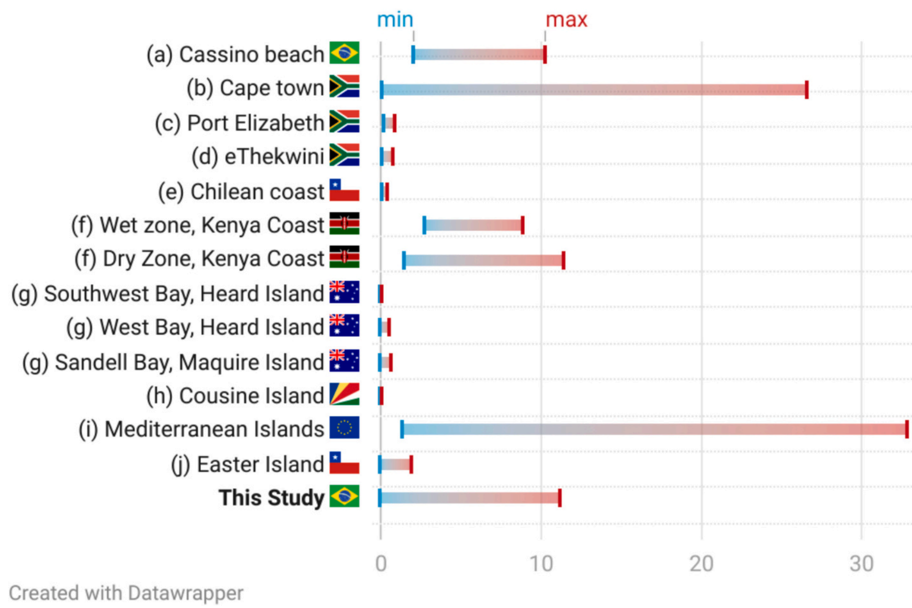

Fig. 7. Minimum and maximum daily marine anthropogenic litter accumulation rates (item.m^{-1}.day^{-1}) recorded on different continental beaches and island beaches around the world, including only studies that used daily collection frequencies. Data compiled from (a) Santos et al. (2005), (b) Chitaka and von Blottnitz (2019), (c) Barnardo et al. (2021), (d) Meakins et al. (2022), (e) Rech et al. (2023), (f) Okuku et al. (2020), (g) Eriksson et al. (2013), (h) Dunlop et al. (2020), (i) Grelaud and Ziveri (2020), and (j) Thiel et al. (2021).

(UNEP, 2025; Plastics Europe, 2025), the final consumers still play a limited role in effectively closing the material loop. Despite the different laws of the prohibited use of plastic items around the world, such as straws and bags or the replacement of paper straws, inadequate disposal practices by consumers remain a significant barrier. The variety of plastic items found in this study reflects the widespread use of disposable products without awareness of their environmental impact.

The findings have direct management implications. Rather than applying uniform cleaning schedules across all zones, it is necessary to prioritize the most impacted sectors, particularly those with food and beverage services. Targeted interventions, such as increasing the number of bins, placing receptacles specifically for cigarette butts, and conducting awareness campaigns directed at vendors and tourists, would reduce the litter load more effectively than generalized measures. Conversely, in recreational or pedestrian-only sectors with lower accumulation rates, a less intensive management approach would optimize resources while maintaining beach quality.

This study shows that spatially explicit monitoring provides actionable evidence for integrated coastal zone management. By identifying zone-specific accumulation patterns and their drivers, decision-makers can focus resources more efficiently, align interventions with usage intensity, and design preventive strategies that reduce long-term costs (Bryce, 2021; Bujold and Williamson, 2025). Also, targeted education campaigns, behavioral nudges, and local engagement strategies are essential to foster a sense of individual responsibility (Zielinski et al., 2019). Additionally, integrating citizen science and community-based monitoring into litter management frameworks can enhance both data collection and public accountability (Rambonnet et al., 2019).

Our study demonstrated that different uses of beach zones significantly influence the daily accumulation rates of marine anthropogenic litter. The accumulation patterns also varied over the months, whereas the weekday effects were less consistent or marginal. Rainfall and the number of beach visitors emerged as important drivers of litter accumulation, with their influence varying depending on the litter type. This study highlights how a high-resolution spatiotemporal sampling design can provide valuable insights for beach management. By combining daily monitoring with the division of zones based on beach use, it was possible to detect specific patterns of litter accumulation and identify key environmental and social drivers. This approach not only enhances the understanding of local litter dynamics where it is applied but also offers a practical framework to support targeted management actions, assess the effectiveness of policies, and guide preventive strategies in highly frequent coastal areas. Therefore, the selection of the most appropriate beach management strategy to combat marine anthropogenic pollution should consider the specific characteristics of each area, including usage intensity, types of litter, seasonality, ecological sensitivity, and the availability of management resources.

CRediT authorship contribution statement

Lucio Brabo: Writing – review & editing, Writing – original draft, Visualization, Formal analysis. **Henrique Araújo de Oliveira:** Methodology, Investigation. **Tamyris Pegado:** Writing – review & editing. **Ryan Andrades:** Writing – review & editing. **Friedrich Wolfgang Keppeler:** Methodology, Formal analysis. **Manoela de Araujo Sampaio:** Methodology, Investigation. **Francisco José Mariano Vasconcelos:** Methodology, Investigation. **Alexandre David Dantas:** Methodology, Investigation. **Regina Kátia Saraiva Carneiro:** Methodology, Investigation. **Kelly Ferreira Cottens:** Methodology, Investigation. **Nelson Guillermo Rangel-Buitrago:** Writing – review & editing. **Tarin Frota Mont'Alverne:** Writing – review & editing. **Marcelo Oliveira Soares:** Writing – review & editing. **Tommaso Giarrizzo:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

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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.

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Data availability

Data will be made available on request.

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