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Research Article

Characterization, accumulation patterns, and conservation implications of marine debris in Puerto López Beach, Manabí, Ecuador

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ABSTRACT. Marine debris (MD) is a growing global environmental issue, driven by unsustainable production and consumption and inadequate waste management. This study characterizes MD accumulation patterns at Puerto López Beach, Ecuador, and examines the environmental and anthropogenic factors that influence them. From April to December 2023, debris was collected every 15 ± 3 days from five sites representing different activity zones (CR: commercial/river mouth; CE: commercial and entertainment; HS: hotel and shipyard; E: ecotourism; ER: ecotourism/river mouth) using standardized protocols. Data from the CR site were treated independently, as accumulation was daily due to frequent beach cleanups conducted there. Results revealed that plastics dominated MD (79-96%), primarily plastic ropes, fragments, and single-use items, with fishing gear significantly contributing to ocean-based debris. Accumulation rates varied by site, with the highest levels at site HS near fishing and shipyard areas (972 items fortnight^{-1}). Generalized linear models indicated that seasonal and tidal dynamics influenced debris distribution, with lower accumulation during the dry season and greater debris dispersal during higher tidal ranges. Land-based debris prevailed in tourist zones, while ecotourism areas showed more fragmented plastics, suggesting prolonged exposure. Notably, most debris originated locally, underscoring the need for targeted waste management strategies. The findings highlight the importance of site-specific interventions, such as improved disposal of fishing gear, enhanced waste infrastructure, restrictions on single-use plastics, and environmental education, to mitigate MD impacts. This study provides evidence to inform policy discussions and local conservation strategies, emphasizing the urgency of addressing plastic pollution in coastal Ecuador and its implications for marine biodiversity and tourism.

Keywords: marine debris; plastic pollution; environmental management; waste accumulation; Puerto López; Ecuador

INTRODUCTION

Marine debris (MD) is becoming an increasingly serious environmental issue worldwide (Ivar do Sul & Costa 2007, Blickley et al. 2016), driven primarily by unsustainable production, consumption patterns, and inadequate waste management (Agamuthu et al. 2019, da Silva-Videla & Vieira de Araujo 2021, Ansari & Farzadkia 2022). It refers to any anthropogenic solid material that enters the marine environment from any source (Agamuthu et al. 2019, Santos et al. 2009, Slavin et al. 2012, United Nations Environment Program 2021).

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Plastics, especially single-use items from daily activities, dominate MD (Napper & Thompson 2020). The majority (60-80%) originates from land-based sources, including beach visitors, household and industrial waste, agricultural runoff, wind, rivers, poor management, and illegal disposal (Santos et al. 2009, Ribic et al. 2012, Slavin et al. 2012, Eriksen et al. 2013, Madricardo et al. 2020, Napper & Thompson 2020, United Nations Environment Program 2021, Ansari & Farzadkia 2022). Tourism and user behavior also directly influence MD accumulation (Currie et al. 2023, Inocente et al. 2023), as environmental conditions and physical factors (Blickley et al. 2016).

In 2010, between 4.8 and 12.7 million tons of MD entered the ocean, of which 80% was plastic (Berry et al. 2023). Plastic production has surged from 1.5 million tons in 1950 to 395 million tons in 2018, driven by its durability, flexibility, and lightness, which also make it a persistent pollutant (Berry et al. 2023). Plastic waste can carry toxins that affect the endocrine systems of marine fauna (Agamuthu et al. 2019). Although toxin transport is not the primary pathway of chemical exposure, it remains a significant concern (Napper & Thompson 2020).

Plastic waste, which constitutes a large portion of MD, is buoyant, long-lasting, and easily transported over vast distances (Santos et al. 2009, Slavin et al. 2012, Eriksen et al. 2013, Agamuthu et al. 2019, Napper & Thompson 2020). Environmental factors such as currents, wind, and waves contribute to its transport and fragmentation, thereby amplifying its impact (Serra-Gonçalves et al. 2019, Madricardo et al. 2020, Vogt-Vincent et al. 2023). This waste often accumulates in convergence zones, with major debris patches reported in the North Atlantic Subtropical Gyre, the North Pacific Subtropical Gyre, and the Indian Ocean Subtropical Gyre (Santos et al. 2009, Eriksen et al. 2013, Agamuthu et al. 2019, Napper & Thompson 2020, United Nations Environment Program 2021).

Ecuador, home to over 17 million people (INEC 2025), is shaped by environmental factors such as the Humboldt Current and El Niño, which influence ocean productivity (Miloslavich et al. 2011, Chinacalle-Martínez et al. 2021) and MD transport along its coast (Jones et al. 2021). Fishing is a key economic activity (Béarez et al. 2012, Martínez-Ortiz et al. 2015), and the country ranks among the top tuna exporters (Bellinger 2011). However, the sector significantly contributes to MD on beaches through abandoned gear, fuel containers, and vessel waste (Osejos-Merino et al. 2017). Given that over 108,000 families (432,000 people) in Ecuador depend on fishing (CNP 2016), this is critical, and over 200 million people globally rely on fisheries (United Nations Development Program 2018). Recent MD studies in Ecuador (Serra-Gonçalves et al. 2019, Gaibor et al. 2020, Ansari & Farzadkia 2022, Salazar et al. 2022) report that plastic is the most prevalent MD, with fishing net fragments and single-use items dominating its composition. However, beach users are also major sources (Mestanza et al. 2019, Gaibor et al. 2020). Notably, no study has yet explored the complex interplay between environmental drivers, human activities, and MD accumulation in Ecuador's coastal ecosystems.

Understanding the types and quantities of MD is essential for guiding effective, long-term management actions (Ribic et al. 2012). This study aimed to: 1) characterize MD accumulation patterns in five areas of Puerto López Beach, Manabí, Ecuador; 2) identify environmental, temporal, and anthropogenic factors influencing it; and 3) provide evidence to inform local management strategies and conservation discussions.

MATERIALS AND METHODS

Study area

The study took place on the Puerto López Beach, Manabí, Ecuador, a fishing village with 13,489 inhabitants (INEC 2022). Visited mainly by national tourists, the sandy beach holds a level C rating in the aesthetic quality index (A: excellent to D: poor) (Mestanza et al. 2019). Since 1980, tourism has grown by 1,500%, peaking from June to September during humpback whale season (Castro et al. 2022). Dominant coastal currents off Ecuador generally transport water offshore (Collins et al. 2013). While the surface Ecuador-Peru Coastal Current flows southward, the subsurface Equatorial Undercurrent and the northwestward Coastal Ecuadorian Current enhance offshore displacement, though seasonal conditions can temporarily alter these flows (Chaigneau et al. 2013).

The 4 km-long beach of Puerto Lopez is divided into an urban area and an ecotourism zone (Fig. 1). The urban area borders anthropogenic structures, including boardwalks, shops, and hotels. In contrast, the ecotourism zone, adjacent to it, lacks beachfront development, features native vegetation, and is accessible only on foot. Five sampling sites were established along the beach to assess MD accumulation across different activity zones. Site commercial/river mouth (CR) (01°33.68´S, 80°48.92´W) is located in front of the artisanal fish market and the river mouth known as "Poza de la Vida," near the tourist dock. Site

Figure 1. Map of the study area, Puerto López beach, showing the division of the beach into five sites. Insets show aerial views of the designated survey area.

commercial and entertainment (CE) (01°33.47´S, 80°48.77´W) corresponds to the commercial and entertainment area, with the highest concentration of swimmers, restaurants, cabins, and street vendors. Site hotel and shipyard (HS) (01°33.07´S, 80°48.67´W) is in front of a hotel, and a shipyard used for boat and fishing gear repairs. Site ecotourism (E) (01°32.33´S, 80°48.65´W) represents a remote ecotourism area, while Site ecotourism/river mouth (ER) (01°32.10´S, 80°48.72´W) is located near the mouth of the Buena Vista River in the farthest area of the ecotourism zone.

Sampling

The methodology followed the NOAA Marine Debris Shoreline Survey Field Guide (Opfer et al. 2012) and used the accumulation protocol. Before sampling, each site was cleared of debris to establish a baseline.

Data sheets were adapted from Opfer et al. (2012), using their hierarchical category system: eight general categories (plastic, paper/wood, glass, metal, objects for personal use, textile, rubber, electronics), each containing multiple specific item categories (e.g. under "plastic": rope, buoys, cups, straws, bags, bottles, caps, cigarettes, etc.; see full list in Table S1). When volunteers encountered an item that did not fit any pre-existing specific category, they marked "other" and described the item, creating an ad hoc category (e.g. "sponges" and "PVC pipe" were added during the study). After each sampling event, the lead researcher reviewed all "other" entries and reclassified items that could be assigned to an existing specific category accordingly. In contrast, genuinely new categories were added to the master list for subsequent surveys.

Once the final category list was consolidated, the researchers assigned a debris origin to each category, following the indicator debris categories defined by Blickley et al. (2016). According to their framework, ocean-based items are those associated with fishing or boat activities (e.g. buoys, nets, ropes, fishing bait, fiberglass); land-based items are those originating from beach users or terrestrial sources (e.g. straws, food wrappers, cigarette butts, napkins, ice cream sticks). General-source items are those that could plausibly originate from either land or ocean (e.g. cups, plastic bags, bottles, unidentifiable fragments). Labels, brand names, and dates were checked, but no notable cases (e.g. foreign or very old items) were found.

Sampling was conducted every 15 ± 3 days. Beach cleanups organized by the local government or environmental groups were recorded, and data were excluded when cleanups occurred within the sampling interval. At site CR, the municipality cleaned daily after each survey; therefore, its data were analyzed separately and are not comparable to other sites due to daily accumulation patterns. Sampling was conducted during low tide, as indicated by the INOCAR (2024) tide tables.

At each of the five sampling sites, a 100 m survey area was demarcated parallel to the waterline. Following the accumulation protocol of Opfer et al. (2012), a complete beach sweep was performed: the entire area from the water's edge to the backshore limit (vegetation line or, where absent, human-made structures such as the dock or the tent area) was searched in a zigzag pattern, and all visible MD items ≥2.5 cm were collected. This procedure ensured full coverage of the defined area at each site and sampling event. Coordinates were recorded using the OsmAnd 4.7.17 mobile app.

Analysis

To explain debris accumulation and retention, two environmental indices were calculated for each sampling day: relative tidal range (RTR) (Short 1996) and intertidal area (IA) (McLachlan & Dorvlo 2005):

$$\mathrm{RTR} = \frac{\mathrm{Ht}}{\mathrm{Hw}} \quad \mathrm{IA} = \frac{\mathrm{Ht}}{\mathrm{S}}$$

where Ht represents the mean tidal height, and Hw represents the mean wave height (m), based on daily records during each survey period provided by INOCAR (2024). Tidal heights ranged from 2.20 to 2.95 m, and wave heights from 1.09 to 2.90 m were also taken from INOCAR (2024). S corresponds to beach slope (°). Climatic seasonality was defined according to WeatherSpark (2023).

Comparison of MD accumulation between sites and cleaning events

The Shapiro-Wilk test assessed data normality (Mudholkar et al. 1995, Razali & Wah 2011, Tapia & Cevallos 2021, Jaramillo et al. 2023). Due to non-normality, the nonparametric Kruskal-Wallis test was used to detect differences among sites (CE, HS, E, ER) and cleaning events (Breslow 1970, Vargha & Delaney 1998, Ostertagová et al. 2014), followed by Dunn's *post-hoc* test to identify differing groups (Ruxton & Beauchamp 2008, Elliott & Hynan 2011). Site CR data were analyzed separately due to daily accumulation.

MD accumulation and the influence of environmental and anthropogenic variables

To evaluate factors influencing waste accumulation (debris items per unit effort DPUE, count 100 m^{-1}) on Puerto López Beach, two separate generalized linear models (GLMs) were built because of differences in sampling design (Vásquez-Salas 1984, Hastie & Pregibon 1992). Both models were fitted using log-transformed DPUE as the response variable to improve normality (West 2022), assuming a Gaussian distribution (Díaz & Fernández 2001, Batanero et al. 2015) with an identity link function (Asimit et al. 2025). An offset term based on the log of days between samplings was included to standardize accumulation rates (Keene 1995, Gelman & Hill 2007, Yan et al. 2009).

Site CR, with daily accumulation, was modeled independently from other sites where accumulation occurred every 15 ± 3 days, preventing direct comparison (Díaz 2009).

The global models included environmental variables (RTR, IA, days since the last spring tide, and climatic season-warm-dry June-September, rainy

April-May, and October-December) and social variables (days since the last holiday and the tourist season). Tourist season was excluded from final models due to collinearity with climatic season, which was retained as a seasonal proxy.

Scatter plots (McCullagh & Pregibon 1987) were used to explore relationships between predictors and log-transformed DPUE.

Multicollinearity was assessed via correlation analysis (Tay 2017), excluding variables with $r \geq 0.7$ to avoid issues.

For site CR, GLMs were first fitted individually for each explanatory variable to assess effects. A stepwise selection then added variables sequentially, using Akaike's information criterion (AIC) (Akaike 1974, Chakrabarti & Ghosh 2011), and reductions in residual deviance via ANOVA (Fernández 1992) to identify the most parsimonious model. For the other sites (CE, HS, E, ER), data collected over longer intervals were analyzed using a full GLM that included all variables and a "site" factor. Stepwise AIC-based selection and ANOVA-supported model selection were supported by the study design despite differing sampling intervals. To avoid overfitting, we limited the data and did not evaluate interactions. We carried out our analyses using R (R Core Team 2024) with the packages "mgcv" (Wood 2011), "car" (Fox & Weisberg 2019), and "MuMIn" (Bartoń 2020).

RESULTS

Between April 11 and December 3, 2023, 17 surveys were conducted per site. Two surveys at site CE (May 13, July 24) were excluded because beach cleanups affected the accumulation time. At site CR, two surveys (April 11, August 22) were excluded because accumulation periods exceeded one day due to cleanup irregularities during daily cleanups. Surveys occurred 1-5 days after spring tides and 0-77 days after local holidays.

Site HS had the highest debris accumulation rate per fortnight ($\bar{x}$ = 972), followed by ER ($\bar{x}$ = 776), CE ($\bar{x}$ = 569), and E ($\bar{x}$ = 538). However, a Kruskal-Wallis test showed no significant differences in debris accumulation among sites with comparable sampling frequency (H = 7.10, df = 3, P = 0.069).

Debris accumulation showed no significant trends over the survey period (Kruskal-Wallis H = 23.59, df = 11, P = 0.098), indicating no consistent differences in median accumulation between sampling dates (Fig. 2).

While HS consistently exhibited the highest debris accumulation, the other sites maintained relatively similar levels until the tenth sampling, when ER experienced a notable increase. However, this rise in ER remained below the levels recorded at HS (Fig. 3).

MD origin varied by site activity and location (Fig. 4). Ocean-based litter was more common in less urbanized areas, while land-based debris was more frequent near tourist and commercial zones. General source items appeared at all sites, especially where human activities overlapped. No old or foreign-branded items were observed, suggesting that locally sourced, recent debris predominates among identifiable items.

MD types at CR (daily accumulation)

At site CR, plastic dominated (81.9%), mainly ropes and single-use items such as cups, bags, straws, wrappers, caps, containers, and bottles (Fig. 5a). Paper/wood and glass were less frequent, mostly as fragments, ice cream sticks, napkins, and fiberglass. Metal caps, batteries, and electronic waste were also notable. RTR and IA showed no seasonal trends, with RTR from 0.78 to 2.00 ($\bar{x}$ = 1.42) and IA from 0.31 to 1.64 ($\bar{x}$ = 0.82).

CR ecological modeling

At site CR, GLMs were fitted individually for each variable (Table 1). The model including "Last spring tide" had the lowest AIC (36.95), but the variable was not a significant predictor of MD accumulation (estimate = -0.1681, standard error SE = 0.1863, t = -0.903, P = 0.383) (Table 2). Due to the lack of significant univariate results and the small sample size, multivariable modeling was not conducted. No clear effect of the evaluated variables on debris accumulation was detected at site CR under the available sample size.

MD types across beach zones (CE, HS, E & ER)

Plastics dominated across all sites, ranging from 79.3 to 96.6% (Fig. 5b-e). The CE area had 81.7% plastic debris, mainly ropes, cigarette butts, fragments, and single-use items like wrappers and bottle caps. At the HS area, plastics comprised 79.3%, dominated by ropes and fragments, with construction debris, fiberglass, and wipes also present. The E area showed the highest plastic proportion (96.6%), mostly ropes and fragments, with fewer single-use plastics and some glass. The ER site contained 96.3% plastic, including fragments and ropes, as well as various single-use plastics and rare items such as medical waste and personal care containers. These patterns reflect both shared and site-specific sources of plastic pollution.

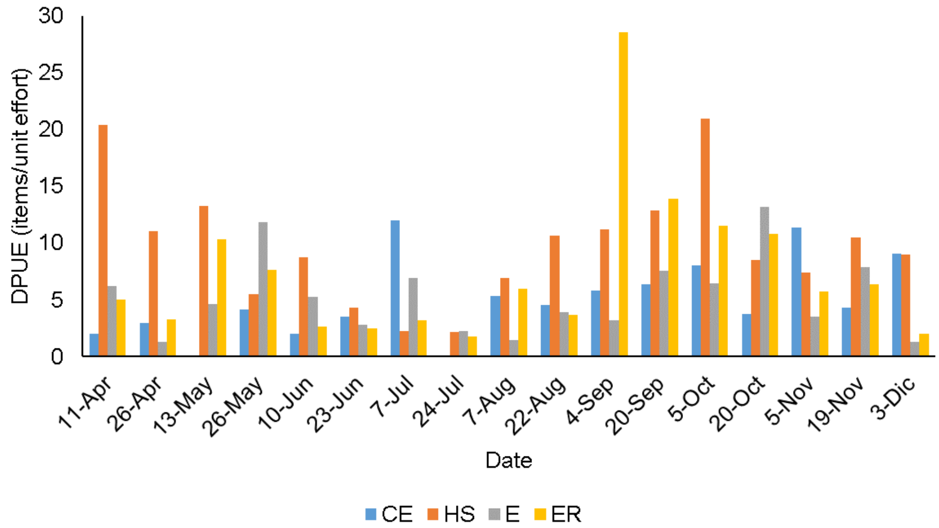

Figure 2. Number of debris items per unit effort (DPUE) in 100 m transects recorded throughout 2023 at each sampling site. Site CR: commercial and river mouth area; CE: commercial and entertainment area; HS: hotel and shipyard area; E: ecotourism area; ER: ecotourism area and Buena Vista river's mouth.

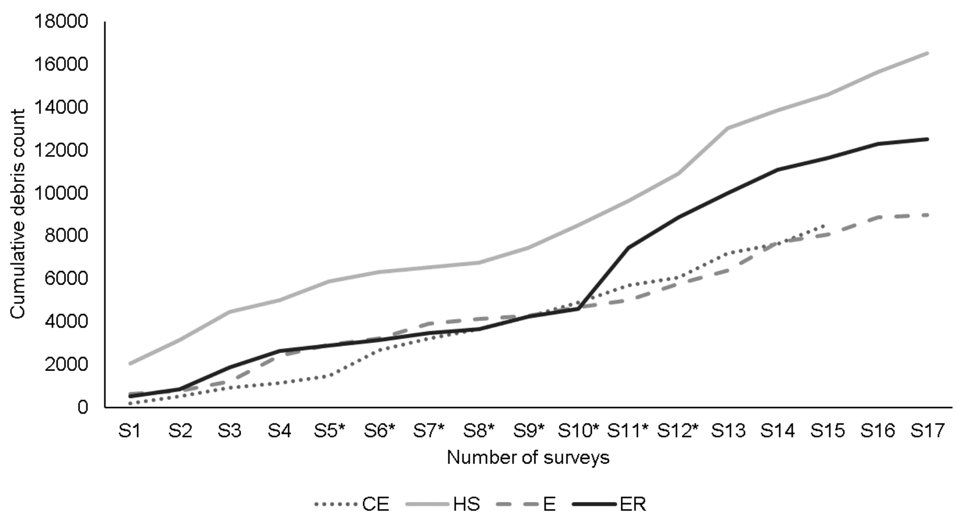

Figure 3. Cumulative debris accumulation at each sampling site across the 17 surveys conducted in 2023. The surveys marked with an asterisk (*) show the high tourist season (Jun-Sep). CE: commercial and entertainment area; HS: hotel and shipyard area; E: ecotourism area; ER: ecotourism area and Buena Vista river's mouth.

RTR and IA showed no clear seasonal trends but contextualized debris variability. At CE, RTR ranged 2.49-1.14 ($\bar{x}$ = 1.54) and IA 1.20-0.39 ($\bar{x}$ = 0.62). HS had similar RTR (2.49-1.14; $\bar{x}$ = 1.57) and IA (1.30-0.33; $\bar{x}$ = 0.61). At E, RTR was 2.49-1.14 ($\bar{x}$ = 1.57) and IA 0.69-0.27 ($\bar{x}$ = 0.37). ER showed RTR 2.49-1.14 ($\bar{x}$ = 1.57) and IA 0.81-0.27 ($\bar{x}$ = 0.46). These consistent tidal patterns and slight IA differences may explain site-specific debris accumulation seen in models.

Ecological modeling across beach zones (CE, HS, E & ER)

The best-fitting GLM for sites CE, HS, ER, and E included last spring tide, season, RTR, and site as predictors. Season had a significant negative effect (β = -0.439, P = 0.013), indicating lower accumulation during the dry season. RTR also showed a significant negative association (β = -0.585, P = 0.020), suggesting that higher tidal ranges facilitate MD dispersal. Site HS

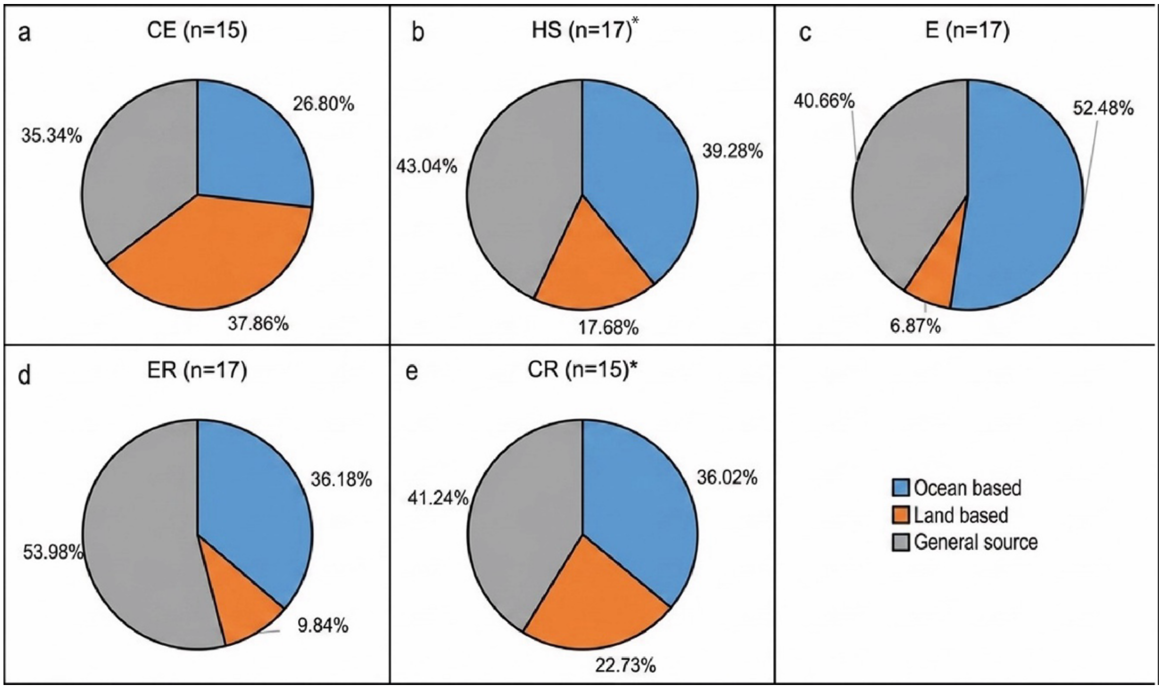

Figure 4. Total percentage of waste origin at each sampling site throughout the sampling period (April to December). a) CE: commercial and entertainment area, b) HS: hotel and shipyard area, c) E: ecotourism area, d) ER: ecotourism area and Buena Vista river's mouth,; e) CR: commercial and river mouth area. *Represents daily accumulation.

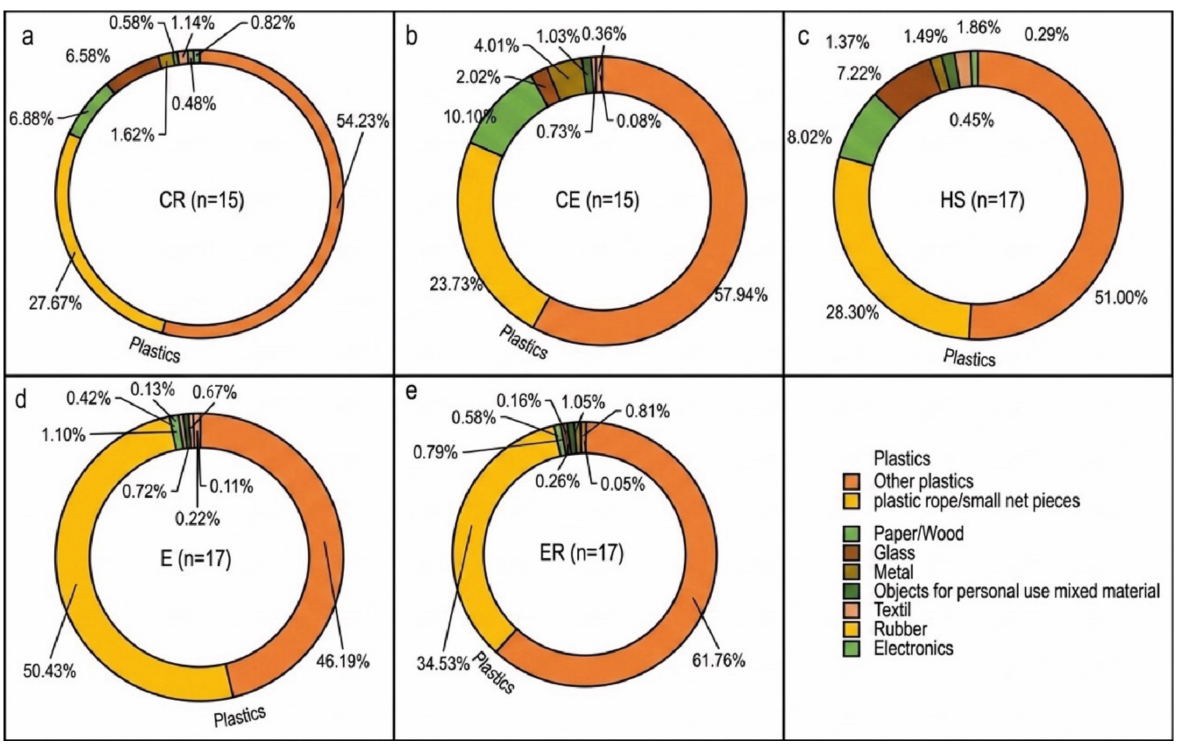

Figure 5. Total percentage of materials by item count found at each sampling site throughout the survey period. a) Site CR: commercial and river mouth area (the thin circle represents the daily accumulation), b) CE: commercial and entertainment area, c) HS: hotel and shipyard area, d) E: ecotourism area, e) ER: ecotourism area and Buena Vista River's mouth.

Table 1. Individual models and their Akaike's information criterion (AIC) values for site CR (commercial and river-mouth areas). RTR: relative tidal range, IA: intertidal area.

Model	AIC	ΔAIC	Deviance explained (%)	Residual deviance	*P*-value
Last spring tide	37	0	10.2	6.915	0.383
IA	37.2	0.22	8.9	7.018	0.404
Season	37.5	0.49	7.2	7.146	0.499
RTR	37.8	0.83	5.1	7.307	0.521
Last holiday	37.8	0.85	5	7.316	0.581

Table 2. Summary of the best-selected model for site CR (commercial and river mouth area) based on Akaike's information criterion (AIC).

	Coefficients:			
	Estimate	Std. Error	*t*-value	Pr(>|t|)
(Intercept)	1.74	0.65	2.68	0.02 *
Last spring tide	-0.17	0.19	-0.90	0.38

showed the highest MD accumulation (β = 1.59, P = 0.015), followed by CE (β = 1.06, P = 0.095) and ER (β = 1.18, P = 0.066), both of which were marginally significant. Site E had the lowest and non-significant estimate (β = 0.93, P = 0.148) (Table 3). These results highlight the roles of site-specific factors and environmental drivers, such as seasonality and tidal dynamics, in shaping debris patterns along Puerto López Beach.

Table 3. Generalized linear model results for debris accumulation (log-DPUE, debris items per unit effort) with environmental and site-level predictors across HS (hotel and shipyard area), CE (commercial and entertainment area), ER (ecotourism area and Buena Vista river's mouth), and E (ecotourism area) beach sites. RTR: relative tidal range.

	Estimate	Std. Error	*t*-value	*P*(>|t|)
Last_spring_Tide	-0.18	0.09	-1.94	0.06
Season	-0.44	0.17	-2.55	0.01*
RTR	-0.58	0.24	-2.40	0.02*
SiteE	0.92	0.63	1.47	0.15
SiteER	1.18	0.63	1.87	0.06
SiteCE	1.06	0.62	1.70	0.09
SiteHS	1.59	0.63	2.51	0.01*

DISCUSSION

Plastic dominated MD on Puerto López Beach, especially ropes and fragments, suggesting an important contribution from local fishing-related activities (Osejos-Merino et al. 2017, Zambrano 2020). Fishing debris is also a major contributor to MD in other parts of the Pacific Ocean, accounting for up to 30% of total waste (Ivar do Sul & Costa 2007).

Our findings align with global and regional patterns where plastics dominate MD, often exceeding 90% in places like the Galápagos Islands (Sánchez-García & Sanz-Lázaro 2023, Benito-Kaesbach et al. 2024), Australia (Smith & Markic 2013), Italy (Buoninsegni et al. 2022, Corbau et al. 2022, 2023), and Somalia (Hassan et al. 2024). Intermediate dominance (55-80%) occurs in the Caribbean, south Atlantic, Mediterranean, and parts of Asia and Africa (Ivar do Sul & Costa 2007, Santos et al. 2009, Slavin et al. 2012, Blickley et al. 2016, Aytan et al. 2020, Gholami et al. 2020, Yona et al. 2024). Lower proportions (37-40%) are reported in the Caspian Sea, Baltic Sea, and Chile (Jonidi-Jafari et al. 2021, Lenz et al. 2023, Salinas et al. 2024).

Plastic predominates globally in marine environments due to its persistence, buoyancy, and widespread use, especially in single-use items. Poor waste management, particularly in developing countries, worsens the problem (Agamuthu et al. 2019). A meta-analysis estimates that plastics comprise about 61% of marine litter worldwide (Ansari & Farzadkia 2022), with the highest densities in Pakistan, South Korea, and China (Gholami et al. 2020), and litter hotspots on beaches in Turkey, Australia, Thailand, and Argentina (Ansari & Farzadkia 2022).

Variation in MD accumulation between sites

Spatial variation in MD accumulation among sites highlights how local activities shape debris patterns, addressing spatial variability. Site HS, with the highest accumulation (972 items fortnight^{-1}), is marked by intense fishing, consistent with studies linking such areas to high debris (Smith et al. 2018, Buoninsegni et al. 2022, Corbau et al. 2022). Likewise, Suárez-Borbor (2022) reported high debris on Ecuador's Santa Elena beaches near fishing and maintenance zones.

Site-specific trends show how human activity influences debris types. At CE, a commercial and entertainment area, land-based debris predominates, matching patterns on Pacific and Atlantic coasts where higher human presence or tourism leads to increased debris (Ivar do Sul & Costa 2007, Ribic et al. 2012, Currie et al. 2019, Gholami et al. 2020).

These findings highlight the need for site-specific waste management. Land-based debris in commercial zones calls for improved waste infrastructure and behavior change among visitors and vendors, while fishing areas need strategies to address marine pollution. As Jonidi-Jafari et al. (2021) observed in the Caspian Sea, debris correlates with urbanization, visitor numbers, and cleanup frequency, underscoring the importance of personalized interventions.

Unlike high-use areas, ecotourism sites ER and E had lower debris totals but notable fragmented plastics, indicating prolonged exposure and limited removal. Similar patterns occur in the Caribbean, Brazil, Mediterranean, and Australia, where plastic fragmentation signals long-term pollution and inadequate cleanup (Smith & Markic 2013, Aytan et al. 2020, Bettencourt et al. 2020, Martínez-Ribes et al. 2020). In Ecuador, Mingas por el Mar (2020) emphasized that regular beach cleanups reduce microplastic accumulation, stressing the need for sustained efforts in tourist zones.

Although no significant seasonal trends in total debris accumulation were found, as in studies in Hawaii and southern Ecuador (Blickley et al. 2016, Salazar et al. 2022), site-level differences in composition suggest the presence of seasonal dynamics. These results align with observations from the Caribbean and Chile (Hidalgo-Ruz & Thiel 2013, Bettencourt et al. 2021), highlighting the need for adaptive management. But the use of nonparametric tests with lower power and the study's limited duration may have masked subtle seasonal changes. Since the climatic season was a significant predictor in the GLM, long-term monitoring is essential to understand temporal variability.

Debris composition varied with site usage and human proximity. At CE, land-based waste was dominant due to high visitor traffic, commercial activity, and poor infrastructure. Conversely, the ecotourism site E had more ocean-derived debris, reflecting less terrestrial litter and less marine current influence, which aligns with findings from Hawaii and other remote coasts, where currents and wind transport debris over long distances (Ribic et al. 2012).

Despite marine influences, the lack of foreign or old debris suggests that much of the observed debris may be locally generated, unlike in Panama, where 57% of debris is international (Ivar do Sul & Costa 2007), which aligns with Brazilian beach studies showing mainly local debris (Santos et al. 2009). Offshore currents here (Chaigneau et al. 2013, Collins et al. 2013) likely limit the retention of foreign debris. Land-based items (37-76% of debris) reflect local pollution due to identifiable packaging, while ocean-based debris, such as fishing gear fragments, may originate locally or from other locations.

Influence of environmental and human variables

The GLM analysis for the combined sites showed that both environmental conditions and human activities influence marine debris accumulation, addressing our objective of identifying distribution drivers. The multi-site GLM used 'Site' as a categorical predictor to compare average accumulation across locations, controlling for environmental variables and sampling effort.

Within the integrated model, site HS showed the highest debris accumulation, with a significantly positive effect. Season (warm and dry) had a significant negative effect, indicating reduced debris during this period. While previous studies attribute this to lower fishing in the dry season (Ribic et al. 2012, Bernal-Guevara & Sáenz-Fernández 2020, Chirinos-Burgos 2023), this may not fully apply to Puerto López, where fishing is year-round and species-driven (Garay-Hernández 1958). Notably, the dry season coincides with humpback whale season (June-September), increasing ecotourism (Díaz & Lasso 2014, Castro et al. 2022). During this period, municipal beach cleanups are intensified, particularly before and after holidays and peak tourist arrivals. This increase in cleanup frequency may explain the seasonal decline in debris, especially at high-tourism sites like HS.

The GLM also revealed significantly higher debris accumulation at sites CE and ER. In contrast, site E, despite a positive estimate, was not statistically significant, likely reflecting differences in human activity: its low accessibility, minimal infrastructure, and limited presence suggest a stronger influence of natural drivers. Among environmental variables, RTR had a significant negative effect, supporting the idea that greater tidal amplitudes facilitate debris transfer by washing it back to sea, which aligns with studies from the Mexican and Caribbean coasts, where tidal and wave exposure, combined with low human activity, shape debris retention (Monterrubio et al. 2011, Cabrera-Hernández et al. 2012, Bettencourt et al. 2021).

Although site CR was excluded from the multi-site GLM due to its unique conditions, a separate model indicated that spring tides and beach slope may reduce debris retention, which aligns with findings from the Mediterranean and Atlantic, where hydrodynamic factors like wave energy and tidal regimes influence debris deposition and export (Galgani et al. 2015, Buoninsegni et al. 2022, Arboleda-Muñoz et al. 2024).

Overall, these findings highlight the combined effects of environmental and human factors on MD accumulation. Broader studies have shown that wind, currents, and hydrodynamic exposure significantly shape debris patterns (Ivar do Sul & Costa 2007, Santos et al. 2009, Ribic et al. 2012, Smith & Markic 2013, Blickley et al. 2016, Currie et al. 2019, Weidlich & Lenz 2022, Vogt-Vincent et al. 2023). In coastal Ecuador, prevailing westward currents transport floating debris offshore, limiting coastal accumulation and promoting long-range dispersal toward oceanic islands (Chaigneau et al. 2013, Collins et al. 2013). This export contributes to the buildup of mainland-sourced debris in the Galápagos, much of it traceable to Ecuador and northern Peru (Sánchez-García & Sanz-Lázaro 2023, Benito-Kaesbach et al. 2024).

Finally, large-scale oceanographic phenomena such as the El Niño-Southern Oscillation (ENSO) and coastal upwelling may further influence debris patterns by altering currents and wind regimes (Currie et al. 2019, Vogt-Vincent et al. 2023).

Implications for waste management

These findings underscore the need for site-specific strategies that address local environmental and human dynamics. In high-fishing areas like HS, interventions should target waste from boat maintenance and fishing gear, especially trammel nets, which are frequently found in this study and in regional surveys (Osejos-Merino et al. 2017). Although Ecuador's National Fisheries Institute proposed measures (IPIAP 2018), field observations reveal ongoing implementation gaps, highlighting the need for stronger monitoring, enforcement, and support for sustainable fishing.

Educational campaigns to reduce single-use plastics and promote sustainable behaviors among visitors and locals can support conservation in ecotourism zones and other areas prone to debris. Similar efforts in Chile and Argentina have effectively raised awareness and changed consumer habits, helping reduce coastal plastic pollution (Hidalgo-Ruz & Thiel 2013). Aligning beach cleanups with natural events like spring tides or heavy rainfall can also improve efficiency, especially when coordinated with local authorities for logistical support and community involvement (Bombana et al. 2016).

Beyond localized efforts, stronger regulatory frameworks to reduce single-use plastics are urgently needed. Their success depends on public education, consistent enforcement, and community involvement (Currie & Stack 2021). In some tourist destinations, high levels of debris stem more from poor waste management than from tourist numbers (da Silva Videla & Vieira de Araujo 2021, Corbau et al. 2022). In Puerto López, improving waste collection, promoting separation, and ensuring safer disposal are key to minimizing environmental impacts and supporting conservation.

Our study underscores the need for an integrated approach to tackle marine debris, as both local sources and environmental factors shape pollution patterns. Effective solutions require coordination across international agreements, national policies, local regulations, and sectors. Strategies include regulatory bans, stronger oversight, awareness campaigns, education programs, and the adoption of circular economy principles and green technologies (Agamuthu et al. 2019). Empowering communities and authorities within supportive policy frameworks is essential to translating science into lasting solutions.

Risk to marine life conservation

Plastic pollution seriously threatens marine fauna through ingestion and entanglement. Ingested plastics can cause injuries, blockages, and toxic effects, leading to stress or death (Currie et al. 2017, Agamuthu et al. 2019, da Silva-Videla & Vieira de Araujo 2021, Kanhai et al. 2022). Entanglement in abandoned fishing gear, such as nets and lines, immobilizes marine mammals, hinders foraging, and often causes drowning (Smith & Markic 2013).

In the study area, frequent negative interactions between marine mammals and fishing activities have been documented. The most affected species are the South American sea lion (*Otaria byronia*) and the pantropical spotted dolphin (*Stenella attenuata*) (Castro et al. 2020). In Ecuador, from 2001 to 2024, 92 strandings were linked to fishing gear, with humpback whales (*Megaptera novaeangliae*) accounting for about 40% (Castro et al. 2024). The coastal ecotype of the bottlenose dolphin (*Tursiops truncatus*) exhibits high entanglement rates: 85.7% bear scars from fishing nets and gear, indicating widespread anthropogenic threats (Castro et al. 2023). These findings highlight that coastal waste management is a critical conservation issue, beyond aesthetics or tourism.

CONCLUSIONS

Plastic waste dominates (79-96%) MD in Puerto López, especially ropes and fragments, highlighting the urgent need for stricter regulations on fishing gear disposal and tailored waste management. High-accumulation sites (e.g. hotels/shipyards) need focused cleanups, while ecotourism zones require strategies to address fragmented plastics.

To mitigate marine debris effectively, Puerto López must prioritize enforcement of fishing waste policies, community-led beach cleanups, and investment in waste infrastructure, supported by environmental education. These locally personalized actions provide a useful basis for local management and may be transferable to similar coastal contexts.

Addressing marine debris in Puerto López is vital to local biodiversity and tourism, and it supports the broader fight against marine plastic pollution in the Eastern Tropical Pacific.

Credit author contribution

L. Barragán-Tabares: conceptualization, project administration, investigation, validation, writing-original draft, writing-review and editing; H. Orellana-Vásquez: data curation, formal analysis, methodology, investigation, visualization, writing-review and editing; J.J. Currie: methodology, formal analysis, resources, project administration, funding acquisition, writing-review and editing; S.M. Barber-Meyer: formal analysis, writing-review and editing; C. Castro: conceptualization, resources, project administration, writing-review and editing. All authors have read and accepted the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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SUPPLEMENTARY MATERIAL

Table S1. Summary of the number of items found by site. This table summarizes the total marine debris items recorded at five Puerto López Beach sites-CR (commercial and river Mouth), CE (commercial and entertainment), HS (hotel and shipyard), E (ecotourism), and ER (ecotourism and river mouth). From April 11 to December 3, 2023 (approximately eight months). Sampling occurred every 15 ± 3 days. Beach cleanups by local authorities and organizations were recorded, and data affected by cleanups within 15 days before surveys were excluded. At site CR, daily municipal cleanings after surveys meant its data were analyzed separately due to daily accumulation, preventing direct comparison with other sites. Visible anthropogenic litter ≥2.5 cm was collected and classified by material and presumed origin: ocean-based (e.g. fishing gear), land-based (e.g. food wrappers), general source (unclear origin), and fragments (indeterminate). Each item's occurrences per site are listed, with color coding indicating relative abundance-red for the most abundant, green for the least.

Fragments | ocean based | land based | general source

Plastic	CR N = 15	CE N = 15	HS N = 17	E N = 17	ER N = 17	Origin
Hard plastic fragment	78	459	836	1121	1479	Fragments
Foamed plastic fragment	18	232	1188	610	2619	Fragments
Film plastic fragment	41	245	462	313	218	Fragments
Total plastic fragments	*137*	*936*	*2486*	*2044*	*4316*	Fragments
Plastic rope/small net pieces	1657	2024	4677	4532	4246	ocean based
Buoys/floats	28	28	59	34	89	ocean based
Fishing bait	20	2	3	0	0	ocean based
Cups	831	435	969	256	462	general source
Food containers	194	120	478	239	332	general source
Plastic utensils	78	183	244	147	17	general source
Straws	441	380	332	67	149	land based
Bags	614	403	1312	155	210	general source
Food wrappers	308	616	1099	266	377	land based
Tetrapack	6	8	45	5	10	land based
Lollipop sticks	28	124	114	74	272	land based
Plastic bottles	189	44	146	67	99	general source

Continuation

Fragments · ocean based · land based · general source

Plastic	CR N = 15	CE N = 15	HS N = 17	E N = 17	ER N = 17	Origin
Bottle or container caps	212	523	741	684	1018	general source
Buckets	2	4	14	6	10	general source
Cleaning product containers	13	5	21	4	7	general source
Cooking oil containers	1	2	4	2	12	land based
Containers for products used in mechanics	25	3	130	12	24	ocean based
Other plastic containers	23	16	44	12	63	general source
Six-pack rings	1	2	13	1	0	land based
Cigarettes	80	1074	100	16	5	land based
Lighters	1	6	4	2	11	land based
Clothes hooks	0	0	17	4	5	land based
Office objects	1	6	17	10	44	land based
Toys	7	19	13	18	33	land based
Sunglasses	0	0	1	1	2	land based
Sponges	5	2	6	22	9	ocean based
PVC pipe	2	2	8	2	12	ocean based
Other plastics	0	0	9	1	6	general source

Paper/Wood	CR N = 15	CE N = 15	HS N = 17	E N = 17	ER N = 17	Origin
Fragments of paper and cardboard	138	266	441	27	23	fragments, general source
Napkins	71	194	223	5	13	land based
Paper bags	5	8	14	0	0	general source
Paper cups	0	0	5	0	0	general source
Paper/cardboard food containers	0	4	7	1	0	general source
Paper straws	6	9	2	1	1	land based
Ice cream sticks	130	152	16	6	10	land based
Toothpick or skewer stick	2	28	2	0	0	land based
Match	0	2	0	0	0	land based
Cardboard boxes	15	24	119	6	1	ocean based
Masking tape	20	5	216	9	0	ocean based
Cork	3	62	9	25	13	land based
Wood and construction material	20	106	240	17	36	ocean based
Brush	2	2	31	2	0	ocean based

Glass	CR N = 15	CE N = 15	HS N = 17	E N = 17	ER N = 17	Origin
Glass fragments	60	54	226	24	10	fragments
Glass bottles	69	82	271	5	9	land based
Glass jars	0	2	2	0	40	land based
Ceramic/Brick	29	6	13	1	2	land based
Fiberglass	236	28	682	8	10	ocean based

Metal	CR N = 15	CE N = 15	HS N = 17	E N = 17	ER N = 17	Origin
Metal fragments	3	24	75	3	4	fragments, general source
Food cans	2	3	4	0	1	land based
Drink cans	12	16	14	5	0	land based
Metal caps	64	281	110	1	5	land based

Continuation

Fragments ocean based land based general source

Metal	CR N = 15	CE N = 15	HS N = 17	E N = 17	ER N = 17	Origin
Aluminum foil	2	3	7	3	4	land based
Aerosol cans	1	0	1	0	1	ocean based
Other metal	13	15	15	0	5	general source

Objects for personal use, mixed material	CR N = 15	CE N = 15	HS N = 17	E N = 17	ER N = 17	Origin
Medical waste	4	12	10	9	39	land based
Face masks	2	0	17	0	2	land based
Band-Aids/Gauze	0	2	1	11	0	land based
Condoms	0	2	10	1	3	land based
Wipes	2	26	128	3	3	land based
Diapers	0	7	10	1	0	land based
Sanitary pads/tampons	0	10	12	2	0	land based
Cotton swabs	0	0	1	2	0	land based
Toothbrushes	15	3	19	11	33	land based
Personal hygiene containers	10	4	32	16	37	land based
Shaver	0	0	1	0	1	land based
Hair objects	2	20	5	4	11	land based
Jewelry	0	2	0	0	0	land based

Textile	CR N = 15	CE N = 15	HS N = 17	E N = 17	ER N = 17	Origin
Ropes or nets (not plastic)	37	42	49	59	6	ocean based
Sacks	13	1	21	1	2	ocean based
Sandpaper	1	0	101	0	0	ocean based
Rags	8	6	83	0	5	ocean based
Cloth gloves	0	2	6	0	1	ocean based
Tarps	0	1	1	0	0	ocean based
Clothes and shoes	9	10	46	5	18	general source

Rubber	CR N = 15	CE N = 15	HS N = 17	E N = 17	ER N = 17	Origin
Rubber fragments	6	18	45	2	37	Fragments, general source
Tires	16	1	11	2	0	ocean based
Rubber gloves	2	2	4	3	4	ocean based
Flip flops	4	2	10	7	44	land based
Balloons	1	7	3	5	5	land based
Other rubber	0	1	1	1	10	general source

Electronics	CR N = 15	CE N = 15	HS N = 17	E N = 17	ER N = 17	Origin
Electric appliances/cables	21	5	36	5	0	ocean based
Batteries	22	0	10	0	0	ocean based
Light bulb	1	2	1	5	4	ocean based
Spark plug	5	0	1	0	2	ocean based