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Influence of rainfall and winds on the arrival of marine litter on two beaches in northern-central Chile

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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

Meteorological conditions have a significant influence on marine litter stranding, although the mechanisms remain poorly understood due to the lack of high-frequency monitoring. Over four years (March 2020–February 2024), this study examined how rainfall and winds influenced the daily amounts of litter stranded on a beach (La Herradura) in northern-central Chile; on a neighboring beach (Changa), additional surveys were done around two rainfall events. Only specific stranded plastic items were collected and classified, distinguishing between land- and sea-based sources. Daily accumulation rates on La Herradura beach were highly variable, ranging from 0 to more than 100 items km^{-1} d^{-1}. After rainfall events, litter from land-based sources increased sharply, from an average of 20.7 items km^{-1} d^{-1} during the three days before to 109.7 items km^{-1} d^{-1} during the three days after the rain, with similar patterns observed at Changa beach, on both beaches dominated by single-use plastic items. Likewise, litter from sea-based sources increased immediately after periods of onshore winds. The fact that litter appeared on the beach immediately after rainfall or wind events, with little delay, suggests that most litter is of very local origin. Since the litter quantified in this study results from local waste mismanagement, coastal communities (including fishing and aquaculture activities) are mostly responsible for this problem. Immediate and effective measures are recommended at the local level, including monitoring, citizen education, enforcement of bans on single-use plastics, and the promotion of sustainable product alternatives within existing extended producer responsibility frameworks.

1. Introduction

Marine litter pollution is a major global environmental problem, commonly defined as any solid waste material entering the marine environment from different sources (GESAMP, 2019). It is usually classified by size into macrolitter (>25 mm), mesolitter (5–25 mm), and microplastics (<5 mm), with recent reviews showing that in Latin America macrolitter still dominates on beaches, particularly single-use plastics (Honorato-Zimmer et al., 2024). Coastal systems accumulate litter due to increasing human activities, including urban development, population growth, and ineffective coastal waste management (Adger et al., 2005; Ariza et al., 2008; Gall and Thompson, 2015; Lozoya et al., 2016; Leal Filho et al., 2025).

Shorelines are thought to accumulate approximately 70 % of all marine litter (Morales-Caselles et al., 2021). This litter reaches the marine environment through a variety of vectors, including river transport (Schmidt et al., 2017; van Emmerik et al., 2022), beach litter (De Veer et al., 2023), activities at sea (Ryan, 2023), and even natural

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disasters (Murray et al., 2018). Rivers are particularly important pathways connecting populated inland areas with the coast, and their impacts are strongest near their mouths (Rech et al., 2014; Bruge et al., 2018; Nelms et al., 2021; Stagličić et al., 2025). Although land-based sources are considered the main input to the oceans worldwide (Jambeck et al., 2015; Lebreton and Andrady, 2019; Mai et al., 2023), the proportion can vary by location, with sea-based sources sometimes more abundant, especially in locations further away from human population centers (Galgani et al., 2015; Prevenios et al., 2018; Ryan, 2020).

Urban beaches often exhibit high daily accumulation rates, directly linked to nearby human activities and local commerce (Chitaka and von Blottnitz, 2019; Rech et al., 2023), whereas remote beaches accumulate litter predominantly from distant sources (e.g., Lavers and Bond, 2017; Nguyen et al., 2025). Most studies on litter abundance, distribution, and origin have been conducted on sandy beaches (Ryan et al., 2009; Browne et al., 2015; De Veer et al., 2023), and typically assess litter standing stocks, providing information on the long-term pollution state. However, this approach provides no information about the actual amounts of litter arriving on beaches, and regular (e.g., daily) sampling is more suitable for determining local litter dynamics (Ryan et al., 2009; Smith and Markic, 2013; Ryan et al., 2014; Zielinski et al., 2022). To understand marine litter dynamics, it is crucial to consider not only the standing stock but also the accumulation rates over extended periods, as short-term measurements may fail to capture seasonal patterns and local input variations (Ryan et al., 2014; Meakins et al., 2022).

Studies from different parts of the world (e.g., Brazil, South Africa, Maui and Rapa Nui) suggest that environmental factors influence daily litter accumulation rates (Santos et al., 2005; Ryan et al., 2014; Imhof et al., 2017; Rech et al., 2023). Rivers transport litter (Gutsa et al., 2024), rainfall mobilizes litter (Duong et al., 2025), winds push litter towards the shore (Thiel et al., 2021a), tides influence whether items remain stranded or are washed back (Sawan et al., 2025), and extreme events, such as storms or typhoons affect litter accumulation (Cheung and Not, 2023). Among these drivers, rainfall is an important predictor of litter outflow, since stormwater runoff and episodic discharges can rapidly transport terrestrial litter to the coast (Zhang et al., 2024), often producing peak inputs within 24 h after an event (Ryan and Perold, 2021). Winds also strongly control litter distribution by interacting with waves (Haarr et al., 2024), with onshore episodes significantly increasing beach accumulation by pushing floating and neutrally buoyant items towards the shore (Thiel et al., 2021a; Nguyen et al., 2025). Due to their predictive capacity and short-term effects, these two factors (rainfall and winds) are central to explaining the spatial and temporal patterns of litter strandings.

Rainfall contributes large amounts of litter due to the runoff via storm-water discharges, overflows, sewers, streams, and drainage channels (Lopes da Silva et al., 2016; Menicagli et al., 2022; Cesarini et al., 2023). Rivers are the main transport vectors of land-based litter towards coastal beaches (Baptista and Monteiro, 2010; Stagličić et al., 2025), with litter amounts during rainy seasons often being significantly higher than in dry seasons (van Emmerik et al., 2023; Zhang et al., 2024; Duong et al., 2025). This observation is supported by other research, such as findings by Moore et al. (2002) and van Emmerik et al. (2019), who documented significant increases in microplastics and macrolitter (respectively) in coastal areas following storm events. Similarly, Patterson et al. (2025) reported a sharp and immediate increase in microplastic abundance (more than tripling in riverine, estuarine and marine waters) within days after a major flood event, highlighting the rapid response of plastic transport to extreme rainfall. In South African rivers, differences in litter response to rainfall have been reported: Gutsa et al. (2024) observed a 2–3 day delay, indicating that in their study area, litter transport does not occur immediately after rain. In contrast, Ryan and Perold (2021) found that most litter types peaked one day after rainfall, using a finer-scale sampling method than that of Gutsa et al. (2024), highlighting the importance of detailed monitoring to capture short-term litter dynamics.

On the other hand, wind blowing from the sea towards the shore might push larger amounts of litter onto the beach (Thornton and Jackson, 1998; Willis et al., 2017). In a study in a UK estuary, Browne et al. (2010) observed that during onshore winds, the amounts of less dense macroplastics (such as polyethylene and polypropylene) and denser microplastics (e.g., polyvinyl chloride) increased. Similarly, in a study of Tasmanian estuaries, Willis et al. (2017) showed that litter entering the estuary upstream was deposited on downstream shores primarily by winds blowing towards the coast. Along the North Pacific coasts, lighters were observed entering the sea through rivers and moving across the oceans via marine currents and seasonal winds (Fujieda, 2023). This pattern is also evident in other contexts, as demonstrated by Thiel et al. (2021a) on a remote beach on the island of Rapa Nui, where litter accumulation rates were higher during days with strong onshore winds. A more recent study on a beach in Vietnam (Nguyen et al., 2025) further showed a positive correlation between prevailing northerly winds and the accumulation rates of floating litter being pushed towards the coast (especially foam and wrappers).

While it is known that rainfall events and strong winds influence the arrival of litter on beaches, there are gaps in knowledge about the exact magnitude of these effects and their temporal dynamics in various geographical contexts. Daily sampling is increasingly recognized as a valuable tool for understanding how litter reaches beaches (Eriksson et al., 2013; Ryan et al., 2014; Meakins et al., 2022). Northern Chile's arid climate, with sporadic, intense rainfall events and a high concentration of human, fishing, and aquaculture activities, creates a distinct coastal pollution scenario that requires region-specific management strategies (Thiel et al., 2013). In this context, our study focused on determining the effect of rain and wind on the daily amounts of marine litter stranded on two urban beaches in northern-central Chile. We tested the hypotheses that (i) after rainfall events, larger amounts of terrestrial litter will arrive on the beach, and (ii) on days with strong onshore winds, more marine litter will wash ashore than on days with strong offshore winds. The findings of this study will contribute to a better understanding of litter dynamics on urban beaches and provide insights that are applicable to similar coastal environments, which can help to design more effective prevention strategies and cleanup plans after deposition events (Ryan and Perold, 2021).

2. Methods

2.1. Study area

The Coquimbo Coastal System in northern-central Chile (Fig. 1) extends approximately 150 km north-south and is characterized by several smaller bays under the influence of the Humboldt Current System (Marín and Delgado, 2007; Thiel et al., 2007; Thiel et al., 2013). Within this area, one of the most intense upwelling centres is located south of Punta Lengua de Vaca, where prevailing south-westerly winds favor upwelling throughout the year (Valle-Levinson et al., 2000; Moraga et al., 2001; Garreaud et al., 2011). Onshore winds are frequent in the Coquimbo Coastal System (Flores et al., 2024), particularly during spring/summer, and are more intense in the afternoon (Rothäusler et al., 2021), representing a relevant factor in the transport of litter to the beach.

Stranded marine litter was studied on two sandy beaches in the area: La Herradura and Changa (Fig. 1). Tidal regimen at both beaches is semi-diurnal with typical ranges of ~1 m (Valle-Levinson et al., 2000; Valle-Levinson and Moraga-Opazo, 2006). Both beaches were classified as reflective beaches (Dean parameter $X < 1$), indicating low-energy conditions (González et al., 2014; Soto et al., 2021). La Herradura beach (29°58′38″S, 71°20′55″W) is located in a small bay and measures 1.68 km in length. It is predominantly sandy, with a gentle slope and fine to medium-grained sand (González and Holtmann-Ahumada, 2017).

To determine whether the findings from La Herradura beach can be generalized to other beaches in the area, we also surveyed the

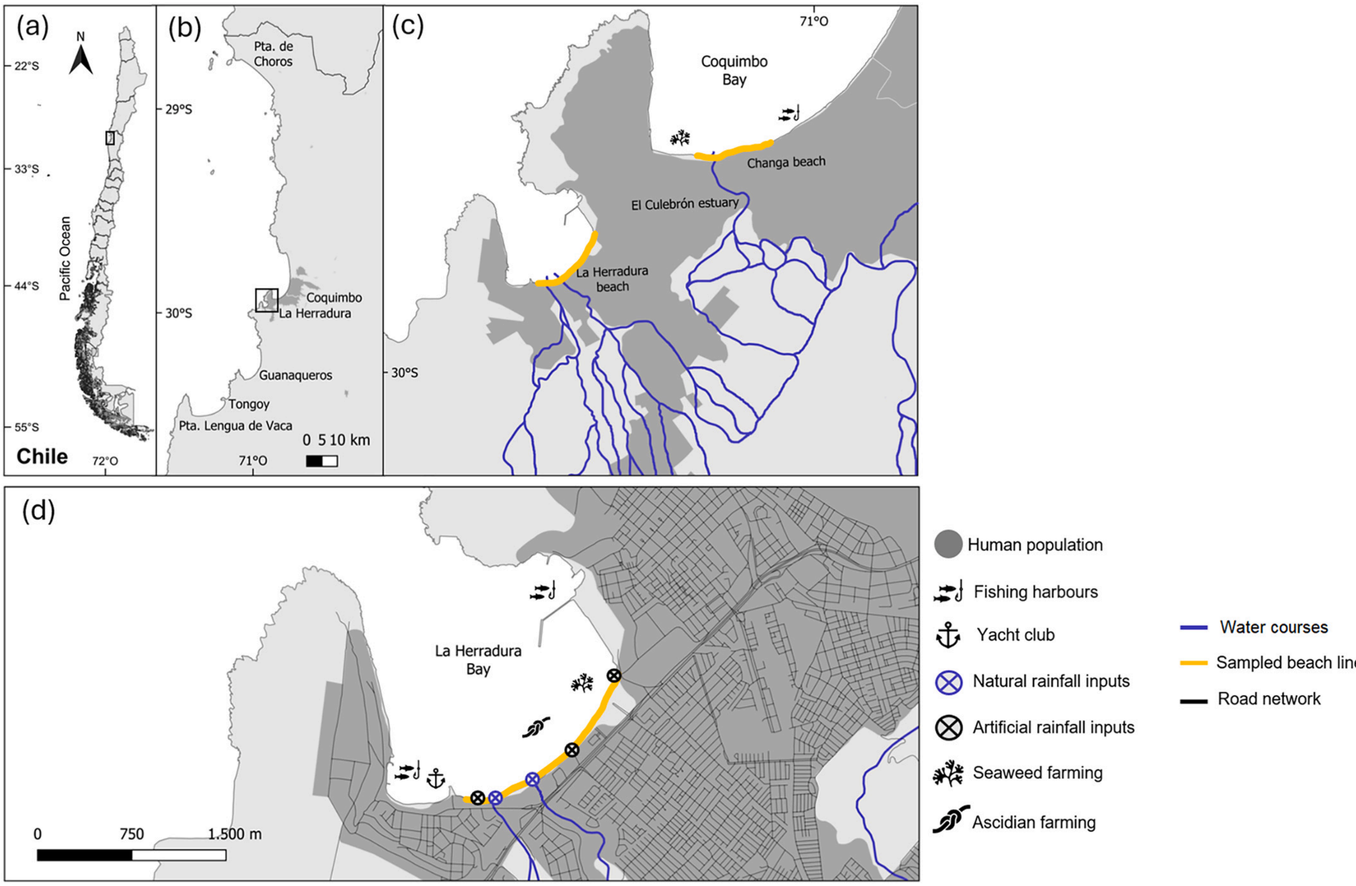

Fig. 1. Geographic characterization of the study area. (a) Chile with the study area (box). (b) Coastal System of Coquimbo, showing the main coastal localities. (c) Detail of Coquimbo city, with sampling extent on La Herradura beach (1.68 km in length) and Changa beach (1.87 km in length), marked with a yellow line. Water courses and human population distribution are shown. (d) Detailed view of La Herradura Bay, including the location of the main natural and artificial rainfall inputs, the road network, the yacht club, fishing harbours, and aquaculture farming areas (seaweed and ascidians).

neighboring Changa beach (29°95′S, 71°32′W) during two rainfall events. Located in the southern part of Coquimbo Bay, Changa is a sandy beach with a slightly steeper slope and medium-grained sand (González and Holtmann-Ahumada, 2017).

La Herradura beach is used for different activities, including tourism, cultivation of seaweed and marine invertebrates, with small fishing harbours for artisanal fishermen, a yacht club, and commercial shipping (Aburto et al., 2013; González and Holtmann-Ahumada, 2017; González et al., 2021). The municipality of Coquimbo conducts regular cleanups, mainly during the summer tourist season (Thiel et al., 2021b). Changa beach is used for fishing and seaweed harvesting (Chávez-Villavicencio and Rivadeneira, 2020). Additionally, the north-eastern part of Changa beach experiences considerable tourism.

Previous studies have reported low environmental quality at these beaches, evidenced by the presence of decomposing algae and anthropogenic solid waste in the water, such as oil stains at Changa beach (González and Holtmann-Ahumada, 2017) and facemasks at La Herradura beach (Thiel et al., 2021b). On Changa beach, the adjacent coastal wetland provides an important resting and foraging area for migratory birds, underlining the need to protect this ecosystem from anthropogenic impacts, including marine litter (Zuleta-Ramos and Bravo-Naranjo, 2020).

2.2. Beach sampling

La Herradura beach (1.68 km in length) was monitored daily for extended periods from 2020 to 2024, whereas Changa beach (1.87 km in length) was surveyed only between June and July 2022 (Table 1). At both sites, stranded litter was surveyed along the entire beach length and across the intertidal zone, from the water's edge to the last high tide line. Specific litter items were then collected and counted daily, ensuring that only items stranded or deposited during the last two tidal cycles were collected (Bettim et al., 2021). During the first two days of each survey period, all items studied herein were removed by members of the research team, but those data were not evaluated because herein we were interested in estimating the daily arrival rates. To identify the last high-tide line, the team used the extension of damp sand and recently

Table 1
Daily samplings of stranded marine litter on La Herradura beach. Collection of the six types of objects started on July 1st, 2020 ($n = 635$ days). *During the initial period, collection days per object type were: red meshes and ropes (122 days), bottle caps (83 days), chululos (61 days), lighters (43 days) and plastic cutlery (29 days); during the following sampling periods, all items were collected.

Period	Samplings days
30 Mar. to 29 Jul. 2020*	122
21 Dec. 2020 to 29 Jan. 2021	40
01 Feb. to 17 Jul. 2021	167
03 Oct. to 27 Nov. 2021	56
30 Nov. 2021 to 28 Feb. 2022	91
02 May to 08 Sep. 2022	130
27 Jun. to 15 Sep. 2023	81
07 Jan. to 16 Feb. 2024	41
Total days	**728**

stranded seaweed as indicators. The surveys were carried out every morning before the municipal staff arrived to clean the beach. The unit of measurement for the daily accumulation rates is recorded as items km^{-1} d^{-1}.

At La Herradura beach, litter collection began on 30 March 2020, initially focusing on two sea-based objects: red meshes and ropes (Table 1). The sampling protocol was progressively expanded throughout the second quarter of 2020 to include the most representative land-based and sea-based litter types: bottle caps were added on 8 May, followed by poly-tubing (chululos) on 30 May and lighters on 17 June. Finally, plastic cutlery was incorporated on 1 July, marking the beginning of comprehensive monitoring of all six object types (3 land-based and 3 sea-based objects). From July 2020 to February 2024, all these objects were systematically collected and analyzed. To examine whether the patterns found on La Herradura beach also apply to other beaches, we sampled Changa beach in Coquimbo Bay for 20 days in 2022 (21–28 June and 08–19 July 2022; see Fig. S2b in Appendix), including two rainfall events.

2.3. Classification of litter

We sampled frequently encountered plastic items that are representative of important anthropogenic activities on and near the surveyed beaches, classifying the items in six types: three corresponding to land-based sources (bottle caps, lighters, and plastic cutlery) and three from sea-based sources (red meshes, ropes, and poly-tubing) (Fig. 2). All land-based items collected were single-use plastics. A buoyancy test was also conducted on these six litter types to assess their transport dynamics. The items classified as positively buoyant litter, such as bottle caps, lighters, plastic cutlery, red meshes, and rope, can float long distances without sinking or decomposing, whereas non-buoyant items like chululos typically sink and are transported locally by strong wave action (see Rech et al., 2014).

Although most of the litter items are positively buoyant, some items transported by rainwater may initially become stranded or buried in the beach sands before reaching the high tide line. Daily monitoring over consecutive days allowed us to capture such items when they became exposed or were moved by subsequent tides and waves.

The selection of these items was based on their representation as land- and sea-based marine litter and the feasibility of standardized daily sampling. Bulky or infrequent items, such as PET bottles or buoys, were not included because of their size, low occurrence, and high likelihood of removal during the day, which could affect estimates of their true accumulation rates and thereby compromise representative monitoring. While this study focuses on specific types of plastic litter, we acknowledge that dynamics may differ for other categories, such as wood, glass, ceramics, or textiles, which were not considered herein.

Among the sea-based objects, poly-tubing (locally called “chululos”), red meshes, and ropes stand out, all related to local aquaculture and fishing activities. The chululos are 1 m long polyethylene tubes filled with sand that were used in the bottom culture of the red seaweed *Gracilaria chilensis*. Their use was extensive during the 1990s, mainly in subtidal environments. However, these objects were subsequently banned due to serious pollution problems (Aguirre Muñoz et al., 2013). In our collection, we classified chululos according to their state of degradation: complete chululos (maintaining their original length of 1 m), medium chululos (partially degraded) and fragmented chululos (highly degraded and in smaller pieces, at least 10 cm long with a terminal part). All chululos (complete, medium, fragment) were counted equally in the analysis.

The red meshes are polypropylene structures originally designed for horticultural products but adapted for use in aquaculture (Macchiavello et al., 2018). In 2017, the small-scale aquaculture program of the Universidad Católica del Norte implemented the use of these red meshes in La Herradura Bay as part of a project for suspended culture of the red seaweed *Chondracanthus chamissoi* (Macchiavello et al., 2018). However, when we began our study in early 2020, local fishermen had already adopted these red meshes for cultivating the native ascidian *Pyura chilensis.* These meshes are 4 cm wide with mesh openings of 2 mm × 5 mm. As for their length, when collecting them on the beach, we separate them into two main sizes: (i) small fragments of less than 20 cm (some even smaller than 5 cm), and (ii) long fragments of more than 20 cm, in some cases exceeding 100 cm. Herein, all size categories were pooled for the analysis.

Most of the ropes collected on La Herradura beach were made of polyethylene. There were ropes of different colors, sizes, and thicknesses. In addition, we observed different rope structures; some were found as individual units, while others were part of more complex structures, such as base components (which we call “mother ropes”) associated with red meshes. It is important to note that some of the individual ropes collected on La Herradura beach have likely been used by fishermen for specific operations of their anchored boats (personal

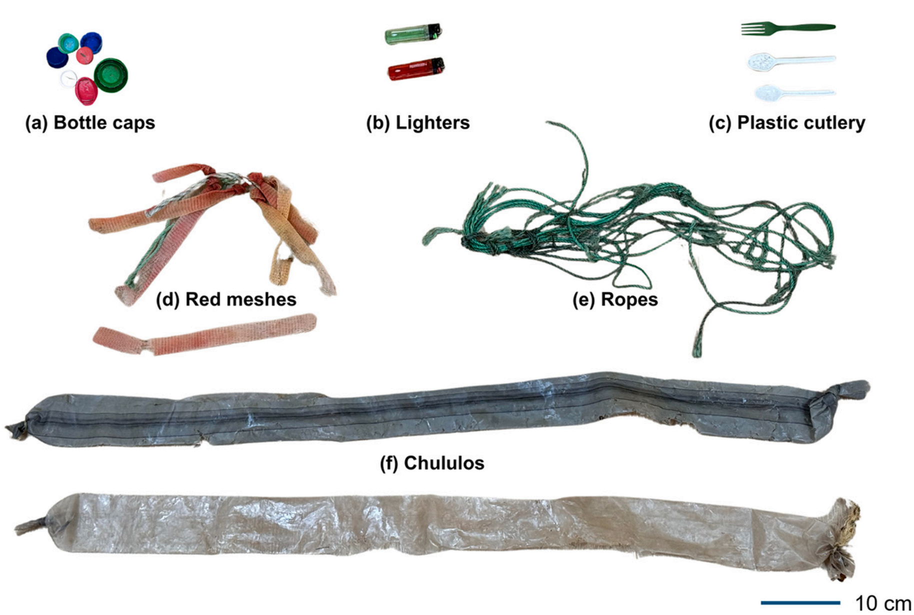

Fig. 2. Plastic items selected. (a) bottlecaps, (b) lighters, (c) plastic cutlery, (d) red meshes, (e) ropes and (f) poly-tubing (chululos).

observation) and for aquaculture farming activities.

2.4. Sources and description of environmental data

The information on weather conditions and their influence on daily litter accumulation rates is based on data from the Center for Advanced Studies in Arid Zones (CEAZA) at a nearby weather station (Panul station, 29°59′55″S, 71°23′54″W, available at www.ceazamet.cl). These data include hourly measurements of precipitation (in mm), and the wind speed and direction at 5 m above ground (in m s^{-1} and degrees, respectively). For the precipitation data, the maximum hourly values were used, and daily precipitation averages were calculated. For the wind data, the average wind speed was calculated from hourly observations, and the average wind direction was obtained from the zonal (u) and meridional (v) components. These components were averaged for each day to get a value prior to the litter sampling. The objective of this study is to analyze how rain events and strong winds influence the daily arrival of stranded marine litter on beaches. An environmental event is a specific natural or climatic phenomenon characterized by intense, often extreme, atmospheric or marine conditions (van den Hurk et al., 2015; Xu et al., 2023). These events can have significant impacts on the natural environment and on local human communities (Hay et al., 2016).

In our study, we established specific criteria for classifying rainfall events and associated sampling (Fig. 3). A "rain event" was defined as an event with accumulated precipitation higher than 7.5 mm during the 24 h before the sampling event (Fig. 3). According to CEAZA (2022), the hydrological system in the Coquimbo Region is currently in a very delicate situation due to below normal rainfall recorded since 2018. Therefore, when rain events occur, the values are generally higher than 7.5 mm. The daily beach sampling done before the main rainfall was classified as "one day before" (−1) the rain event, and the sampling done right after the rainfall event was considered as "one day after" (+1), even when the rain continued during the sampling (Fig. 3). Subsequent samplings were numbered consecutively as second day, third day, and so on. This system provided us with a consistent framework for analyzing how rainfall events affected litter item counts, allowing us to examine both preconditions and short- to medium-term changes after rainfall events. Due to the progressive sampling protocol described in Section 2.2., the number of land-based objects evaluated in relation to rainfall events varied temporally. Specifically, the first two rainfall events (03 and 17 June 2020) included only bottle caps (which are by far the most abundant terrestrial items); lighters were included after the third rainfall event (30 June 2020), and plastic cutlery after the fourth rainfall event (23 June 2021). Sea-based objects (chululos, red meshes, and ropes) were evaluated for all seven rainfall events, as their collection began prior to the first rainfall event analyzed.

Wind intensity was characterized by using a methodology similar to that applied for rainfall events. Average wind direction and wind speed were calculated based on the 24 h prior to each sampling, from 10 h to 9 h the following day. Regarding the wind speed criteria, it was considered that the study area is in a very protected bay and that wind speeds follow a breeze regime that intensifies on sunny days due to rapid heating of the semi-arid soil (Valle-Levinson et al., 2000). The daily average wind speed magnitude during the study period ranged from 0.1 m s^{-1} to 5.7 m s^{-1}. Given the sheltered nature of the bay, two main regimes of wind speeds were distinguished: (i) low winds (< 2 m s^{-1}), and (ii) high winds (≥ 2 m s^{-1}), with high winds potentially transporting greater amounts of marine litter to the beach (Fig. 4). Wind classification criteria were also established to recognize directions that could favor the arrival of significant amounts of litter to the beach. Two main categories were defined: onshore winds and offshore winds. Onshore winds, which blow from sea to land, were recorded in directions between 225.01° and 44.99°. These winds were considered favorable for the arrival of litter, as they blow towards the shore. On the other hand, winds blowing from land to sea (between 45.00° and 225.00°) were considered less likely to favor the accumulation of litter on the beach.

It is important to note that, although waves, tides and longshore currents are recognized as major drivers of nearshore litter transport and resuspension processes (e.g., Imhof et al., 2017; Krelling and Turra, 2019), herein we did not consider these variables because (i) they were considered of minor importance in the semi-enclosed bays studied, and (ii) while tides influence the general circulation in these bays (e.g., Valle-Levinson et al., 2000), they are unlikely to drive litter transport, as surface waves and currents are induced primarily by wind forcing (Valle-Levinson and Moraga-Opazo, 2006). For these reasons, for the quantitative analysis presented herein, we focused on the major drivers of marine litter transport in coastal environments, i.e., wind and rainfall.

2.5. Data analysis

A paired-samples *t*-test was conducted to evaluate the daily litter accumulation rates before and after each rain event. For each event, the amounts collected for each item were summed over the three days before and the three days after the event and then averaged across the seven rain events. Due to the presence of zeros in the dataset, a natural logarithmic transformation log (x + 1) was applied to meet the parametric assumption of normality and to reduce the influence of outliers (Quinn and Keough, 2002).

Wind directions (onshore and offshore) and speeds (low and high) were examined using a factorial analysis of variance (ANOVA) to determine how they, individually and in interaction, affected the daily total litter collected. Normality and homogeneity of variances were evaluated visually using the "*performance*" package (Lüdecke et al., 2021). Since the raw data did not meet the assumptions of the linear model, the response variable was transformed using log (x + 1) to handle the presence of zeros in the dataset. A post hoc test for multiple pairwise comparisons was performed to identify differences among the factors and levels of the factorial model using the "*emmeans*" package with a Tukey adjustment (Lenth, 2022). We used a Lomb-Scargle periodogram, an analysis method for irregular time series, to test the assumption of temporal independence of the ANOVA residuals using the "*lomb*" library in R (Ruf, 1999).

To determine how wind direction and speed affect the amounts of the different litter types arriving on the beach, we used the nonparametric

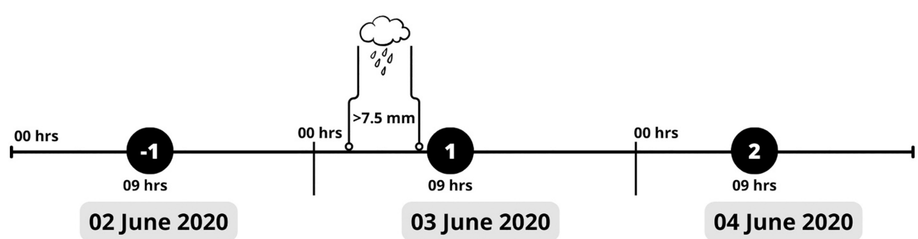

Fig. 3. Schematic representation of the criteria for rainfall events. The black circles represent the daily samplings. The number "-1" refers to the sampling one day before the rain event, whereas the number "1" refers to the sampling right after the rain event, and "2" to the second daily sampling after the rain event. The daily beach samplings were done at approximately 9 am.

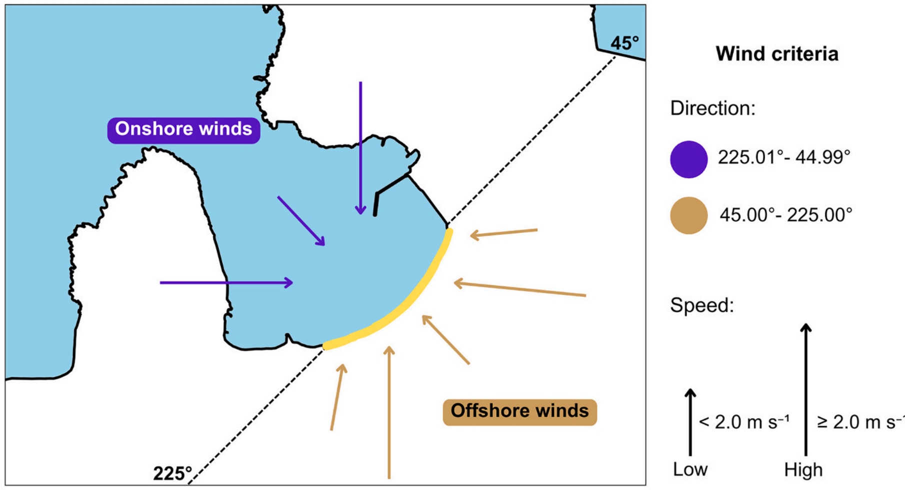

Fig. 4. Schematic representation of the criteria for identifying winds that could increase the amounts of litter on La Herradura beach. Onshore winds are considered from 225.01° to 44.99°. The yellow line represents the length of the beach sampled (1.68 km).

Mann-Whitney test for two independent samples, recommended for comparisons with nonnormal distributions (Crawley, 2005). To adjust for the response variables (items km^{-1} d^{-1}), a logarithmic transformation (log (x + 1)) was applied due to the presence of outliers. The complete dataset was divided into two subsets: one for onshore winds and the other for offshore winds. Then, an individual analysis was carried out for each dataset. The amounts of litter stranded on the beach were compared for each type of litter (the three types of land-based sources, plus the three types of sea-based sources) between days with low speeds and days with high speeds. Significance levels at 5 % were used in all models. All analyses were carried out using R 4.2.2 (R Core Team, 2023).

3. Results

3.1. Variation of sources and daily marine litter

From July 2020 to February 2024, a total of 20,313 plastic items were collected on La Herradura beach, of which 43.4 % corresponded to the three land-based objects (8809 items, all single-use plastics) and 56.6 % to the sea-based objects (11,504 items). This resulted in an average total accumulation rate of 19.0 ± 28.3 items km^{-1} d^{-1} (mean ± standard deviation, Table 2). Bottle caps were the most common objects, comprising 35.1 % of all items, followed by red meshes (33.3 %), ropes, chululos, plastic cutlery, and lighters (Table 2).

The daily litter accumulation rates on La Herradura beach were highly variable (Fig. 5). Some days, over 100 plastic items km^{-1} arrived on the shore, while other days none of the six litter types were found on the entire beach. The periods with high accumulation rates generally lasted several consecutive days, during which large amounts of litter reached the beach. After those periods, the daily litter accumulation rates usually decreased noticeably (Fig. 5). For the first sampling period of 2020, a similar temporal pattern was observed in the accumulation rates of litter from land- and sea-based sources. However, over the years 2021 to 2024, there were some exceptions, observing notable tendencies in the amounts of the different litter objects. These long-term differences in the daily accumulation rates between land- and sea-based objects (Fig. 5) are mainly due to the decrease in red meshes (see Fig. S1d in Appendix).

On Changa beach, a total of 876 plastic items were collected on the 20 sampling days between June and July 2022 (Fig. S2b in Appendix). In contrast to La Herradura beach, on Changa beach only the ropes were found, but not the other types of sea-based objects (chululos and red meshes). A total average accumulation rate of 23.4 ± 27.2 items km^{-1} d^{-1} was found (mean ± standard deviation). Of these, 98.5 % were from land-based sources (all single-use plastics), with bottle caps being the most collected (82.1 %), followed by lighters (10.3 %), plastic cutlery (6.2 %), and finally ropes (1.5 %) (see Table S1 in Appendix).

3.2. Influence of rainfall events on the arrival of marine litter

During the sampling period, a total of seven rainfall events were

Table 2
Daily accumulation rates for the total period, sources, and items recorded from July 2020 until February 2024 on La Herradura beach ($n = 635$ days).

Total period	Rates (mean ± sd) of (items km^{-1} d^{-1})	Median	Confidence interval	Min	Max	Total	%
Land-based							
Bottle caps	6.7 ± 20.9	2	0.8	0	398.2	7125	35.1
Lighters	0.5 ± 1.9	0	0.1	0	32.1	586	2.9
Plastic cutlery	1.0 ± 1.3	1	0.1	0	9.5	1098	5.4
Total Land	**8.3 ± 23.2**	**3**	**0.9**	**0**	**436.3**	**8809**	**43.4**
Sea-based							
Chululos	1.4 ± 1.6	1	0.1	0	10.1	1452	7.2
Red meshes	6.3 ± 12.4	2	0.5	0	91.7	6773	33.3
Ropes	3.1 ± 3.4	2	0.1	0	25	3279	16.1
Total Sea	**10.8 ± 14.0**	**7**	**0.6**	**0**	**98.2**	**11,504**	**56.6**
Total Land + Sea	**19.0 ± 28.3**	**11**	**1.1**	**0**	**464.9**	**20,313**	**100**

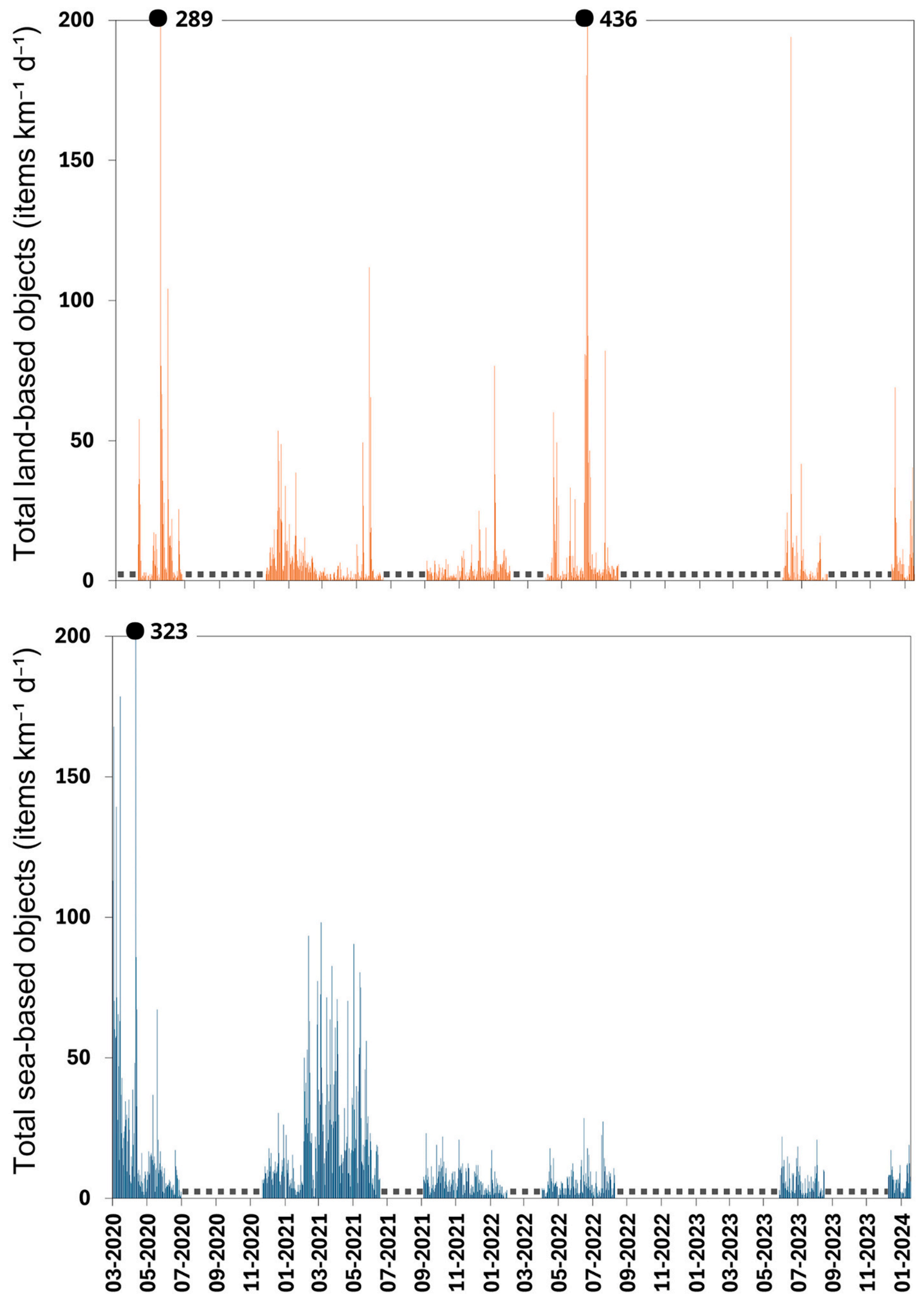

Fig. 5. Daily rates of litter accumulation during the entire sampling period on La Herradura beach. Land-based objects are shown in orange and sea-based objects in blue. The initial collection was progressive throughout 2020: bottle caps and chululos were added to the sampling protocol in May, lighters in June, and plastic cutlery in July. Dashed grey lines indicate periods when no sampling occurred. Three outlier values are highlighted with black dots.

identified (see Table S2 in the Appendix). In general, the daily accumulation rates of beached items reached their peak one day after the rainfall events (Fig. 6). For land-based objects, a marked pattern was observed between the days before and after the events, with maximum values recorded in the samplings after each rainfall event, and a notable decrease in the total amount of land-based objects from the second day of sampling after the rainfall (Figs. 6 and 7). In the case of sea-based objects, the situation was different, and the increases after the rainfall events were much more moderate and somewhat more variable (Fig. 6). The results of the paired *t*-test for the average of the three days before and after each rainfall event showed no clear response for sea-based objects, as for some events their daily accumulation rates after the rainfall were similar to those observed in the days preceding the event (Fig. 7). In contrast, land-based items showed a clear and consistent increase, with overall averages nearly quintuplicating from 20.7 items km^{-1} d^{-1} before rainfall to 109.7 items km^{-1} d^{-1} after.

On Changa beach, rainfall events n°5 and 6 were recorded during the sampling period (see Table S2 in the Appendix). Although the paired-samples t-test could not be performed due to the limited dataset, an increase in accumulation rates after rainfall was observed across all land-based objects (see Fig. S2c in the Appendix). The average number of land-based objects before rainfall was 4 items km^{-1} d^{-1} (47 items), while after rainfall, the average was 49 items km^{-1} d^{-1} (551 items).

3.3. *Influence of winds on the arrival of marine litter*

The factorial ANOVA (direction and speed) examining the effect on daily litter amounts detected a significant interaction between wind

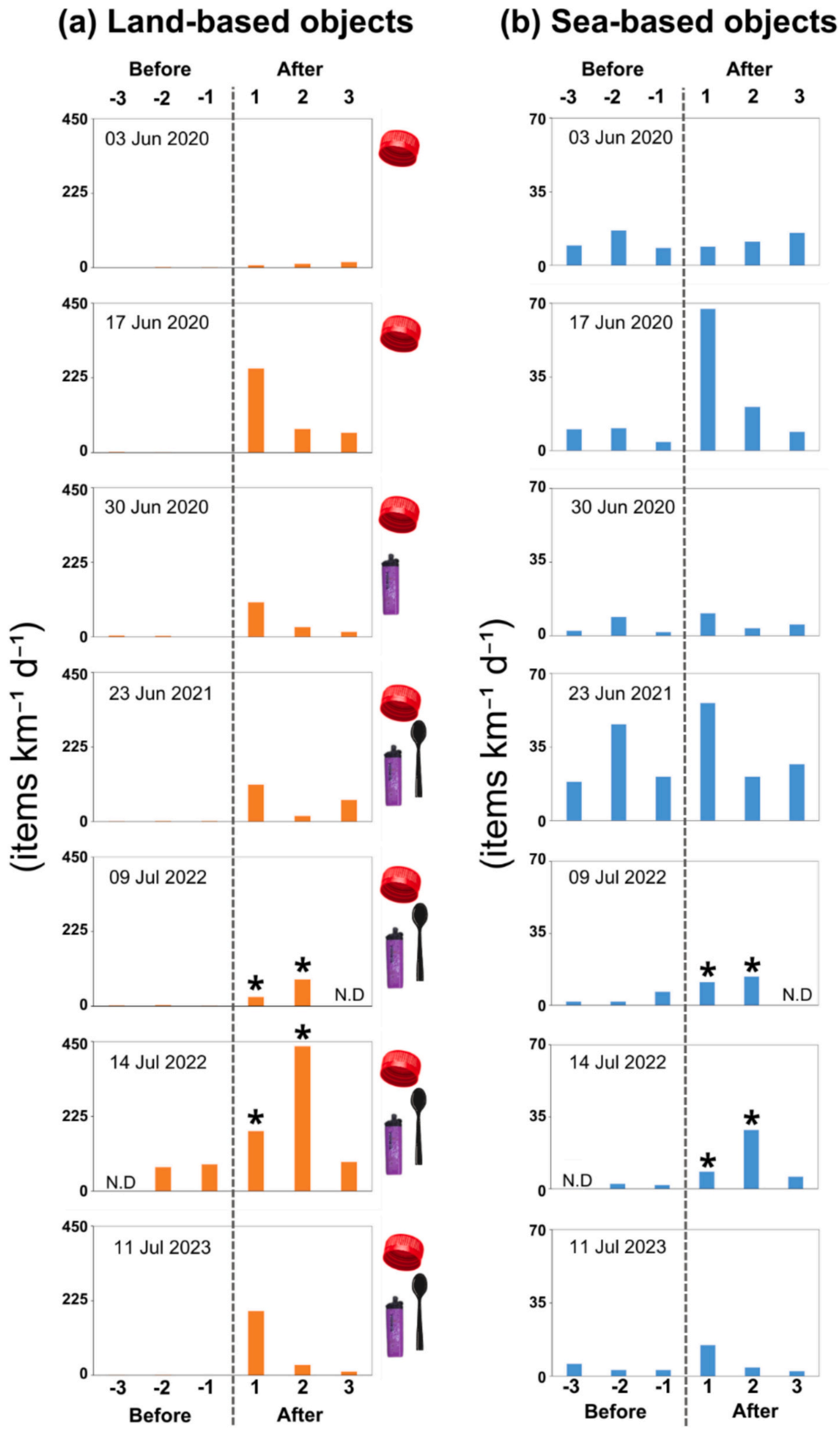

Fig. 6. (a) Daily variation of items from land-based objects, and (b) from sea-based objects that were collected three days before and after along the entire beach of La Herradura (1.68 km) during seven periods of rainfall (N.D = No Data). Dashed grey lines indicate rainfall events. *Two consecutive days of rainfall events (on July 9 and 14, 2022). The evaluation of land-based objects was progressive, as shown in the figure (see also Table 1).

direction and wind speed (Table 3, Fig. 8). There were greater amounts of litter on La Herradura beach on days with high onshore wind speeds than on days with low onshore wind speeds, while on days with offshore winds there was no difference between days with low and high wind speeds (Fig. 8). Additionally, high wind speeds of both types of wind (onshore and offshore) were associated with significant changes in the total daily amount of litter collected: on days with high onshore wind speeds there was more litter than on days with high offshore wind speeds (Fig. 8). Residual analyses showed no temporal structure, validating the use of the ANOVA (see Fig. S3 in the Appendix).

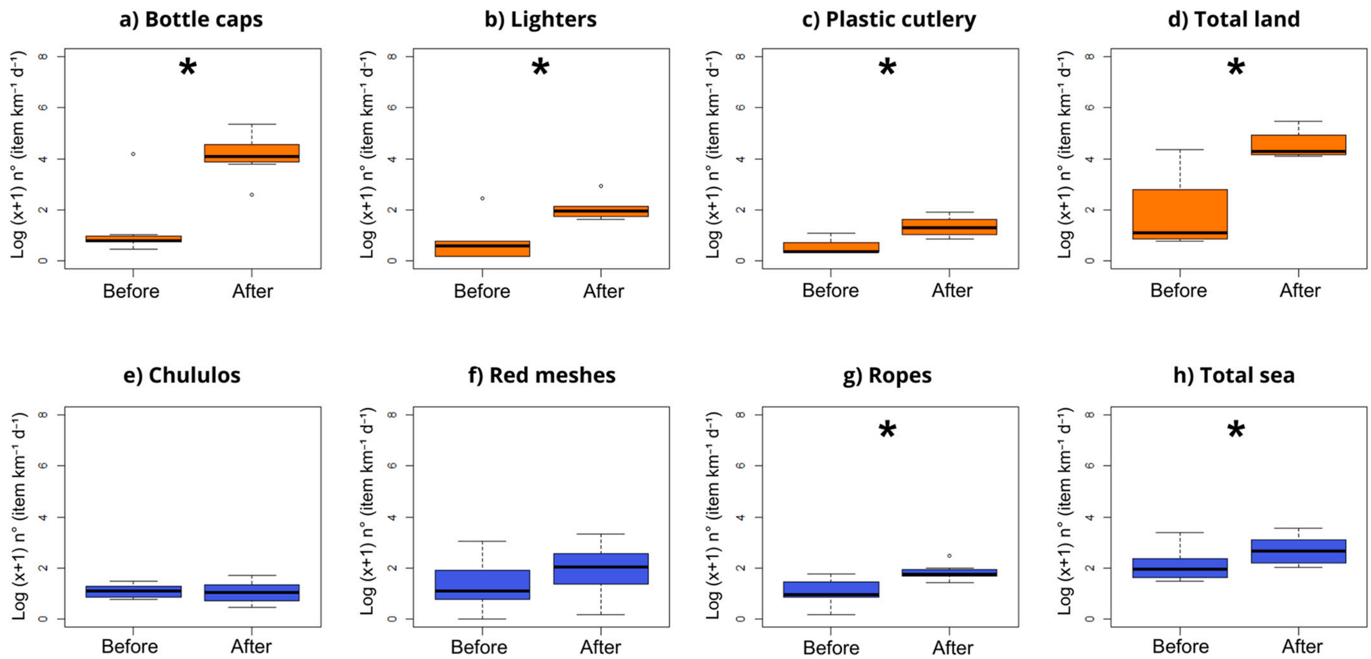

Fig. 7. Boxplots comparing the respective litter items on La Herradura beach between the 3-day periods before and after rainfall events. Statistically significant differences are observed at the $p < 0.05$ (*) level. In the boxplot, the thick black line in the middle represents the median, and the box shows the interquartile range (the middle 50 % of the data). The lines extending from the box (whiskers) represent the full range of data, excluding the outliers, represented as circles in the graph. It should be noted that lighters were evaluated in five rain events (from 30 June 2020), while plastic cutlery was evaluated in four events (from 23 June 2021). The other objects were evaluated in all seven rainfall events in the study (from 03 June 2020).

Table 3
Results of the two-way factorial ANOVA on the total amount of daily litter on La Herradura beach, considering wind direction and wind speed as factors ($n = 635$ days).

Source of variation	df	MS	F value	*p* value
Wind direction	1	1.30	1.73	0.19
Wind speed	1	10.41	13.77	< 0.001
Wind direction X wind speed	1	7.72	10.20	0.001
Residuals	631	0.75		

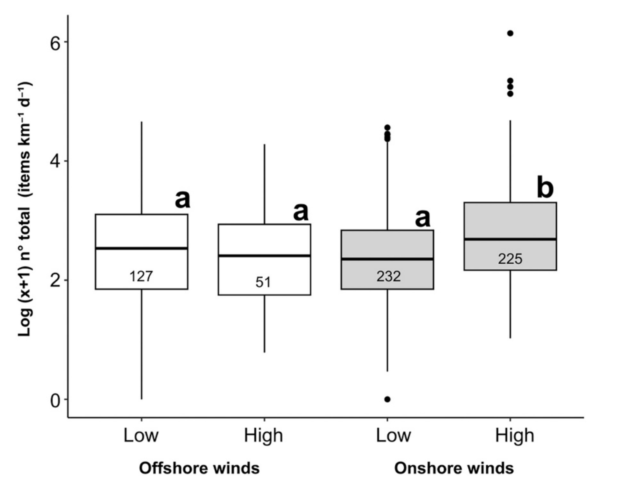

Fig. 8. Boxplots of litter items on La Herradura beach, showing the variations in the total amount of litter collected between low and high offshore and onshore wind speeds ($n = 635$ days). The letters above the boxes indicate significant differences based on the Tukey HSD post hoc test. The presence of the same letter above two boxes indicates no statistically significant difference between the groups, whereas different letters indicate significant differences. The numbers in the box represent the number of days that the wind was blowing from that direction and speed.

The application of the nonparametric Mann-Whitney test to analyze daily litter accumulation rates yielded different results depending on wind speed. In the case of offshore wind speeds, no significant differences were found between daily amounts of objects and high or low speeds in that direction (see Fig. S4 in the Appendix). However, a noticeable trend was observed for onshore wind speeds, where the daily amounts of litter for each object and source were higher at higher speeds (Fig. 9). This observation was statistically significant for most of the land-based objects, except for lighters. For sea-based objects, significance was only observed for red meshes, ropes, and total sea-based objects but not for the chululos (Fig. 9).

4. Discussion

4.1. Daily marine litter accumulation rates

There was a large variability in daily litter accumulation rates on La Herradura beach. Accumulation rates recorded in this study are lower than those reported for most previous studies (Table 4), which is likely due to the fact that herein only selected litter items were sampled, whereas most other studies had quantified the arrival of all litter items.

On urban beaches, high daily litter accumulation rates are often directly associated with beach visitors or nearby cities (Santos et al., 2005; Chitaka and von Blottnitz, 2019). Bottle caps were one of the most common terrestrial objects, with an accumulation rate at La Herradura of ~7 items km^{-1} d^{-1}. Surprisingly, for Apina Nui beach on Rapa Nui, Thiel et al. (2021a) recorded a similar accumulation rate of ~11 bottle caps km^{-1} d^{-1}, which likely came from bottles used by Asian fishing fleets operating in the South Pacific Ocean (see also Ryan, 2023). During March 2021, Rech et al. (2023) obtained litter accumulation rates of ~6.4 bottle caps km^{-1} d^{-1} for another beach in Rapa Nui (Anakena). Also, during March 2021, they reported ~1.2 bottle caps km^{-1} d^{-1} for the remote Choros beach, which is ~80 km north of our main study

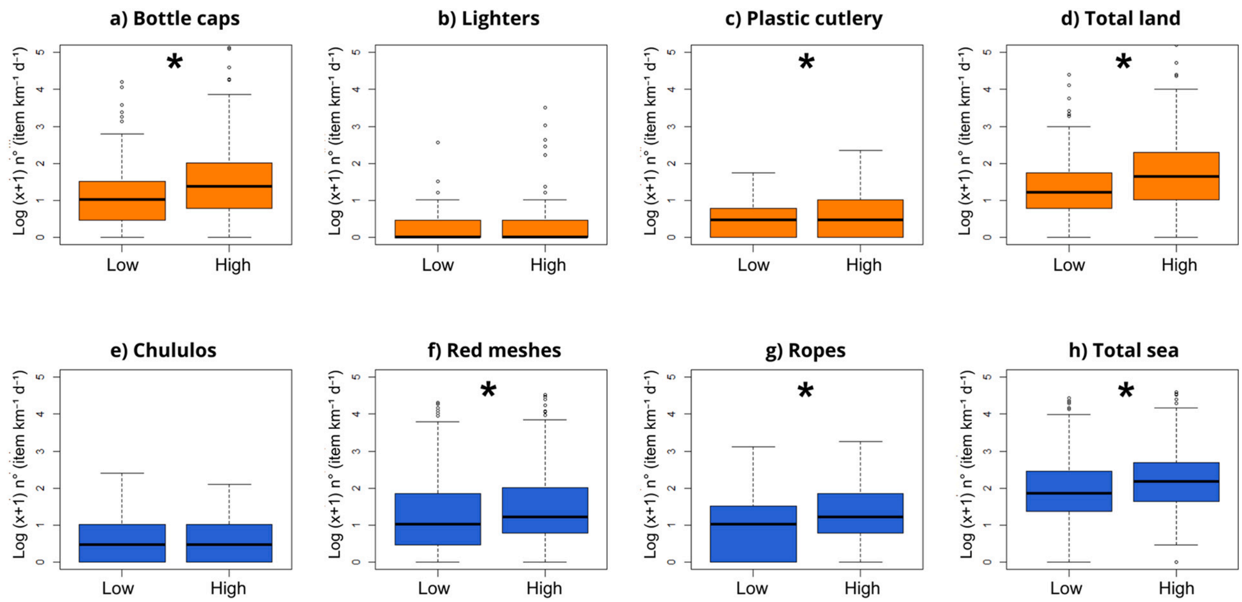

Fig. 9. Boxplots of litter items on La Herradura beach, comparing days with low and high onshore wind speeds for each item and source ($n = 457$ days in total, 232 days with low wind speeds and 225 days with high wind speeds). Statistically significant differences are observed at the $p < 0.05$ (*) level. In the box plot, the thick black line in the middle represents the median, while the box itself shows the interquartile range (the middle 50 % of the data). The lines extending from the box (whiskers) represent the full range of data, excluding outliers, which are represented as circles in the graph.

Table 4
Daily litter accumulation rates reported from studies according to Thiel et al. (2021a), updated and arranged from lowest to highest average. Studies with the highest average accumulation rates are marked in bold.

Sampling site	Longitude/ Latitude	Study year (days sampled)	Items km^{-1} d^{-1}			Reference
			Avg.	Min.	Max.	
Urban Beaches						
La Herradura, Chile	71°W/29°S	2020–24 (635)	19	0	465	This study*
Changa, Chile	71°W/29°S	2022 (20)	23	0	101	This study*
Maitencillo, Chile	71°W/32°S	2021 (12)	255	20	973	Rech et al., 2023
Ritoque, Chile	71°W/32°S	2021 (12)	520	69	1703	Rech et al., 2023
Cape Town, S Africa	18°E/34°S	1994 (15)	950	350	1550	Ryan et al., 2014
uMhlanga, S Africa	31°E/30°S	2019 (10)	1230	0	3120	Meakins et al., 2022
Cape Town, S Africa	18°E/34°S	2020 (36)	1650	200	19,900	Ryan and Perold, 2021
Amanzimtoti, S Africa	31°E/30°S	2019 (9)	1930	480	3750	Meakins et al., 2022
Cape Town, S Africa	18°E/34°S	1995 (14)	2090	1300	2870	Ryan et al., 2014
Coffs Harbor, Australia	153°E/30°S	2013 (7)	2210	1540	2650	Smith and Markic, 2013
Cassino, Brazil	52°W/32°S	2003 (60)	6200	2100	10,300	Santos et al., 2005
Cape Town, S Africa	18°E/34°S	2012 (30)	8310	2040	14,580	Ryan et al., 2014
Cape Town, S Africa	18°E/34°S	2017 (10)	**12,610**	360	29,610	Chitaka and von Blottnitz, 2019
Remote Beaches						
Cousine Isl., Seychelles	55°E/4°S	2003 (61)	10	–	–	Dunlop et al., 2020
Pitcairn Island	130°W/25°S	2019 (90)	10	–	–	Ryan and Schofield, 2020*
Macquarie Island	159°E/55°S	2001 (124)	10	0	70	Eriksson et al., 2013
Heard Island, S—W Bay	73°E/53°S	2001 (123)	20	0	80	Eriksson et al., 2013
Cousine Isl., Seychelles	55°E/4°S	2019 (90)	30	0	40	Dunlop et al., 2020
Mar Brava North, Chiloé	74°W/41°S	2021 (12)	37	16	80	Rech et al., 2023
Heard Island, West Bay	73°E/53°S	2001 (123)	40	0	570	Eriksson et al., 2013
Mar Brava South, Chiloé	74°W/41°S	2021 (12)	74	30	146	Rech et al., 2023
Choros, Chile	71°N/29°S	2021 (12)	151	9	565	Rech et al., 2023
Anakena, Rapa Nui	109°W/27°S	2021 (10)	200	44	360	Rech et al., 2023
Apina Nui, Rapa Nui	109°W/27°S	2017 (190)	230	0	1900	Thiel et al., 2021a
Ovahe, Rapa Nui	109°W/27°S	2021 (10)	300	75	500	Rech et al., 2023
Maui Island, Hawaii	156°W/21°N	2015 (28)	2090	–	–	Blickley et al., 2016
Can Gio, Vietnam	107°E/10°N	2021–22 (30)	2400	600	13,300	Nguyen et al., 2025
Henderson Island	128°W/24°S	2015 (6)	**14,250**	1700	26,800	Lavers and Bond, 2017
Sulawesi	120°E/6°S	2016 (17)	**14,300**	–	–	Hermawan et al., 2017

* In these studies, only a specific selection of objects was sampled while the other studies collected all litter objects on the beach.

beach in urban La Herradura Bay, where herein we found for the same time period a bottle cap accumulation of ~2.6 items km^{-1} d^{-1}. An urban beach in South Africa received an average of ~27 bottle caps km^{-1} d^{-1}, with important rainfall dynamics, indicating that this land-based litter accumulates close to source areas (Ryan et al., 2024). For a remote beach, these authors reported a very similar accumulation rate

(26 bottle caps km^{-1} d^{-1}), but the fact that most bottle caps (>60 %) had epibionts suggested that they had come from distant sources. Rech et al. (2023) also reported high accumulation rates for an urban beach, Maitencillo, with ~20 bottle caps km^{-1} d^{-1}. These comparisons suggest that remote and urban beaches could have similar accumulation rates, but their catchment area may differ substantially, being typically small and land-based for urban beaches and enormous and sea-based for remote beaches.

Lighters were listed as the third most frequently found item from land-based sources, with a mean accumulation rate of ~0.5 items km^{-1} d^{-1} on La Herradura beach. In contrast, in the Seychelles, Dunlop et al. (2020) and in Apina Nui Thiel et al. (2021a) recorded a lower mean number of lighters (~0.2 items km^{-1} d^{-1}). However, Rech et al. (2023) reported no lighters for Anakena beach and ~0.3 lighters km^{-1} d^{-1} for Maitencillo beach. Lower accumulation rates of lighters on remote beaches were probably due to the distance from their main sources. In the case of La Herradura, these objects were common throughout the sampling period and given that no objects with pelagic epibionts were found (which would indicate prolonged time in the ocean), the land-based litter collected on La Herradura beach is likely of very local origin.

Regarding sea-based objects, specifically ropes, an accumulation rate of ~3 items km^{-1} d^{-1} was observed in La Herradura, notably lower than that reported for Rapa Nui by Thiel et al. (2021a) in Apina Nui (~45 items km^{-1} d^{-1}) and by Rech et al. (2023) in Anakena (~55 items km^{-1} d^{-1}). This marked contrast suggests that the high concentration of ropes on the Rapa Nui beach may be linked to industrial fishing activity in the open South-East Pacific (Luna-Jorquera et al., 2019; Rech et al., 2023). Similarly, when comparing the same 12-day period in 2021 (14–25 March), Choros beach had a much higher accumulation of ropes (~61.3 items km^{-1} d^{-1}; Rech et al., 2023) than La Herradura (~1.7 items km^{-1} d^{-1}). The high accumulation of ropes in Rapa Nui could be explained by the geographical position of the island and its proximity to the South Pacific Subtropical Gyre (SPSG) (Rech et al., 2018; Rech et al., 2023), while in Choros it may be due to its location in productive coastal areas with greater fishing activity. La Herradura beach shows lower rope accumulation rates, even with significant boat traffic, likely due to the bay's sheltered configuration and reduced wave action, which minimize rope losses. When comparing with five urban beaches in South Africa, Chitaka and von Blottnitz (2019) reported highly variable accumulation rates of ropes, with one beach having high accumulation (~44.4 ropes km^{-1} d^{-1}) similar to Rapa Nui, while the lowest accumulated only 3.5 ropes km^{-1} d^{-1}. For the urban beach of Maitencillo, Rech et al. (2023) reported ~9 ropes km^{-1} d^{-1}. The rates from La Herradura are similar to these low accumulation rates, suggesting that these ropes are of very local origin. Furthermore, the presence of chululos exclusively in La Herradura indicates that they are extremely local because they do not float, while red meshes are also local, but they do float, and their dispersion might be mostly coastal and might also not be so limited to the bay.

Our results suggest that La Herradura has relatively moderate litter accumulation rates compared to other urban and remote beaches. The daily rates of bottle caps, lighters, and ropes indicate that marine litter on this beach is predominantly of local origin, with little input from large-scale ocean currents or distant fishing activities. This contrasts with beaches such as those of the oceanic islands of Rapa Nui or the Galapagos, where litter mainly comes from large international fishing fleets operating in the wider South Pacific Ocean (Luna-Jorquera et al., 2019; Muñoz-Pérez et al., 2023; Benito-Kaesbach et al., 2024). La Herradura's status as a sheltered bay seems to limit the accumulation of litter of distant origin, with litter pollution coming mostly from local sources. Importantly, all land-based objects collected consisted of single-use plastics, highlighting the direct impact of local human activities in the area. It is recommended that further studies include daily and spatial sampling at other urban beaches to better understand local litter dynamics and sources.

4.2. Influence of rainfall events on marine litter arrivals

The relationship between rainfall events and litter accumulation rates was evident in this study's results. Specifically, after rainfall events, we observed a significant increase in all three types of land-based litter (bottle caps, lighters, and plastic cutlery) at both La Herradura and Changa beaches. In contrast, litter from sea-based sources showed no clear relationship with rainfall patterns. Results from several other studies support this trend, showing that litter amounts increased after rainfall events (Baptista and Monteiro, 2010; Ryan and Perold, 2021; Zhang et al., 2024). For example, higher amounts of litter on beaches often coincide with the rainy season (Lopes da Silva et al., 2016; Duong et al., 2025). On a beach in Cape Town, South Africa, litter levels peaked after rainfall events and decreased thereafter, attributed to litter flushed out from a nearby coastal wetland (Ryan and Perold, 2021). These findings indicate that most floating litter accumulates on coastal beaches near river mouths and streams, as also documented by Rech et al. (2014) for several Chilean beaches.

Previous studies have demonstrated that rainfall events significantly enhance litter accumulation on shorelines, with this effect being particularly pronounced near large rivers and population centers (Zhao et al., 2014; Kiessling et al., 2019; Honorato-Zimmer et al., 2021; Palmas et al., 2022; Liro et al., 2023; Stagličić et al., 2025). On the beaches of Mangaluru, India, Sulochanan et al. (2019) found that the amounts of plastic are positively related to rainfall and river flow, and plastics were the most abundant (such as bottle caps, plastic cutlery, meshes and ropes), coinciding with the maximum runoff values. However, rainfall-driven litter accumulation is not limited to areas with large river systems. On La Herradura and Changa beaches, land-based litter items (single-use plastics) also increased significantly after rainfall events, despite the absence of major rivers in the study area. This pattern suggests that surface runoff during rainfall efficiently mobilizes litter from nearby sources to coastal areas. In Bahia La Herradura, where paved areas and bare soil predominate and grassy surfaces are scarce, litter is unlikely to be retained before reaching the beach, and the comparatively steep slopes in the terrain surrounding the bay further facilitate transportation to the shore. Experimental evidence shows that the mobilization of macroplastics is greater on paved and steeper terrain than on vegetated surfaces (Mellink et al., 2024), reinforcing the idea that local terrain characteristics strongly influence litter arrival on the beach.

The absence of large rivers in the study area is also expected to affect the observed patterns. La Herradura beach has small streams that only drain into the sea when it rains, while on Changa beach there is a slightly larger estuary (El Culebrón) that depends on an underground aquifer (Menceyra, 2016). This scenario of small streams or small estuaries at both beaches, combined with the observed immediate response to rainfall events, suggests that most land-based litter comes from nearby sources rather than from distant upstream cities. This is also suggested by van Emmerik et al. (2019), who observed a tenfold increase in macroplastic litter in the Seine River, France, directly after rainfall events. Due to the short distances from sources (adjacent urban areas) to the local beaches, typically there is no lag time, i.e., terrestrial litter objects appear on the beach within hours after being mobilized by rain runoff (see also in Cheung et al., 2019; Chitaka and von Blottnitz, 2019; Ryan and Perold, 2021). This rapid or short-lag response has been documented elsewhere. For example, in Victoria Harbor (Hong Kong), the abundance of microplastics specifically correlated with same-day rainfall events (Zhang et al., 2024). Similarly, in the SW Baltic Sea, elevated microplastic concentrations have been documented shortly after rainfall events (Ory et al., 2020), and in the Têt River (north-western Mediterranean), higher concentrations of macroplastics were recorded during moderate discharges on rainy days, including notable accumulations of cigarette butts at the beginning of increased flow (Laverre et al., 2023; Cesarini et al., 2023). These findings highlight the rapid appearance of plastics immediately after rainfall events, evidencing that pollution sources are predominantly local and proximate to water bodies, rather than distant in origin. This close temporal relationship between rainfall and contamination confirms the importance of implementing litter management measures focused on adjacent urban areas to effectively reduce plastic inputs to the marine environment. Local authorities should prioritize waste management, especially following rainfall events (and also during the summer), to prevent litter accumulation and dispersal.

4.3. Influence of winds on marine litter arrivals

On La Herradura beach, the arrival of marine litter is directly driven by high onshore wind speeds, which aligns with numerous studies documenting a strong positive relationship between wind intensity and litter accumulation in coastal areas (Kako et al., 2010; Blickley et al., 2016; Sawan et al., 2025). The observed wind-litter relationship is strongly influenced by the windage factor of different litter types. Red meshes, chululos, and ropes have relatively low windage factors and often exhibit neutral buoyancy, which may explain why only strong winds significantly affect litter accumulation. Strong winds can mobilize deeper water layers and generate more turbulent conditions, enabling the transport of neutrally or even negatively buoyant items that would otherwise remain unaffected by moderate onshore breezes. This finding is consistent with Haarr et al. (2024), who observed on three Norwegian beaches that while moderate onshore winds did not affect litter accumulation, strong winds significantly increased litter deposition.

Although our results clearly highlight the influence of wind on daily litter accumulation, wind-driven processes are strongly coupled with other nearshore hydrodynamic factors, such as waves and tides (Bettim et al., 2021). The direction and strength of the wind can modify wave heights and local wave patterns, thereby affecting the pathways and deposition of floating and neutrally buoyant items on the beach (Meakins et al., 2022). The observed wind-litter relationship may also reflect, at least in part, the effect of these coupled hydrodynamic processes.

This wind-influenced distribution pattern is evident across diverse geographical contexts worldwide. In a NE Atlantic estuary, Browne et al. (2010) recorded high concentrations of low-density plastics specifically in downwind areas, demonstrating the directional effect of wind on plastic distribution. Similarly, studies conducted in South Africa confirmed that wind is a determining factor in dispersion direction, with most objects recovered from downwind locations (Maclean et al., 2021). In insular environments such as the remote island of Rapa Nui, Thiel et al. (2021a) observed that strong onshore winds led to increased amounts of litter washed up on the studied beach. This positive relationship has also been documented for the Chilean continental coastline, where strong onshore winds that characterize this coast have been identified as possible transport mechanisms for floating marine litter (Thiel et al., 2013) and even floating kelps (Rothäusler et al., 2021).

Wind speed and direction can also influence daily variations in marine litter in coastal environments (Blickley et al., 2016; Thiel et al., 2021a; Nguyen et al., 2025). The time scale of this influence can vary considerably depending on local conditions and litter characteristics. Maclean et al. (2021) demonstrated that expanded polystyrene (EPS) blocks moved rapidly downwind shortly after release in two South African rivers. A study on a subantarctic island revealed that winds from the previous day also significantly correlated with the number of litter items and that some had attached epibionts, indicating long-distance transport and prolonged time at sea (Eriksen et al., 2013). The rapid accumulation of litter in La Herradura Bay, which occurred within 24 h of the wind events, strongly suggests that these objects originate from very local rather than distant sources.

La Herradura beach is located in a very sheltered bay, which could explain a weaker relationship between wind and litter compared to other studies on oceanic islands. For example, on the coast of Maui, increased litter abundances were observed under the influence of the North Pacific Subtropical Gyre and strong onshore winds (Blickley et al., 2016). A similar finding was observed by Thiel et al. (2021a), where the coasts of Rapa Nui Island are receiving a continuous and wind-enhanced input of floating plastic litter from the surrounding polluted waters of the South Pacific Subtropical Gyre (e.g., Miranda-Urbina et al., 2015). On the shores of these oceanic islands, catchment areas are very large, and litter is constantly arriving, which may also explain the very high accumulation rates of ropes and other objects (see above). In contrast, the catchment area of La Herradura Bay is relatively small and possibly limits the input of litter arriving from the sea. The relationship between onshore winds and litter amounts highlights the importance of considering local-scale processes when developing effective management strategies for coastal litter, as targeted interventions focused on nearby sources could produce immediate improvements in sheltered bays.

5. Conclusions and outlook

This study shows that most litter arriving on the shores of La Herradura and Changa beaches originates from local sources, including nearby urban development, aquaculture, and fishing activities. Temporal patterns are strongly associated with local meteorological conditions. Specifically, land-based objects (bottle caps, lighters, and plastic cutlery) showed significant increases after rainfall events, while the accumulation of sea-based objects (particularly ropes) was correlated with strong onshore winds. The high amounts of land-based litter found on beaches immediately after rainfall events support the conclusion that post-rainfall litter on urban beaches has a very local origin (from urban areas surrounding the beach). This study also corroborates the strong positive relationship between strong onshore winds and the arrival of marine litter on La Herradura beach. Given the location of the very sheltered bay, it is highly unlikely that litter from distant locations reaches the studied beach.

The local situation in this bay can serve as a model for protected bays and urban beaches, as the current study confirms that the problem is primarily local and that litter does not come from distant sources. At the national level, immediate actions are needed to address upstream drivers of pollution, including phasing out single-use plastics (many identified in this study) and promoting reusable or refillable alternatives. Chile's Extended Producer Responsibility law should be fully enforced to hold manufacturers accountable throughout the product life cycle. The marine industry, particularly aquaculture and fisheries, should also transition to biodegradable, sustainable materials (Moore, 2014). Additionally, public awareness campaigns are essential to reduce single-use plastics and protect coastal areas. In summary, this study confirms that local littering is a key contributor to pollution on semi-enclosed urban beaches. Addressing marine litter requires more than local cleanup efforts; it should focus on preventive, systemic change, including sustainable product design, producer responsibility, regulatory reform, and community engagement, to achieve long-term reductions in coastal pollution.

CRediT authorship contribution statement

Josefa Araya-Campano: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Investigation, Formal analysis, Data curation, Conceptualization, Methodology, Funding acquisition. **Diamela De Veer:** Writing – review & editing, Investigation. **Mauricio Ergas:** Writing – review & editing, Investigation. **David Jofré-Madariaga:** Writing – review & editing, Visualization, Formal analysis. **Ninoshka López-Xalín:** Writing – review & editing, Investigation. **Camilo Merino von Brand:** Writing – review & editing, Validation, Investigation, Data curation. **Macarena Pozo-Rodríguez:** Writing – review & editing, Investigation. **Marcel Ramos:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Marcelo M. Rivadeneira:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Diego Valdés:** Writing – review & editing, Investigation. **Nelson Vásquez:** Writing – review & editing, Investigation. **Martin Thiel:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.118949.

Data availability

All data extracted from the reviewed literature and used for the preparation of this manuscript are openly accessible at Zenodo.org (https://doi.org/10.5281/zenodo.17544372).

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