Marine Pollution Bulletin 174 (2022) 113310

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Baseline

Disentangling beach litter pollution patterns to provide better guidelines for decision-making in coastal management

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ARTICLE INFO

Keywords:
Beach debris
Waste management
Anthropogenic litter
Aquatic pollution
Tourism

ABSTRACT

Beach litter represents a worldwide problem impacting both terrestrial and aquatic environments. In the present study, we assessed beach litter pollution in a prominent touristic site in Brazil, the Jericoacoara National Park. In particular, we applied a delta-generalized additive modeling (GAM) approach in order to investigate pollution hotspots and to provide better guidelines for coastal environmental managers. A total of 7549 litter items were collected, resulting hard and flexible plastics the most abundant type. Our GAM analysis revealed that the distribution of each type of litter was affected by distinct drivers in the protected area, with the extension of the beach, tourist attractions, wind angle, and the distance to water bodies and villages as the most significant explanatory variables. Our model is suitable in predicting litter pollution hotspots on beaches, which is a valuable tool for future guidelines and effective management strategies to prevent beach pollution worldwide.

Anthropogenic litter can be defined as “any persistent, manufactured, or processed solid material discarded, disposed, or abandoned into the environment” (Bergmann et al., 2015; UNEP, 2009). Originated from both marine and land-based activities, litter sources and its pathways to the coastal environment are numerous, including commercial and artisanal fisheries, shipping, industrial installations, and densely-populated urban and tourist centers (Brownie, 2015; Li et al., 2016). Since the first studies of marine plastic pollution conducted in the 1970s, beaches are one of the best-known habitats where litter often accumulates (Cundell, 1973; Merrell, 1980). Beaches occupy approximately 40% of the world’s coastlines at the land-ocean interface, which poses several human pressures by activities such as fisheries, tourism and recreation (Babić et al., 2019; Radziejewska et al., 2017). In this issue, beach litter is a major environmental problem, which impacts socio-economic activities (e.g., tourism and recreation), the provision of ecosystem services and goods to society, and local wildlife (Asensio-Montesinos et al., 2019; Garcés-Ordóñez et al., 2020).

Sandy beaches are highly dynamic environments, where local weather conditions, in particular winds, tides, and waves, can strongly influence the abundance and distribution of litter (Andrades et al., 2018; Rangel-Buitrago et al., 2018). The identification of the local factors that influence beach litter pollution is crucial to better inform stakeholders, coastal managers, and society, as well to provide suitable guidelines for the effective monitoring and mitigation of the potential loss of economic goods and ecosystem services. In fact, the presence or absence of litter is a key parameter for the definition of the beach scenic score, that is, its attractiveness to tourists (Anfuso et al., 2017; Williams et al., 2016), which those polluted beaches often being avoided by beachgoers (Krelling et al., 2017). In general, beach litter studies that provide practical tools to identify pollution hotspots and guide science-based management are still scarce (but see Battisti et al., 2020; Micallef and Willians, 2002).

In the present study, we assessed the influence of local variables on the abundance and distribution of beach litter in the Jericoacoara National Park, Ceará state (northeastern Brazil), which is a popular tourist destination. Then, we used a modeling approach to track beach litter pollution hotspots according to the litter type and beach use.

Brazil has the longest shoreline in the South Atlantic, which covers approximately 8000 km of equatorial, tropical, subtropical, and warm temperate latitudes (Araújo et al., 2018). Beach tourism is an important

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https://doi.org/10.1016/j.marpolbul.2021.113310
Received 22 October 2021; Received in revised form 20 December 2021; Accepted 28 December 2021

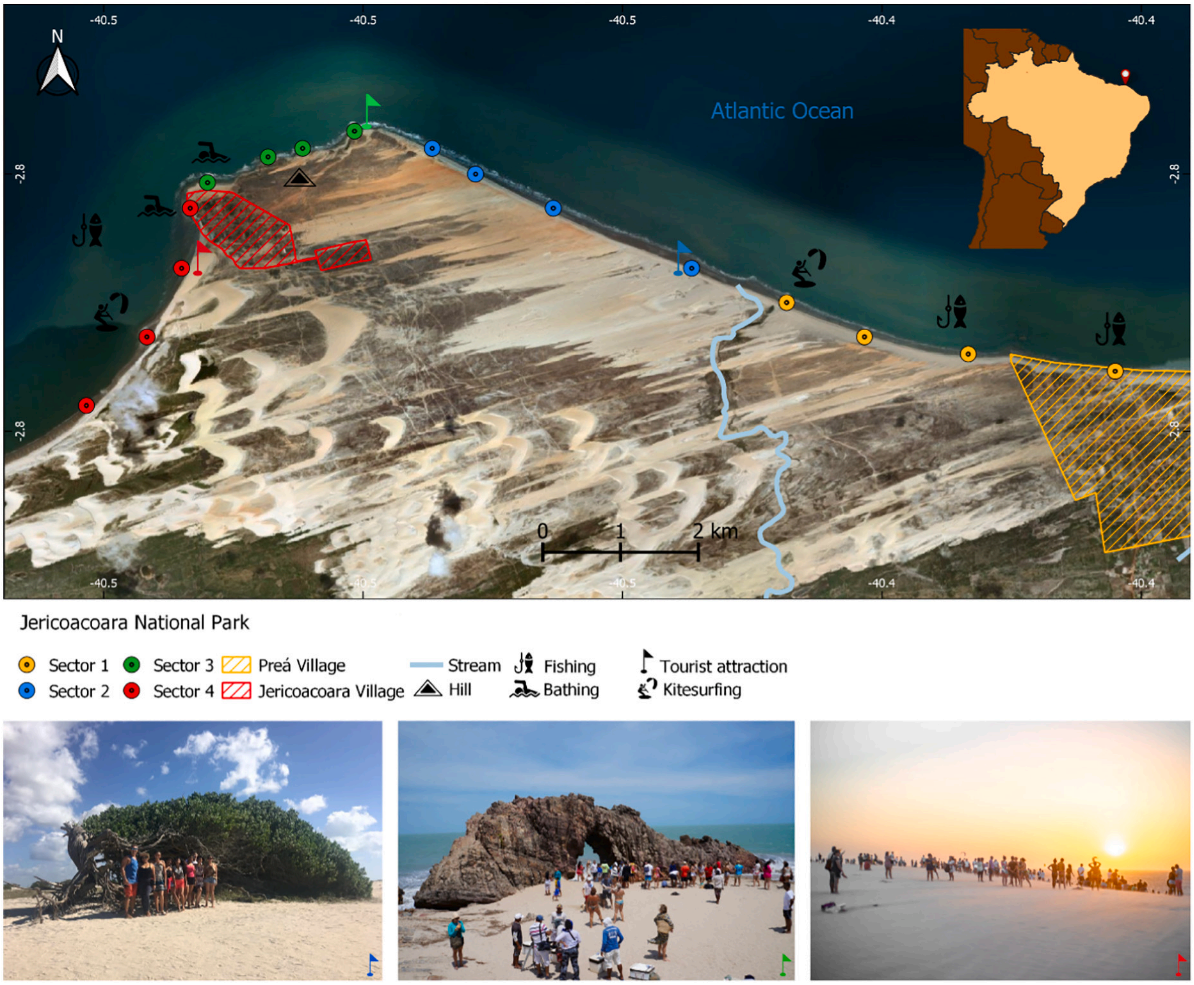

Fig. 1. Jericoacoara National Park (Ceará state, northeastern Brazil). Villages, study sectors (color-coded), with the main human activities and the tourist attractions highlighted by the icons.

economic activity for the local and regional economies of many coastal environments (Sousa et al., 2014). The Jericoacoara National Park (Fig. 1) was created in 2002 under the premise to protect coastal ecosystems and ensure the harmony of local tourism and the preservation of natural resources (ICMBio, 2011). Jericoacoara is currently the Brazil's fourth most frequently-visited national park, with an annual average of approximately one million tourists (Castro, 2020). This protected area comprises 8416 ha covering a mosaic of different coastal landscapes, including sandy beaches, mobile dunes, mangroves, and rocky shores (de Meireles, 2011).

The variation in local wind patterns is associated with seasonal shifts of the Intertropical Convergence Zone (ITCZ) marked by confluence of the northeasterly and southeasterly trade winds (Medeiros et al., 2020). In general, the southeasterly trade winds are most intense (5–7 $m.s^{-1}$) when the ITCZ is in its northern extreme, between August and October, decreasing progressively as the zone migrates southward toward the equator, until reaching their lowest annual values (1–2 $m.s^{-1}$) in March and April (de Meireles, 2011). The rainfall regime of the area is tropical semiarid, with rainy season concentrated in the first half of the year (90% of the annual rainfall) (de Meireles, 2011).

Beach litter monitoring surveys were conducted in June (rainy season) and November (dry season) 2019 in four sectors (Fig. 1) with four samples sites. Each sector has distinct characteristics in terms of access (by vehicle or on foot), recreational activities (fishing, kitesurfing practice, bathing), tourist attractions, and the presence of villages and other infrastructures. Beach sectors were also classified in relation to their wind exposure according to Forsberg et al. (2020) and Turrell (2018), which onshore (sectors 1 and 2), corresponded locations where winds blowing from sea toward the coastal areas with angles between 0° and 180°, while offshore (sectors 3 and 4) locations were those winds blowing from continent to sea, making angles between 0° and −180° with coastline. The angles of wind direction in relation to the coastline were measured by an online protractor (https://www.ursupplier.com/tools/angle_measurement/) on pictures of wind vectors provided by the online software Windy (https://www.windy.com).

Beach litter surveys were performed during low tides along five perpendicular transects with width of four meters starting from the edge of the water to the supralittoral zone. The transect length was measured during the litter sampling and all the debris was manually collected the litter items were quantified, measured, and classified according to their type (plastics and other materials; see Table S2) and color.

We also measured the following five environmental parameters along 168 equidistant points located along the shoreline at intervals of 100 m: Beach extension (meters), wind angle (degrees), distance from the villages (i.e. Preá and Jericoacoara), and the distance from coastal body of water and presence or absence of tourist spots (Fig. 1). To determine the influence of these variables on the distribution and abundance of litter, a delta-generalized additive modeling (GAM) approach was applied to account for the zero inflation of the count data (Rubec et al., 2016). In this approach, the positive values were fitted by the GAM using a Gaussian distribution, while the presence-absence data were fitted by a GAM with a binomial distribution, using the mgcv

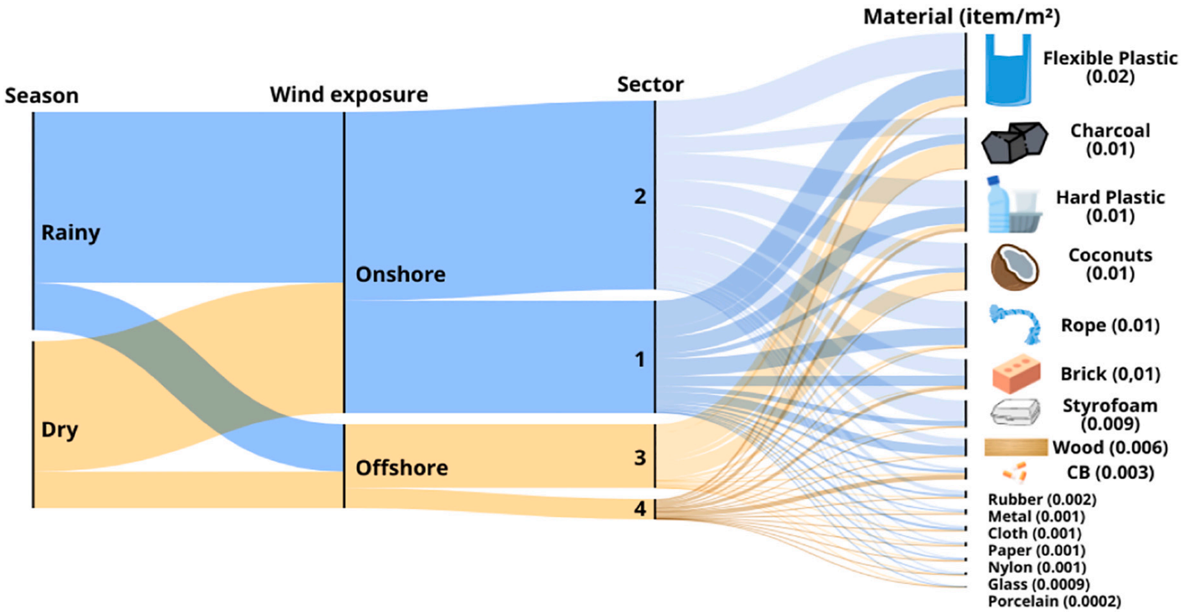

Fig. 2. Alluvial diagram showing the distribution of different types of beach litter (items/m^2) between seasons and among the sectors surveyed in Jericoacoara National Park (Ceará state, Brazil).

package (Wood, 2012). A penalized cubic regression spline was applied as the smoothing function. This procedure selects the degree of smoothing automatically based on the Generalized Cross-Validation (GCV) score. The best model was then selected through the application of the criterion of explained deviance, the GCV score and the Akaike Information Criterion, AIC (Akaike, 1973), which provides a balance between the model fit and the parameters used.

We investigated all possible combinations of the variables, selecting the best models according to the above-described criteria, and the package functions. Once the best model for each litter category was selected, we ran a predictive GAM in R software (R core team, 2019) to estimate the potential number of items according to the variables selected, with the independent (input) variables being estimated for points along study area. The output variables (the number of litter items) were predicted for each point on the basis of the most suitable model. Finally, we built maps using Microsoft 3D Maps in Excel to evidence possible litter hotspots along the shoreline.

A total of 7549 items (mean = 0.23 items/m^2) were found along all four sectors in the Jericoacoara National Park. The sites in sectors 1 and 2 (onshore side) returned the highest litter densities in both seasons (rainy and dry seasons) with mean densities 0.27 and 0.47 items/m^2, respectively (Fig. 2), while sectors 3 and 4 recorded mean densities of 0.14 and 0.04, respectively. These differences reflect the role of wind exposure (onshore vs. offshore) on the accumulation of litter in study area (e.g., coastal promontory). In general, the main factor influencing litter deposition on Brazilian beaches is their proximity to an estuarine run-off (Andrades et al., 2020). However, as this factor is not present in the area, wind, coastal geomorphology and wave exposure played a major role in affecting the distribution and accumulation of beach debris (Andrades et al., 2018).

The highest mean density was recorded for plastic litter, including flexible plastic (0.02 item/m^2) and hard plastic (0.01 items/m^2), which recorded densities that can be compared to other studies worldwide (Abreo, 2018; Aytan et al., 2020; Munari et al., 2016). Small plastic litter (<5 cm) was more abundant than larger pieces, thereby confirming once again previous literature data. (Andrades et al., 2020; Galgani et al., 2015; Topçu et al., 2013). In our study, the majority of small-sized litter consisted fragments of larger pieces, rather than virgin plastic (e.g., pellets), which hampers the implementation of specific strategies for the prevention and removal from beach, since the origin of litter fragments is hard to track. Also, conventional beach cleaning methods are less effective against small-sized fragments rather larger pieces (Zielinski et al., 2019).

The variable that best explained the litter distribution was touristic spots, while the distance from bodies of water was marginally significant (Table 1). The extension of the beach was a significant variable for all assessed different litter types (Table 1).

Besides plastic, ropes were also abundant in our study (mean density = 0.01 items/m^2), particularly blue nylon fibers commonly used in maritime activities (Welden and Cowie, 2017). The extension of the beach and its proximity to Jericoacoara village were the main drivers of pollution by rope on the studied beaches (Table 1). Small blue polyester and polyamide (nylon) fibers are also the most abundant litter ingested by many coastal fish species in the study region (Dantas et al., 2020; Dantas et al., 2012; Possatto et al., 2011).

It is important to note that the density of cigarette butts, even in low density (< 0.003 items/m^2), was clearly associated with touristic spots. Our GAM analysis (Table 1) confirmed that pollution by cigarette butts

Table 1
Significance values in bold of the generalized additive models (GAM) of the environmental variables: beach extension (EXT), wind angle (WA), distance of body waters (D_riacho), distance of jericoacoara village (D_Jeri), distance of Prea village (D_Prea) and tourist spots.

Item	EXT	WA	D_riacho	D_Jeri	D_Prea	Tourist	Intercept	R-sq.(adj)	Deviance explained
Total litter	(+) **<0.01**	(+) 0.12	(−) **0.04**	–	(+) 0.28	(+) **<0.01**	<0.01	0.51	53.9%
Cigarette	(+) **<0.01**	(−) **<0.01**	–	–	(−) **0.02**	(+) **<0.01**	0.93	0.22	26.1%
Rope	(+) **<0.01**	–	(+) 0.29	(±) **<0.01**	(−) 0.23	(+) 0.94	<0.01	0.61	66.3%
Hard Plastic	(+) **<0.01**	–	(+) 0.28	–	(−) 0.42	(+) 0.33	< 0.01	0.50	52.9%
Flexible Plastic	(+) **<0.01**	(+) **<0.01**	(−) 0.01	–	(+) 0.28	(+) **<0.01**	< 0.01	0.50	54.4%
Styrofoam	–	(−) **<0.01**	–	(+) **<0.01**	–	(+) 0.85	0.63	0.45	50.3%

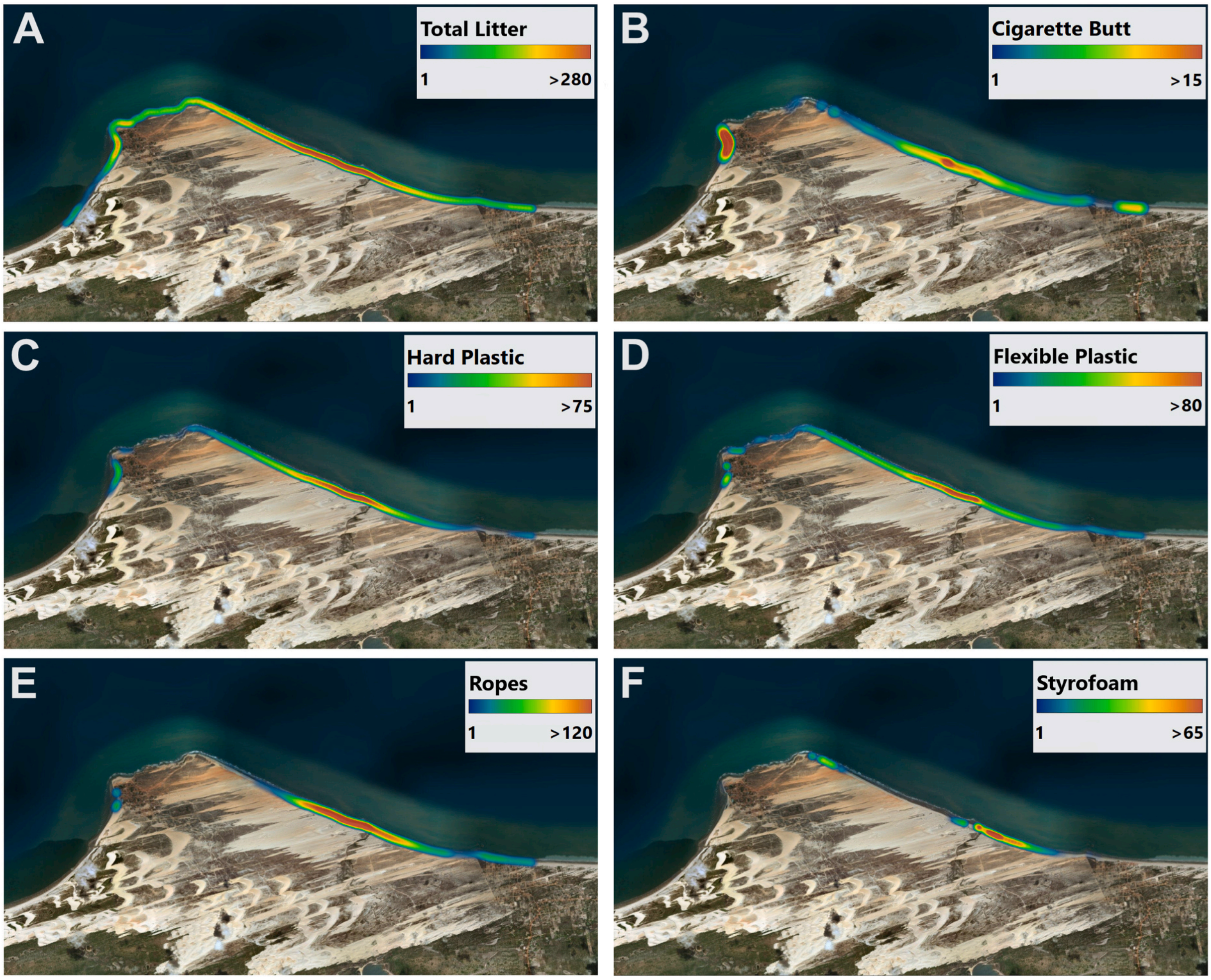

Fig. 3. Predicted litter abundance and distribution of all types (A) and the most abundant types of litter (B–F) observed in the Jericoacoara National Park (Ceará state, Brazil).

was influenced strongly by tourist attractions and the wind angle, and, to a lesser extent, the proximity of bodies of water. In this regard, Garcés-Ordóñez et al. (2020) recorded high amounts of cigarette butts on touristic beaches in Colombia, which also is similar to the observed on touristic beaches in Argentina (Becherucci et al., 2017) and Chile (Honorato-Zimmer et al., 2019). In addition to plastics, cigarette butts are the main litter type found on most Brazilian beaches (Andrades et al., 2020). In this sense, some studies have shown that bodies of water may be contaminated by toxic compounds leached from cigarette butts (e.g., nicotine) (Akhbarizadeh et al., 2021; Dobaradaran et al., 2021; Qamar et al., 2020).

Overall, beach extension and presence of touristic spots influenced the distribution of almost all the types of litter recorded in our study (Table 1). Other factors, such as the distance to water bodies and the villages (Jericoacoara and Preá) were also important, as also seen in other studies (Crosti et al., 2018; Poeta et al., 2016). The most striking result of this analysis is that the certain types of litter, in particular cigarette butts and styrofoam, accumulate in different patterns along the study areas (Fig. 3), whereas plastics (both hard and flexible) and rope presented a pattern similar to that of the total litter distribution (Fig. 3). These results are important for the design of science-based management strategies, such as beach cleaning, the positioning of trash cans, and the implementation of local campaigns of awareness focusing on specific litter types, such as cigarette butts. These efforts would help ensure the preservation of the natural beauty of the national park, increasing the satisfaction of tourists and the sustainable use of local beaches.

The predictive GAM was not able to estimate precisely the amount of litter, but rather the potential location of litter hotspots, as can see by the color gradient showed in the Fig. 3. Here, the GAM approach allowed the identification of priority areas for waste management. Litter-specific guidelines can improve the effectiveness of beach pollution management, since we have observed that different types of litter can be generated and deposited across varied spatial patterns along the coastline.

Today, Jericoacora National Park is the fourth most-visited national park in Brazil (Castro, 2020), being important to local and federal tourism economy. The present baseline assessment and GAM analysis revealed that the distribution of each type of litter were influenced by distinct drivers in the protected area, with the extension of the beach, tourist attractions, wind angle, and the distance to water bodies and villages acting as the most significant litter pollution predictors. Our model was also suitable in predicting litter pollution hotspots in the beaches, which is a valuable science-based tool for future guidelines and effective strategies to prevent marine pollution on beaches worldwide.

CRediT authorship contribution statement

Lucio Brabo: Methodology, Formal analysis, Writing – original draft, Visualization, Writing – review & editing. **Ryan Andrades:** Writing – original draft, Visualization, Writing – review & editing. **Simone Franceschini:** Formal analysis, Visualization, Writing – review & editing. **Marcelo de Oliveira Soares:** Visualization, Writing – review

& editing. **Tommaso Russo:** Formal analysis, Visualization, Writing – review & editing. **Tommaso Giarrizzo:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Writing – original draft, Resources, Visualization, Supervision.

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.

Acknowledgment

LB would like to thank the National Council for Scientific and Technological Development (CNPq) for the financial support by grant number 130550/2019-1. TG is funded by CNPq grant number 311078/2019-2. MOS thanks the CNPq (Research Productivity Fellowship No. 313518/2020-3), "PELD Costa Semiárida do Brasil-CSB" (No. 442337/2020-5), CAPES-PRINT, CAPES-AVH (Alexander Von Humboldt Foundation), and "Fundação Cearense de Apoio ao Desenvolvimento Científico e Tecnológico" (Chief Scientist Program and I-plastics Consortium/JPI Oceans) for their financial support. Also, we would like to thank the Chico Mendes Institute for Biodiversity Conservation (ICMBio) for welcoming us to its facilities on Jericoacoara National Park. Our thanks to all the postgraduate program students in Aquatic Ecology and Fishing (PPGEAP) who participated in the data collect. Finally, thanks to Editor Bruce J. Richardson and reviewers for constructive comments and recommendations that improved the quality of the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2021.113310.

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