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From categories to producers: Dual regulatory and Anthropocene-based classification of macrolitter on an uninhabited Caribbean island

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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

Marine macrolitter accumulation on islands provides a sensitive indicator of regional transport processes and production–consumption dynamics. In this study, coastal macrolitter assemblages were assessed on Isla Arena, a small uninhabited island in the Colombian Caribbean, using an integrated analytical framework that combines standardized regulatory monitoring (Joint List of Litter Categories) with the Anthropocene Taxonomy of Plastic Litter (ATPL). A total of 830 macrolitter items were collected across 779 m^2 during a single survey campaign, corresponding to a mean density of 1.07 items·m^{-2}, comparable to values reported for inhabited island systems worldwide. Plastics dominated the assemblage (>95%), with food consumption–related items prevailing. Plastic beverage bottles alone accounted for nearly 80% of all recorded macrolitter, indicating strong functional simplification. Classification based on the Joint List effectively characterized material composition and dominant use patterns but provided limited resolution regarding producer diversity. Application of ATPL revealed heterogeneity at producer, brand, and product levels within standardized item categories; however, producer or geographic origin could be confidently assigned to only 28% of plastic items due to environmental degradation and conservative visual identification criteria. For identifiable items, attribution indicated dominance by a limited number of corporate actors, primarily regional beverage producers. Although the study is based on a single island and one sampling campaign, the dual-classification approach demonstrates added analytical resolution relative to regulatory categories alone. The results suggest that Isla Arena functions as a convergence and retention zone for marine litter rather than a primary source area. The proposed framework preserves regulatory comparability while offering an expanded perspective for source-sensitive and responsibility-oriented interpretation in island and coastal environments.

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1. Introduction

Marine macrolitter, particularly plastic debris, is widely recognized as one of the most pervasive, persistent, and rapidly increasing forms of pollution affecting coastal and marine ecosystems worldwide (Rangel-Buitrago, 2025; Shumway and Ward, 2025). Plastics frequently dominate litter assemblages, often accounting for most recorded items, due to their buoyancy, durability, and resistance to degradation (Jambeck et al., 2015). In coastal environments, macrolitter generates multiple pressures, including physical damage to habitats such as coral reefs (Hendrawan et al., 2026; Shankar et al., 2025), mangroves (Guruge et al., 2026; Ponmani et al., 2026), dunes (Andriolo et al., 2021; Andriolo and Gonçalves, 2022), and beaches (Andriolo et al., 2020; Roome et al., 2026), entanglement and ingestion risks for marine organisms (Gracia et al., 2018; Compa et al., 2022), and degradation of scenic quality (Rangel-Buitrago and Ben-Haddad, 2024). These impacts translate into ecological degradation, public health concerns, and economic losses, particularly in regions where coastal tourism and ecosystem services are central to local livelihoods (Ponmani et al., 2026).

Islands, as remote environments, are especially susceptible to macrolitter pollution due to their geographic isolation, exposure to oceanographic transport processes, and constrained waste management capacity (Ilechukwu et al., 2025; Nisanth et al., 2025; Lavers et al., 2026; Rangel-Buitrago and Galgani, 2026). Coastal and insular settings act as effective accumulation zones for floating and stranded debris, receiving litter from both local activities and distant sources transported by currents, winds, and extreme events like storms and hurricanes (Rangel-Buitrago et al., 2019, 2026; Shankar et al., 2024; Garcés-Ordóñez et al., 2025a, 2025b). In many islands, such as Mauritius, Madagascar, Isla Colon and Providencia (Colombia), Nicobar resident populations, intense tourism, recreational activities, and fisheries merges to generate elevate litter loads that exceed local management capacity (Rhodes, 2018; Garcés-Ordóñez et al., 2021; Shankar et al., 2024; Kasa et al., 2025). Tropical and Caribbean islands have been frequently identified as sentinel sites for marine litter studies, as they integrate signals of regional transport, consumption patterns, and global production systems (Rangel-Buitrago et al., 2019, 2026; Garcés-Ordóñez et al., 2021, 2025a, 2025b). Consequently, island macrolitter assemblages often reflect complex, multi-origin pollution dynamics, making them particularly suitable for advanced compositional and source-oriented analyses (Krelling et al., 2017; Brabo et al., 2024).

Marine litter transport is increasingly recognized as a transboundary phenomenon, with floating debris capable of crossing national jurisdictions through large-scale circulation systems and episodic extreme events (Macias et al., 2022; Shankar et al., 2023, 2024). Oceanographic modeling and field-based studies have demonstrated that plastic items released from densely populated coastal regions may travel hundreds to thousands of kilometers before stranding in remote islands or coastal convergence zones (Ryan et al., 2019; Brabo et al., 2024; van Duinen et al., 2022). Such transboundary transport complicates attribution and governance, as accumulation sites may not coincide with production or disposal regions. Remote islands, therefore, frequently function as passive recipients of regional or basin-scale litter fluxes, integrating signals from multiple source territories and production systems.

Over the past two decades, standardized macrolitter monitoring frameworks have been widely developed and implemented across coastal, riverine, floating, and seafloor environments, particularly under the Marine Strategy Framework Directive (MSFD) and associated regional conventions such as OSPAR (González-Fernández and Hanke, 2017; Canals et al., 2020; Galgani et al., 2024). Key tools such as the Joint List of Litter Categories (Fleet et al., 2021) have substantially improved the harmonization of data collection by providing common classification schemes, enabling robust quantification, temporal tracking, and spatial comparability of macrolitter across regions and environmental compartments (Haarr et al., 2022; Galgani et al., 2024). These frameworks have been significant in establishing baselines, identifying dominant litter categories, and supporting environmental status assessments and mitigation policies (Falk-Andersson et al., 2025). Nevertheless, despite their regulatory and scientific value, standardized monitoring approaches have inherent analytical limitations, especially in island settings where litter assemblages are strongly shaped by long-range transport and external inputs (Rangel-Buitrago et al., 2019). Their categorical resolution is typically insufficient to identify producers, brands, or specific products, limiting the capacity to trace sources, evaluate responsibility, or distinguish locally generated debris from transboundary pollution (Brabo et al., 2024; Rangel-Buitrago et al., 2026). As a result, while standardized frameworks effectively describe the magnitude and composition of macrolitter, they provide limited insight into the primary production–consumption systems driving litter accumulation in insular environments.

The analytical limitations of conventional macrolitter monitoring frameworks point to the need for approaches that connect environmental characterization with the socio-economic dimensions underlying plastic production, consumption, and disposal (Claro et al., 2019; Hanke et al., 2025). While regulatory classification systems such as the Joint List of Litter Categories provide a robust and harmonized basis for quantifying litter composition and supporting environmental status assessments (Fleet et al., 2021), they lack the resolution to identify specific producers, brands, or specific products. In island environments, where litter originates from both local activities and transboundary sources (Weidlich and Lenz, 2022; Markić et al., 2024), this limitation constrains the interpretation of observed patterns and weakens links to corporate responsibility and prevention strategies. Anthropocene-based taxonomic approaches, such as the Anthropocene Taxonomy of Plastics Litter (ATPL) developed by Rangel-Buitrago et al. (2026), offer a complementary analytical tool by classifying plastic litter as anthropogenic entities structured across hierarchical levels analogous to biological taxonomy, from broad material categories to specific products and corporate producers. Integrating regulatory classification systems with ATPL does not seek to replace standardized monitoring, but rather to extend its interpretative capacity by enabling litter assemblages to be examined simultaneously as environmental indicators and as expressions of production–consumption systems. This integrative perspective is particularly relevant in island settings, where understanding the origin and structure of macrolitter is essential for distinguishing local and external contributions.

Unlike conventional brand-audit or producer-attribution approaches, which typically record visible manufacturer information as flat descriptive categories, the Anthropocene Taxonomy of Plastic Litter (ATPL) introduces a hierarchical and formally structured classification system analogous to biological taxonomy. Within ATPL, plastic litter is organized across nested levels (Phylum, Class, Order, Family, Genus, Species), embedding producer, brand, and product information within a broader material and functional architecture. This structure allows litter assemblages to be interpreted not only as collections of branded items, but as stratified anthropogenic entities reflecting production systems. A dedicated theoretical paper detailing the conceptual foundations and classification criteria of ATPL can be found as Rangel-Buitrago et al. (2026), while the present study focuses on its applied implementation in an island setting.

From a broader aquatic environmental governance perspective, marine macrolitter represents more than a contamination problem, constituting a visible manifestation of upstream production and waste-management failures that affect ecosystem integrity. While the present study does not directly quantify water security indicators, the accumulation of externally generated debris on uninhabited islands highlights structural vulnerabilities in regional pollution control and transboundary governance systems. In this sense, island macrolitter assemblages may serve as diagnostic indicators of broader environmental security pressures acting on coastal and marine systems.

This study evaluates the analytical benefits of integrating standardized regulatory monitoring with an Anthropocene-based classification framework for the assessment of coastal macrolitter in an island environment. Focusing on Isla Arena in the Colombian Caribbean, the paper aims to: (1) characterize the coastal macrolitter accumulated using the Joint List of Litter Categories (Fleet et al., 2021); (2) apply the Anthropocene Taxonomy of Plastics Litter developed by Rangel-Buitrago et al. (2026) to the same litter assemblage; (3) assess the added analytical value of a dual-classification approach in understanding litter structure and composition in an island setting; and (4) discuss the implications of this integrated framework for macrolitter monitoring, source attribution, and responsibility-oriented interpretations.

2. Material and methods

2.1. Study area

Isla Arena is a small, uninhabited island located in the central Colombian Caribbean Sea, within the Bolívar Department, at approximately 10°44′20.83″ N and 75°21′03.35″ W (Fig. 1). The island should not be confused with Isla Arenas located farther southwest along the Colombian coast. Isla Arena has a total surface area of 779 m^2, a perimeter of approximately 213 m, and very low elevations, not exceeding 1 m above mean sea level. Its narrow and barely emergent morphology makes the island highly exposed to overwash processes, facilitating the deposition and retention of floating and stranded litter within the island interior.

Geomorphologically, Isla Arena represents the emergent portion of a dormant carbonate bank whose origin is linked to mud diapirism, a characteristic process of the central Caribbean coast of Colombia (Bosence, 2005; Gracia et al., 2012). The upward movement of mud volcanoes has generated localized seafloor highs that, upon reaching the zone of active carbonate production, evolved into limestone platforms that define the present island morphology.

The study area is currently a shallow-marine setting, isolated from direct siliciclastic inputs and dominated by carbonate sedimentation. Previous ecological surveys have documented at least 33 benthic species in the surrounding waters, including stony corals, zoanthids, octocorals, macroalgae, and seagrasses organized into distinct ecological zones. The island and its adjacent reef-flat and lagoonal environments support coral assemblages and seagrass beds that contribute to habitat complexity and local biodiversity. This ecological setting increases the environmental relevance of macrolitter accumulation, as plastic debris interacts directly with sensitive carbonate reef and seagrass systems typical of tropical island environments (Pinzón et al., 1998).

Isla Arena is situated within a semi-arid tropical environment, with mean annual temperatures around 30 °C and precipitation values

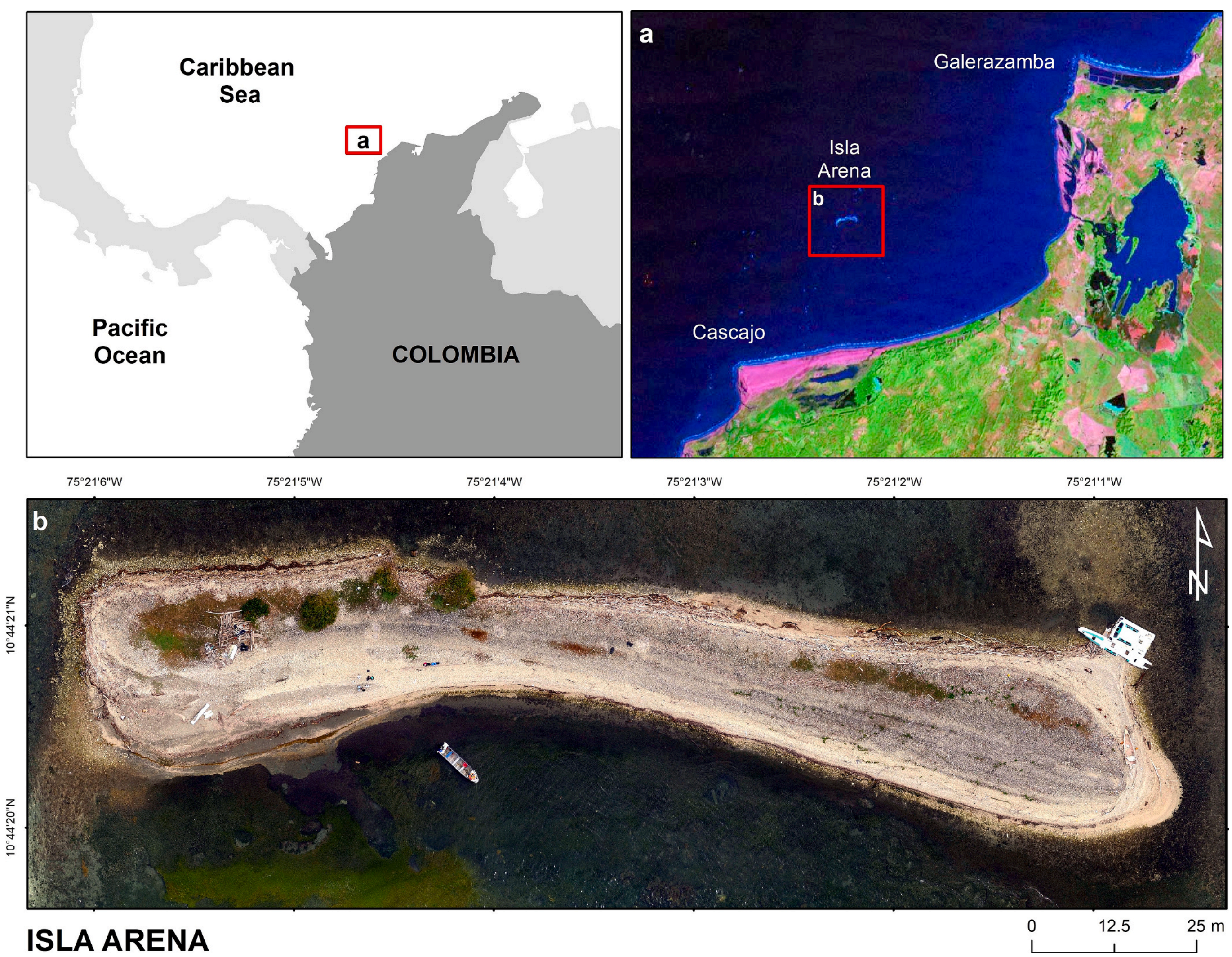

Fig. 1. Location and morphology of Isla Arena, Colombian Caribbean. (a) Regional setting showing the position of Isla Arena offshore the central Caribbean coast of Colombia. (b) Aerial view of Isla Arena showing its narrow, low-lying morphology, shoreline configuration, and limited vegetation cover, highlighting its exposure to overwash processes and suitability as a macrolitter accumulation site.

reaching up to 2700 mm yr^{-1} (Rangel-Buitrago et al., 2013). The rainfall regime is characterized by two dry periods (December–March and July–September) and two rainy periods (April–May and October–November), while wind velocities generally remain below 15 m/s (Rangel-Buitrago et al., 2018). Tidal conditions correspond to a mixed semi-diurnal, micro-tidal regime, with maximum tidal amplitudes of approximately 70 cm (Rangel-Buitrago et al., 2017, 2018). Wave dynamics in the area are dominated by NE swells from November to July, with additional contributions from NW, WSW, and SW directions during the remaining months. Average significant wave height is approximately 1.7 m, with a mean peak period of 7.3 s (Gracia et al., 2018). Longshore currents predominantly flow towards the southwest, with episodic reversals towards the northwest during the rainy seasons (Anfuso et al., 2015).

Although Isla Arena is uninhabited and lacks local waste-generation activities, it is surrounded within a densely populated and economically active regional setting. The island lies offshore from the central Colombian Caribbean coast, influenced by nearby urban centers (i.e., Barranquilla and Cartagena), coastal tourism, artisanal and industrial fisheries, maritime transport routes, and regional ocean circulation connecting the Colombian coast with the wider Caribbean basin. These human activities represent potential upstream and cross-border sources of marine litter that can be transported and accumulated on the island through prevailing currents, winds, and episodic extreme events (Rangel-Buitrago et al., 2017). From a governance perspective, Isla Arena falls within the national framework for marine and coastal protection in Colombia, where marine litter is addressed primarily through broader environmental and waste-management policies rather than site-specific measures. This combination of physical exposure and regional socio-economic connectivity reinforces Isla Arena's role as an uninhabited yet highly connected recipient of Anthropocene-driven material flows.

2.2. Field survey design and litter collection

The field survey was conducted over the entire emergent surface of Isla Arena, covering a total area of 779 m^2, which corresponds to the full extent of the island above mean sea level. Given the small size, low elevation, and narrow morphology of the area, the survey boundaries encompassed all accessible zones, including the shoreline, supratidal areas, and interior sectors subject to overwash and litter accumulation. This spatially exhaustive approach minimized sampling bias and ensured that the collected litter assemblage was representative of the island-scale accumulation pattern rather than restricted to selected transects or sectors.

The field survey was conducted on 10/11/2025, between 8 am and 12 pm, during the dry season. Sampling occurred under stable meteorological conditions, with prevailing winds from the NE at approximately 2 m/s and no precipitation during the survey period. According to regional meteorological records, no major storm events, hurricanes, or extreme wave conditions were recorded in the 5 weeks preceding the survey. Tidal conditions corresponded to a low stage of the local mixed semi-diurnal regime, with an approximate tidal amplitude of 25 cm. These conditions suggest that the recorded macrolitter assemblage reflects accumulated deposition rather than an immediately post-storm pulse event.

Litter collection was carried out using a plogging-based approach, applied strictly as a systematic retrieval method rather than as a recreational activity (Martinez-Mirambell et al., 2025; Schoeppe et al., 2025). Surveyors moved across the island following parallel walking paths adapted to the island's geometry, visually scanning the surface and collecting all visible macrolitter items. All items with a longest dimension ≥25 mm were included, in accordance with widely accepted macrolitter definitions used in international monitoring frameworks (i.e., Ocean Conservancy, 2010, 2018; OSPAR, 2009, 2010). Each item was manually retrieved, inspected in situ to confirm eligibility, and subsequently stored for further classification. Fragmented items were collected when they could be clearly identified as anthropogenic debris and met the size threshold, while natural materials such as unworked wood, shells, or biogenic remains were excluded. This protocol resulted in the recovery of a dense and spatially constrained macrolitter assemblage (830 items), suitable for high-resolution classification using both standardized regulatory and Anthropocene-based frameworks.

The survey was conducted by 2 trained surveyors over a total duration of approximately 4 h. Given the small size (779 m^2) and simple morphology of Isla Arena, the survey was designed as a complete census rather than a transect-based or stratified sampling exercise. All accessible areas of the emergent surface were systematically covered through parallel walking paths, ensuring exhaustive retrieval of visible macrolitter items ≥25 mm. The reported mean density (1.07 items·m^{-2}) represents an island-scale density calculated from the total number of items divided by the total surveyed area, rather than an extrapolation from subsampled units.

Although formal sub-area density calculations were not performed due to the island's limited spatial extent, visual inspection indicated higher accumulation along shoreline and overwash-prone sectors, with secondary deposition in interior depressions. This pattern is consistent with hydrodynamic-driven retention processes described for low-lying island systems.

2.3. Classification using the Joint List of Litter Categories (J-Code system) and the Anthropocene Taxonomy of Plastic Litter (ATPL)

All collected macrolitter items were classified according to the Joint List of Litter Categories for Marine Macrolitter Monitoring, developed under the Marine Strategy Framework Directive (MSFD - Fleet et al., 2021). This classification system applies to a hierarchical structure that assigns each item to a material category, use category, and specific item type, resulting in a full type code and corresponding J-Code (Fig. 2). For each litter item, the material category (e.g., artificial polymers, metal, glass/ceramics, rubber, paper/cardboard, worked wood) was first identified, followed by attribution to a use category reflecting the item's original function (e.g., food consumption, fishing-related, personal hygiene, smoking-related). Items were then classified at the highest possible level of detail available in the Joint List, allowing assignment of a specific item description and its associated full type of code and J-Code.

Classification followed MSFD technical guidance to ensure consistency and comparability with international monitoring programs. Items composed of multiple materials were assigned to the material category representing the dominant component by volume or mass. Fragmented or degraded items were classified when their original form or function could be reliably inferred from remaining features, such as shape, texture, labeling, or manufacturing characteristics. When such identification was not possible, fragments were assigned to the appropriate fragment category within the Joint List, in accordance with size and material criteria. This approach ensured that all collected macrolitter items were systematically recorded within a standardized, policy-relevant framework, enabling direct comparison with regional and global macrolitter datasets.

Although most items could be clearly assigned to a specific J-Code category, occasional borderline cases arose when degraded or multi-component items exhibited characteristics potentially corresponding to more than one code. In such instances, classification followed the hierarchical guidance of the Joint List (Fleet et al., 2021), prioritizing the dominant material component and primary functional form. Secondary attributes (e.g., partial labeling or accessory features) were not used to override material-based classification. When uncertainty persisted, items were reviewed jointly by surveyors and assigned through consensus to the category most consistent with MSFD technical criteria.

In parallel with the standardized classification, all plastic litter items were independently classified using the Anthropocene Taxonomy of

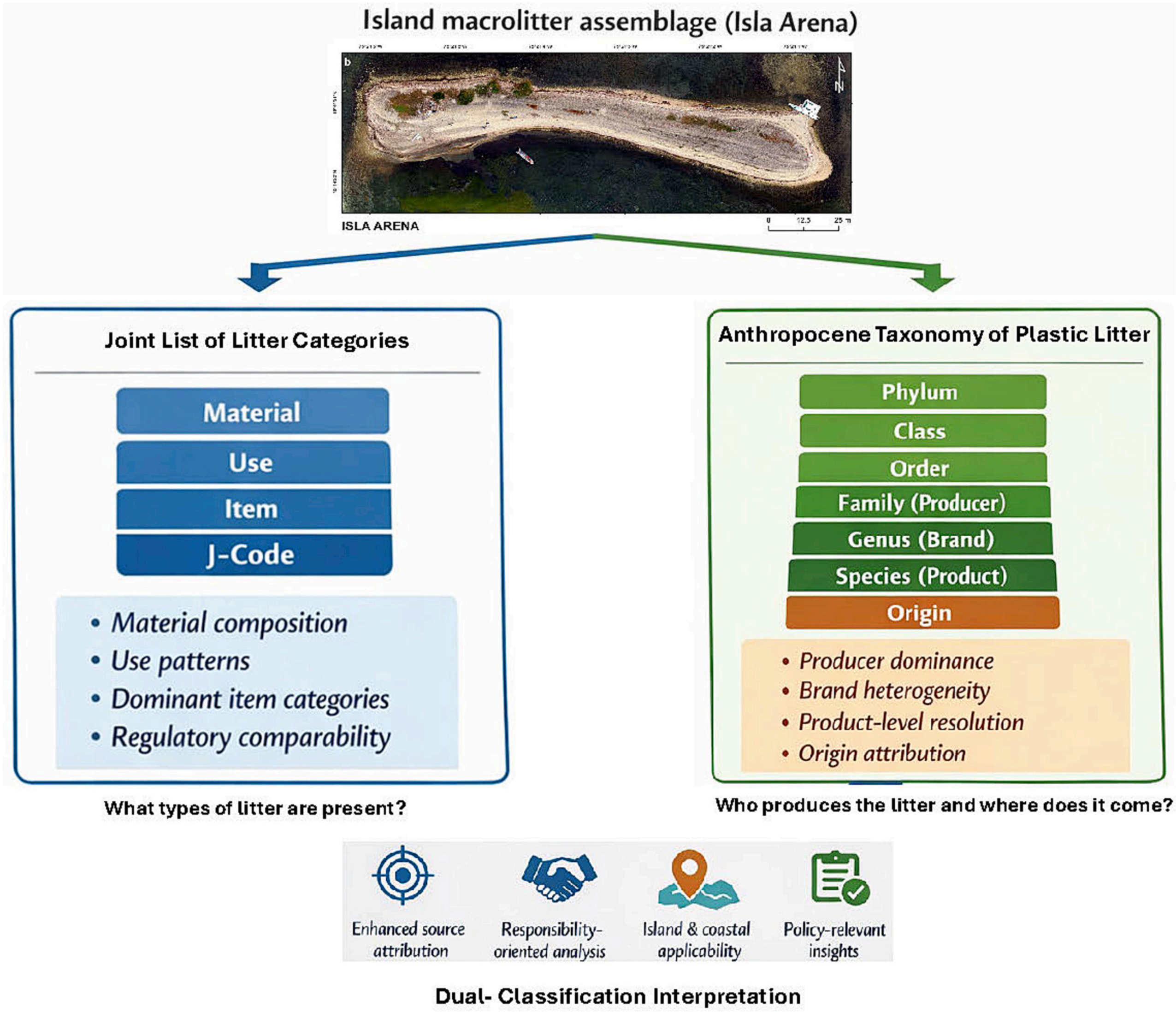

Fig. 2. Conceptual framework that illustrates the dual-classification approach applied to the Isla Arena macrolitter assemblage. The Joint List of Litter Categories captures material composition, use patterns, dominant item categories, and regulatory comparability, while the Anthropocene Taxonomy of Plastic Litter resolves litter at hierarchical levels from material to producer, brand, product, and origin. The integrated framework enhances source attribution, responsibility-oriented analysis, and policy relevance in island and coastal environments.

Plastic Litter (ATPL) developed by Rangel-Buitrago et al. (2026). This framework applies to a hierarchical structure analogous to biological taxonomy, allowing plastic litter to be organized across successive levels of resolution: Phylum, Class, Order, Family, Genus, and Species (Fig. 2). Within this system, plastics are treated as anthropogenic entities whose classification reflects material characteristics, functional form, corporate origin, brand identity, and specific marketed products.

For each plastic item, the Phylum and Class levels corresponded to the broad categorization of litter and plastic materials, while the Order level reflected the general functional form (e.g., rigid plastics, films, composites). At finer taxonomic resolution, the Family level was assigned to the corporate producer or manufacturer when identifiable, the Genus level to the brand or product line, and the Species level to the specific commercial product. Assignment was based on visible labels, logos, brand markings, residual text, distinctive packaging design, color schemes, and standardized product shapes. When available, country or regional origin was recorded based on manufacturer information, labeling, or recognized brand provenance.

Ambiguous or partially degraded items were handled conservatively. When producer or brand identification was not possible due to fragmentation, abrasion, or loss of labeling, items were still classified at higher taxonomic levels (Phylum, Class, and Order), while lower levels (Family, Genus, Species, and origin) were recorded as unidentified. This approach explicitly retained uncertainty within the dataset, avoiding speculative attribution while preserving the hierarchical structure of the assemblage. By applying ATPL alongside the Joint List, plastic litter could be resolved beyond material and use categories, enabling producer-, brand-, and product-level analysis that is not achievable through conventional monitoring frameworks alone.

To ensure terminological consistency, we distinguish between functional and taxonomic uncertainty. Within the Joint List framework, the category "Undefined use" refers exclusively to items whose original function could not be reliably inferred based on remaining physical characteristics, in accordance with MSFD guidance. In contrast, within the Anthropocene Taxonomy of Plastic Litter (ATPL), the term "Unidentified" is applied at the Family (producer), Genus (brand), Species (product), or origin levels when visual evidence was insufficient for confident attribution. Fragment categories (e.g., foamed and non-foamed plastic fragments) were assigned strictly according to Joint List size and material criteria and do not imply absence of anthropogenic origin. This distinction ensures separation between functional ambiguity and producer-level uncertainty.

2.4. Data structure and analytical approach

All macrolitter data were compiled into a single structured dataset in which each collected item corresponded to one unique record, ensuring a one-to-one correspondence between field observations and analytical classifications (Supplementary Material 1). For every item, standardized descriptors derived from the Joint List of Litter Categories (material, use, item type, full type code, and J-Code) were recorded alongside the hierarchical attributes assigned through the Anthropocene Taxonomy of Plastics (Phylum, Class, Order, Family, Genus, Species, and origin, when identifiable). This dual-classification structure allowed direct cross-referencing of regulatory and Anthropocene-based descriptors at the individual-item level.

Analyses focused on descriptive statistics, including absolute and relative frequencies of litter categories, producers, brands, and products, as well as simple aggregations across taxonomic and functional levels. Cross-framework comparisons were conducted to examine how litter assemblage structure differed when interpreted through standardized monitoring categories versus Anthropocene-based taxonomic resolution. Emphasis was placed on transparency and interpretability of results rather than on statistical complexity, allowing clear identification of dominant materials, uses, producers, and products, and facilitating discussion of source attribution and responsibility in an island context.

3. Results and discussion

3.1. Characteristics of island macrolitter

The field survey conducted on Isla Arena resulted in the collection of a total of 830 macrolitter items across a surveyed area of 779 m^2, corresponding to a mean litter density of approximately 1.07 items·m^{-2}. This value indicates a high level of macrolitter accumulation within a very small and spatially constrained island environment. All collected items met the macrolitter size criterion ($\geq$25 mm) and were retrieved from shoreline, supratidal, and interior areas of the island, reflecting the combined influence of direct deposition and overwash-driven transport.

Litter densities recorded on Isla Arena are comparable to values reported for other island environments worldwide (Table 1), including the Gulf of Aqaba (Al-Najjar and Al-Shiyab, 2011), the Azores archipelago (Ríos et al., 2018), Trindade Island, Brazil (Andrades et al., 2018), and Gun Beach on the Cocos (Keeling) Islands, Australia (Lavers et al., 2019). The observed density falls within the range reported for other island systems; however, direct comparison should be interpreted cautiously given the single-campaign nature of the present survey and potential variability associated with seasonal or storm-driven deposition. Also, direct comparison should be interpreted cautiously, as cited studies differ in sampling design (transect-based vs. full-area census), temporal coverage, and reporting metrics (e.g., items·m^{-2} vs. items·km^{-1} shoreline).

Plastic items dominated the macrolitter assemblage (Table 2). Artificial polymers accounted for 794 items, representing approximately 95.7% of the total litter collected. Non-plastic materials occurred at much lower frequencies, including glass and ceramics (23 items; 2.8%), metal (9 items; 1.1%), and trace occurrences of textiles (2 items), paper/cardboard (1 item), and rubber (1 item). This dominance of plastic debris is consistent with patterns reported for island and coastal accumulation zones, where buoyant and persistent materials are preferentially retained (Andrady, 2015; Rangel-Buitrago et al., 2026). The observed accumulation pattern is consistent with Isla Arena functioning as a convergence and retention environment for marine debris. This interpretation is supported by the island's low-lying, overwash-prone morphology and by previously documented regional transport pathways along the Colombian Caribbean coast (Rangel-Buitrago et al., 2017, 2019, 2026). The term “sink” is therefore used in a functional geomorphological sense, rather than implying quantified residence time or mass-balance assessment. However, as this assessment represents a single temporal snapshot, repeated surveys across seasons and post-event conditions would be necessary to confirm the persistence and temporal stability of this accumulation pattern.

The ecological implications of macrolitter accumulation are particularly relevant in the context of Isla Arena's carbonate reef and seagrass ecosystems. Plastic debris in coral reef environments has been associated with physical abrasion, shading, tissue necrosis, and increased susceptibility to disease, while entanglement and smothering can affect seagrass meadows and associated benthic fauna (Shumway and Ward, 2025; Rangel-Buitrago, 2025). Global studies have documented elevated coral disease incidence in contact with plastic debris and structural impacts on reef-building organisms in island settings across the Indo-Pacific and Caribbean regions (Hendrawan et al., 2026; Shankar et al., 2025). In seagrass systems, plastic entrapment can alter sediment dynamics and reduce photosynthetic efficiency through shading (Gracia et al., 2018). Given that Isla Arena hosts coral, macroalgal, and seagrass communities within a shallow and exposed platform, sustained macrolitter accumulation may compromise ecosystem structure and ecological function, even if the present study did not directly quantify biological impacts. These observations align with global reports identifying tropical island ecosystems as particularly vulnerable to marine litter pressures.

At the level of use categories, items associated with food consumption were by far the most abundant, comprising 675 items (81.3%) of the total assemblage (Table 2). This category included plastic drink bottles, food containers, caps and lids, and packaging-related items. The second most frequent group corresponded to items classified as undefined use (102 items; 12.3%), largely representing degraded or fragmented plastics whose original function could not be reliably inferred. Additional use categories occurred at much lower frequencies, including medical-related items (20 items; 2.4%), clothing-related items (12 items; 1.4%), and personal hygiene and care items (11 items; 1.3%), with minor contributions from vehicle-related, recreation-related, fisheries-related, and smoking-related uses, each representing less than 1% of the total items collected.

Analysis at the item and J-Code level demonstrated that the macrolitter assemblage was strongly concentrated within a limited number of dominant standardized categories (Fig. 3). Plastic drink bottles $\leq$0.5 L (J7) were the most abundant item, with 539 items, followed by plastic drink bottles >0.5 L (J8; 123 items). Together, these two categories accounted for more than 79% of all recorded macrolitter. Other frequent J-Code categories included glass bottles (J200; 23 items), plastic fragments of foamed polystyrene 2.5–50 cm (J82; 21 items), plastic

Table 1
Reported macrolitter densities in selected remote and island systems.

Island/System	Region	Density	Unit	Sampling Design	Temporal Scope	Reference
Isla Arena	Colombian Caribbean	1.07	items·m^{-2}	Full census (779 m^2)	Single campaign	This study
Gulf of Aqaba	Red Sea	2.5	items·m^{-2}	Transects	Single/Repeated	Al-Najjar and Al-Shiyab, 2011
Azores Archipelago	North Atlantic	3	items·m^{-2}	Beach transects	Multi-seasonal	Ríos et al., 2018
Trindade Island	South Atlantic	2.5	items·m^{-2}	Transects	Single campaign	Andrades et al., 2018
Cocos (Keeling) Islands	Indian Ocean	3.6	items·m^{-2}	Shoreline-based	Single	Lavers et al., 2019

Table 2
Macrolitter assemblage found in Isla Arena. The macrolitter assemblage was dominated by artificial polymers, which accounted for 794 items. All other plastic use categories, including medical, personal hygiene, clothing, recreation, fisheries, and vehicle-related items, occur at much lower frequencies. Non-plastic materials were scarce and included glass and ceramics, metals, paper/cardboard, and rubber, collectively representing less than 5% of the total macrolitter collected.

Material/use/full type code	Total
Artificial Polymers/Plastic	**794**
Clothing	**12**
Footwear Made of Plastic - Not Flip Flops	10
Plastic Flip-Flops	2
Fisheries Related	**1**
Plastic Nets and Pieces of Net > 50 cm	1
Food Consumption	**672**
Cups And Lids of Hard Plastic	1
Plastic Crisps Packets/Sweets Wrappers	5
Plastic Drink Bottles >0.5 L	123
Plastic Drink Bottles ≤0.5 L	539
Plastic Food Containers Made of Foamed Polystyrene	2
Plastic Food Containers Made of Hard Non-Foamed Plastic	1
Plastic Straws	1
Medical Related	**20**
Plastic Medical/Pharmaceuticals Containers/Tubes/Packaging	20
Personal Hygiene And Care	**10**
Plastic Diapers/Nappies	1
Plastic Non-Beach Use Related Body Care and Cosmetic Bottles and Containers	9
Recreation Related	**1**
Plastic Toys and Party Poppers	1
Smoking Related	**1**
Plastic Cigarette Lighters	1
Undefined Use	**72**
Fragments of Foamed Polystyrene >50 cm	6
Fragments of Foamed Polystyrene 2.5 cm ≥ ≤50 cm	21
Fragments of Non-Foamed Plastic >50 cm	7
Fragments of Non-Foamed Plastic 2.5 cm ≥ ≤50 cm	6
Other Identifiable Foamed Plastic Items	1
Other Identifiable Non-Foamed Plastic Items	3
Other Plastic Bottles & Containers (Drums)	8
Plastic Bottles and Containers of Cleaning Products	17
Plastic Caps/Lids Unidentified	2
Plastic Engine Oil Bottles & Containers 2.5 cm ≥ ≤50 cm	1
Vehicle Related	**5**
Metal Vehicle Parts/Batteries	1
Plastic Engine Oil Bottles & Containers >50 cm	2
Plastic Engine Oil Bottles & Containers 2.5 cm ≥≤50 cm	2
Clothes/Textile	2
Undefined Use	**2**
Other Textiles	2
Glass/Ceramics	23
Undefined Use	**23**
Glass Bottles	23
Metal	9
Food Consumption	**2**
Metal Drinks Cans	2
Personal Hygiene And Care	**1**
Metal Aerosol/Spray Cans	1
Recreation Related	**1**
Metal Aerosol/Spray Cans	1
Undefined Use	**5**
Metal Aerosol/Spray Cans	4
Metal Bottle Caps, Lids & Pull Tabs From Cans	1
Paper/Cardboard	1
Food Consumption	**1**
Paper Cartons/Tetrapak (Non-Milk)	1
Rubber	1
Recreation Related	**1**
Rubber Balls	1
Total	830

medical/pharmaceutical containers and packaging (J100; 20 items), and plastic bottles and containers of cleaning products (J9; 17 items). All remaining J-Code categories were represented by fewer than 10 items each.

The strong dominance of a small subset of food consumption–related plastic categories indicates that, despite the apparent diversity of litter types, macrolitter accumulation on Isla Arena is structurally driven by a narrow group of standardized items. Plastic beverage bottles, which accounted for approximately 79% of the total macrolitter assemblage when combining size classes ≤0.5 L and >0.5 L, are consistently reported as one of the most prevalent forms of marine litter on beaches worldwide (Savage et al., 2024; Garcés-Ordóñez et al., 2025a, 2025b). Their dominance has been documented across a wide range of coastal and island environments, reflecting high production volumes, widespread consumption, and frequent mismanagement (Brabo et al., 2024; Ryan et al., 2024). Beverage bottles are characterized by high persistence in the marine environment, buoyancy that facilitates long-range transport by ocean currents and winds, and repeated stranding along shorelines (Ryan et al., 2019). Beyond their numerical dominance, these items pose well-documented ecological risks through physical abrasion of habitats, fragmentation into secondary microplastics, and ingestion by marine organisms (Rangel-Buitrago, 2025). As a result, plastic beverage bottles are widely recognized as a priority item for monitoring, mitigation, and policy intervention within global marine litter frameworks.

At the highest taxonomic levels of the Anthropocene Taxonomy of Plastics, the macrolitter assemblage was entirely assigned to the **Phylum Litter (n = 830)**, reflecting its anthropogenic origin. Within this phylum, the **Class Plastics** dominated, accounting for **798 items (96.1%)**, while **glass (23 items; 2.8%)** and **metal (9 items; 1.1%)** represented minor contributions. This class-level structure reflects the material dominance observed under the Joint List classification, confirming plastics as the defining component of the island macrolitter assemblage.

At the Order level, plastic items were strongly concentrated within a small number of functional forms (Fig. 4). Rigid plastics constituted the dominant order, with 757 items (91.2%), followed by foams (29 items; 3.5%), bottles (23 items; 2.8%), composites (9 items; 1.1%), and aerosols (6 items; 0.7%). This distribution highlights the prevalence of structurally robust, buoyant plastic forms that are resistant to fragmentation and well suited for long-range transport and repeated stranding in island environments.

Substantial heterogeneity emerged at finer taxonomic resolution. At the Family (producer) level, 49 identifiable producers were recorded, while 73 brands or product lines (Genus) and 96 specific products (Species) were identified across the assemblage. However, producer and brand information could not be assigned for 597 items (71.9%), primarily due to degradation, abrasion, or loss of labeling. Among identifiable producers, a small number of multinational and regional beverage companies dominated the assemblage, including Bavaria–Anheuser-Busch InBev (64 items), AJE Group (26 items), Postobón S.A. (22 items), and The Coca-Cola Company (20 items) (Fig. 5). At the brand level, Pony Malta (63 items), Big Cola (18 items), Gatorade (15 items), and Coca-Cola (13 items) were the most frequently recorded genera. Species-level resolution further revealed dominance by a limited number of specific beverage products, particularly small-volume PET bottles.

Information on geographic origin could be assigned for 233 items (28.1%), while the remaining items lacked sufficient labeling for reliable attribution. Among identifiable items, Colombia was the dominant origin (225 items), followed by minor contributions from Panama (6 items), Guatemala (1 item), and Thailand (1 item). This pattern reflects a predominance of regionally produced consumer goods, combined with a smaller fraction of transboundary inputs. The high proportion of unidentified origins shows the effect of environmental exposure and degradation on traceability, while the diversity of identifiable producers and brands reveals substantial heterogeneity that remains hidden under conventional regulatory classifications.

Within the identifiable subset of plastic items (n = 233), ATPL revealed heterogeneity at producer, brand, and product levels, alongside concentration among a limited number of corporate actors. However,

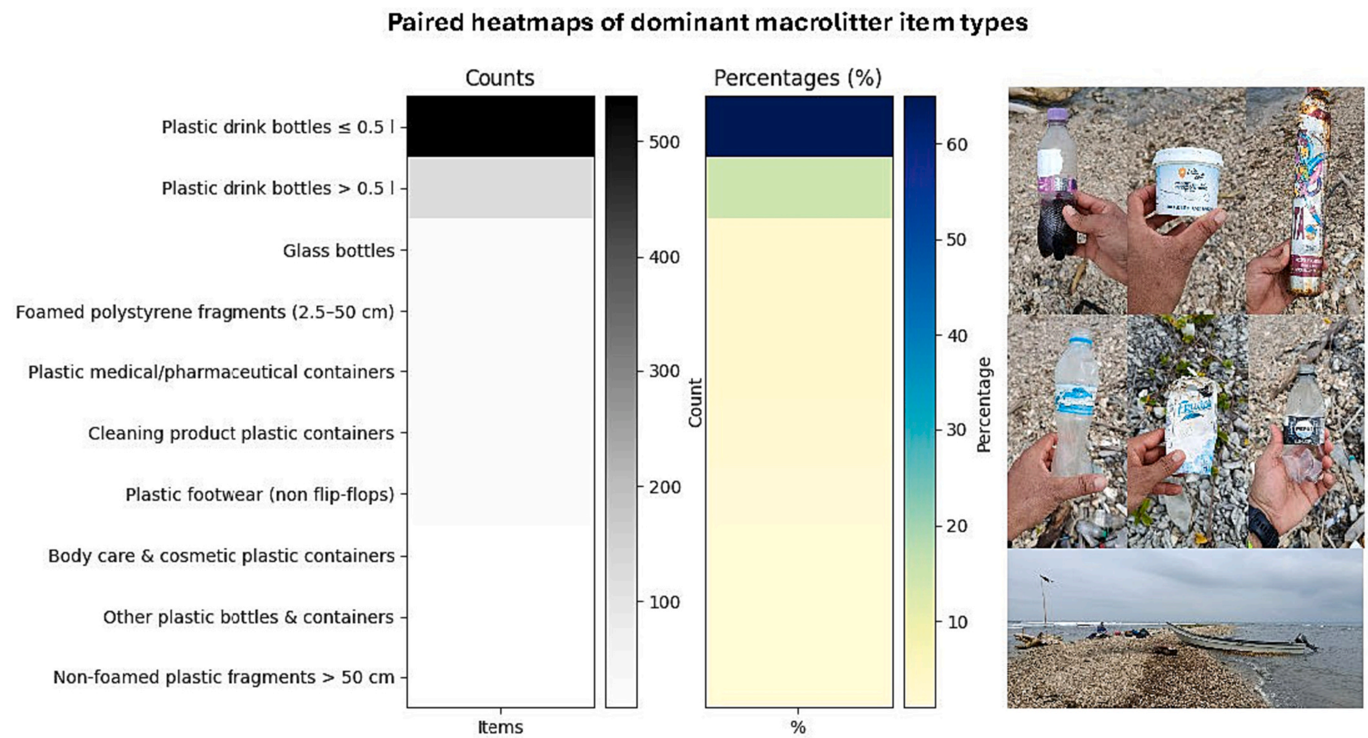

Fig. 3. Paired heatmaps showing absolute counts (left) and relative contribution (%) (right) of the most abundant macrolitter types recorded on Isla Arena. The comparison highlights the strong dominance of plastic beverage bottles, particularly those ≤0.5 L, and the highly skewed structure of the island macrolitter assemblage.

Fig. 4. Representative examples and relative abundance of plastic litter categories classified at the Order level of the Anthropocene Taxonomy of Plastic Litter. Rigid plastics dominate the assemblage, followed by foams, bottles, composites, aerosols, caps, cans, and non-rigid plastics, illustrating strong functional simplification of the plastic litter assemblage on Isla Arena.

approximately 71.9% of plastic items lacked sufficient labeling for producer-level attribution, indicating substantial loss of traceability. Therefore, dominance patterns described here reflect structure within the traceable fraction of the assemblage rather than the total plastic load.

The previous presented results indicate that Isla Arena supports a high-density macrolitter assemblage despite the absence of a permanent resident population and local waste-generation activities. The litter density observed is comparable to, or within the range of, values reported for inhabited island systems worldwide (i.e., Gulf of Aqaba, the Azores archipelago, Trindade Island), reinforcing the role of the island as a convergence and retention zone for marine debris rather than a primary source area. This pattern highlights the influence of regional transport processes and overwash dynamics in shaping island-scale macrolitter accumulation.

At the same time, the assemblage exhibits a marked functional simplification, with plastic beverage bottles dominating item composition, while showing substantial socio-economic complexity at finer analytical resolution. Although a limited number of standardized item categories account for most recorded macrolitter, ATPL-based classification revealed a diverse pool of producers, brands, and products, coupled with strong dominance by a small subset of corporate actors.

The high proportion of items lacking identifiable origin further demonstrates the rapid loss of traceability due to environmental degradation, emphasizing that macrolitter assemblages simultaneously reflect concentrated production systems and constrained attribution potential once items enter the marine environment. Also, the absence of permanent human occupation, combined with strong physical and socio-economic connectivity to regional production and consumption systems, makes Isla Arena a particularly suitable natural laboratory for

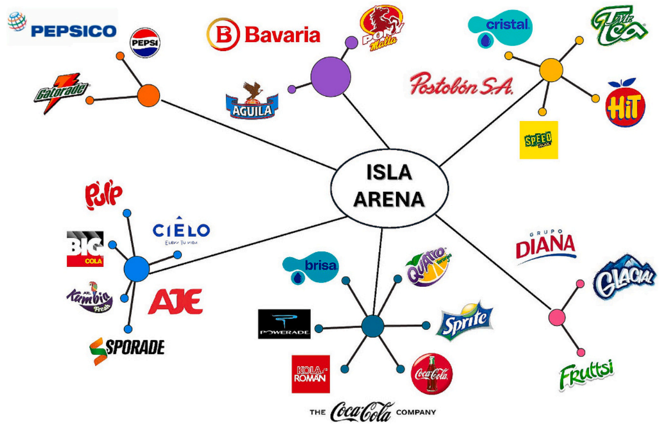

Fig. 5. Producer–brand network derived from the Anthropocene Taxonomy of Plastics Litter applied to the Isla Arena macrolitter assemblage. Isla Arena is represented as a central sink receiving inputs from multiple corporate producers (Family level), with associated brands shown as subordinate nodes (Genus's level). Node size is proportional to item abundance, illustrating producer dominance and brand-level heterogeneity within the assemblage.

high-resolution analysis of coastal waste assemblages.

3.2. Cross-framework interpretation and added analytical value of Anthropocene-based classification

Direct comparison between the Joint List of Litter Categories and the ATPL revealed marked differences in analytical resolution and interpretative capacity. Under the Joint List framework, the macrolitter assemblage on Isla Arena appeared strongly dominated by a small number of standardized categories, particularly food consumption–related plastics, with plastic beverage bottles representing the most abundant item type. This classification provided a robust and reliable description of material composition and dominant use patterns, confirming plastics as the defining component of the assemblage and enabling direct comparison with island and coastal datasets worldwide (Vriend et al., 2020; Fleet et al., 2021; van Nguyen et al., 2026).

Fig. 6 provides an integrated visualization of the macrolitter assemblage by explicitly linking standardized regulatory descriptors with Anthropocene-based taxonomic resolution. Using a flow-based representation, the figure traces macrolitter items from material and uses categories defined by the Joint List of Litter Categories through specific item types, producers, brands, and, where identifiable, geographic origin. This visualization highlights how dominant standardized categories, particularly food consumption–related plastics and plastic beverage bottles, aggregate a wide diversity of producers and brands, while also illustrating the progressive loss of traceability caused by environmental degradation. By making visible both information compression within regulatory categories and information recovery

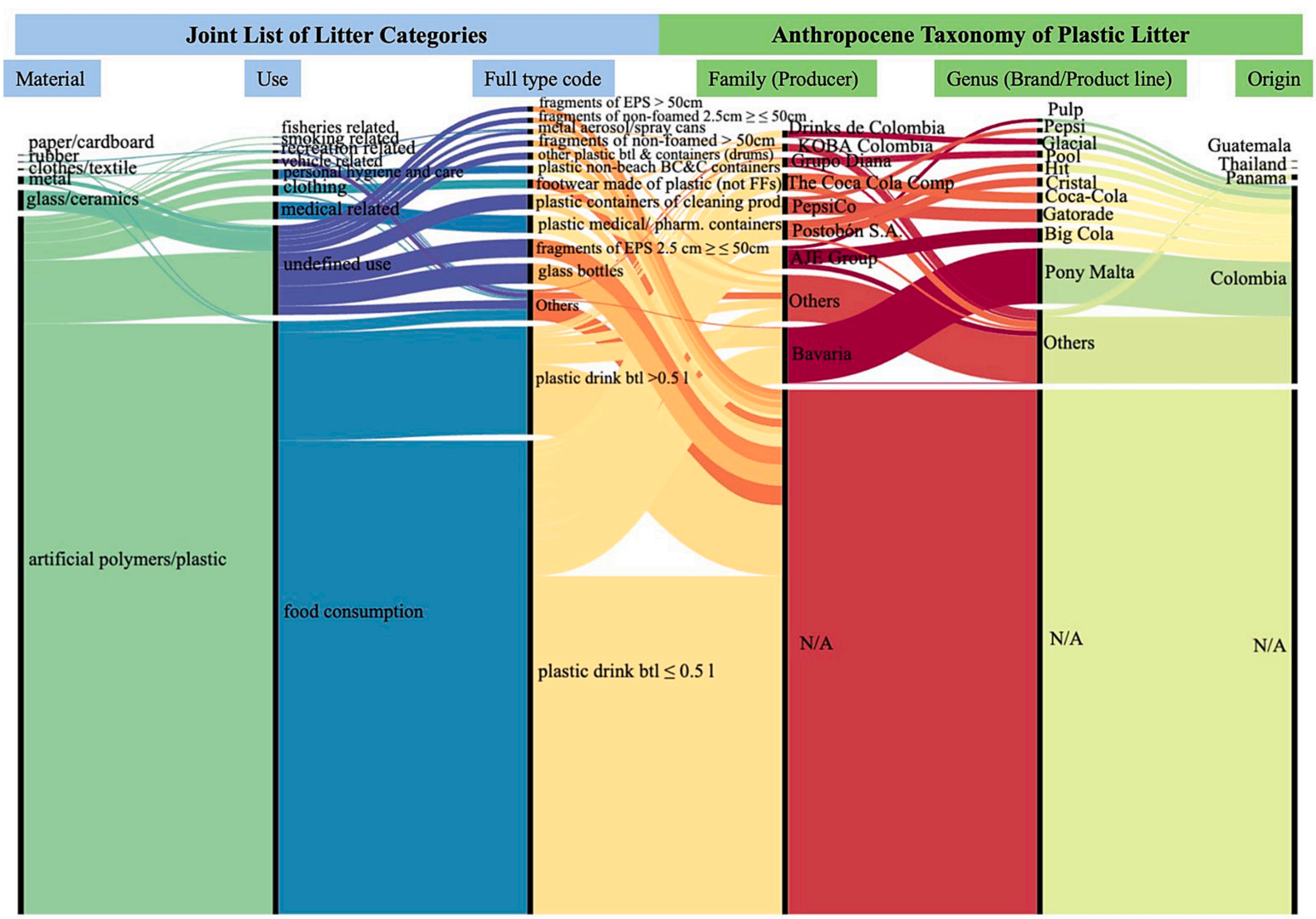

Fig. 6. Flow-based (Sankey-style) visualization linking standardized regulatory descriptors from the Joint List of Litter Categories (material, use, and full type code) with hierarchical levels of the Anthropocene Taxonomy of Plastic Litter (producer [Family], brand/product line [Genus], and origin, where identifiable). The figure illustrates how dominant standardized categories, particularly food consumption–related plastics and plastic beverage bottles, aggregate multiple producers and brands, while also highlighting the progressive loss of traceability due to environmental degradation.

through ATPL, Fig. 6 reinforces the added analytical value of the dual-classification framework for source attribution, responsibility-oriented interpretation, and aquatic environmental security assessment.

Beyond their descriptive strength, standardized monitoring frameworks play a critical role in regulatory reporting, baseline establishment, and assessment of temporal and spatial trends in macrolitter pollution (Vriend et al., 2020; Galgani et al., 2024). Their hierarchical structure allows aggregation and disaggregation across environmental compartments, supporting comparability among beaches, the water surface, and the seafloor (Rangel-Buitrago, 2025). In island and exposed coastal settings, this capacity is particularly valuable for documenting accumulation hotspots and tracking changes associated with seasonal variability, extreme events, or management interventions (Arcangeli et al., 2025).

However, results from Isla Arena also highlight the analytical limitations of standardized classification systems when addressing source complexity. While Joint List outputs effectively identify which item types dominate the assemblage, they treat items within the same J-Code category as functionally homogeneous, offering limited insight into producer identity, geographic origin, or the structure of production and distribution systems. This limitation is not unique to island environments but extends broadly across coastal and marine settings, where macrolitter often reflects a mixture of local inputs and long-range transported debris (Schreyers et al., 2024).

Application of ATPL to the same assemblage demonstrated that this apparent homogeneity masks substantial heterogeneity at finer analytical resolution. Single dominant J-Code categories, such as plastic beverage bottles, encompassed a wide diversity of producers, brands, and specific products. Within these categories, ATPL revealed pronounced dominance patterns by a limited number of producers and brands, accompanied by a long tail of less frequent contributors. This producer- and brand-level structure remained invisible under standardized monitoring alone, despite the numerical dominance of a few item categories.

This enhanced resolution is particularly relevant in island environments, where litter assemblages frequently integrate inputs from both local consumption and long-range transport (Rangel-Buitrago et al., 2019, 2026; Garcés-Ordóñez et al., 2025a, 2025b). By resolving macrolitter beyond material and use categories, ATPL provides a clearer understanding of how global and regional production systems are expressed in island-scale pollution patterns, revealing concentration and dominance dynamics that are not detectable through regulatory classification schemes.

The contrast between frameworks has important implications for interpreting island macrolitter sources. While Joint List–based classification indicates the prevalence of consumer-derived plastic items, ATPL shows that island macrolitter assemblages are shaped by specific production and distribution systems rather than by generic item types alone. In an island context influenced by both regional transport and limited local activity, dual classification clarifies that litter accumulation reflects not only functional use categories but also concentrated contributions from identifiable producers and brands.

This added analytical resolution has direct implications for responsibility-oriented interpretations and extended producer responsibility frameworks. Identifying the relative contribution of specific producers and brands allows macrolitter data to be linked more explicitly to production, packaging, and market distribution practices (Iglesias et al., 2023; Brabo et al., 2024; Schreyers et al., 2024). In island and coastal contexts, where local waste management capacity is often limited and external inputs are significant, such information is critical for distinguishing locally generated debris from imported pollution and for informing prevention strategies that extend beyond site-level cleanup (Williams and Micallef, 2009; Williams and Rangel-Buitrago, 2019, 2022).

While ATPL does not provide direct proportional responsibility allocation in the absence of production-volume or market-share data, it can function as a complementary informational layer within existing EPR and marine litter monitoring systems. Authorities could use recurrent producer-level signals within identifiable fractions to inform dialogue, voluntary reporting, or targeted mitigation strategies. However, formal liability assignment would require integration with market and production datasets beyond the scope of the present study.

Overall, these findings demonstrate that standardized monitoring frameworks are indispensable for characterizing macrolitter composition and magnitude (Vriend et al., 2020; Fleet et al., 2021), but insufficient on their own to resolve the socio-economic drivers underlying coastal and marine pollution. By complementing regulatory classification with Anthropocene-based taxonomy, ATPL extends interpretation towards producer-, brand-, and product-level resolution, enabling macrolitter assemblages to be examined simultaneously as environmental indicators and as expressions of Anthropocene-driven production and consumption systems (Rangel and Gracia, 2026; Rangel-Buitrago and Galgani, 2026).

3.3. *Implications of a dual-classification framework for island litter monitoring*

The combined application of standardized regulatory classification and Anthropocene-based taxonomy has important implications for macrolitter monitoring in island and small-territory settings. Islands are often characterized by limited spatial extent, high exposure to marine transport processes, and constrained monitoring resources, which makes the efficiency and interpretative value of monitoring strategies particularly critical (Ratter, 2018; van Rheenen et al., 2024). In this context, dual classification allows standardized frameworks, such as the Joint List, to retain their role in ensuring comparability, regulatory reporting, and trend detection, while simultaneously extending analytical resolution through ATPL without requiring changes to field sampling protocols. This compatibility makes the approach especially suitable for island monitoring programs, where maximizing information gain from limited datasets is essential (Rees and Pond, 1995).

Beyond island-specific applications, the dual-classification framework is readily transferable to other coastal and marine environments. Beaches, estuaries, lagoons, and exposed coastal sectors that function as litter accumulation zones share many of the analytical challenges observed in insular systems, including mixed local and transboundary inputs and dominance by a narrow set of consumer-derived items (van Duinen et al., 2022; Brabo et al., 2024). Applying ATPL alongside standardized monitoring in these environments would allow existing datasets to be reinterpreted at producer, brand, and product levels, enhancing source attribution and comparative analyses across regions without compromising methodological consistency.

The scalability of the dual-classification approach supports its application across different spatial and temporal scales. At local scales, it can improve the interpretation of site-specific accumulation patterns, while at regional or multi-site scales it enables comparative assessments of producer and brand dominance across island groups, coastlines, or marine regions. By maintaining standardized descriptors while adding an Anthropocene-based analytical layer, this framework provides a flexible and complementary tool for advancing macrolitter research, particularly in environments where understanding source complexity and responsibility is central to effective monitoring and management.

From an aquatic environmental security perspective, the macrolitter assemblage documented on Isla Arena reflects a structural vulnerability of marine systems to externally generated pollution pressures. The accumulation of high-density plastic litter in an uninhabited island environment, combined with strong producer dominance and rapid loss of traceability, illustrates how failures in upstream production, consumption, and waste governance materialize as risks to aquatic system integrity. While standardized monitoring frameworks effectively characterize the magnitude and composition of macrolitter, the integration of Anthropocene-based taxonomy reveals concentration patterns among specific producers and brands that are directly relevant for responsibility-oriented governance and pollution prevention. In this sense, Isla Arena functions as a sentinel system, exposing how trans-boundary material flows compromise the ecological safety of coastal and marine environments beyond the reach of local management. The dual-classification framework applied here therefore strengthens the role of macrolitter monitoring not only as an environmental assessment tool, but also as an instrument that contributes to understanding how macrolitter monitoring can inform broader discussions on aquatic environmental governance and system resilience.

3.4. Methodological limitations and uncertainties

As with most macrolitter assessments, this study is subject to limitations related to the visual identification of items and the effects of environmental degradation (Rangel-Buitrago, 2025). Prolonged exposure to sunlight, abrasion, biofouling, and fragmentation can damage/destroy labels, logos, and manufacturing features (Bianco et al., 2020; Andrady et al., 2022), reducing the ability to assign producer, brand, product, or origin information with certainty. This limitation was reflected in the proportion of items that could only be classified at higher taxonomic levels within the ATPL. To address this uncertainty, a conservative attribution strategy was applied, whereby ambiguous or partially identifiable items were classified only at levels supported by clear visual evidence, avoiding speculative assignments while preserving the hierarchical structure of the dataset.

An additional limitation arises from the spatial scope of the study, which is based on a single island-scale accumulation environment. While Isla Arena is representative of exposed, low-lying island settings in the Colombian Caribbean, the results cannot be directly extrapolated to all island, coastal, or marine environments without caution. Macrolitter composition and source structure are influenced by local geomorphology, hydrodynamic conditions, proximity to population centers, and regional circulation patterns, which may vary substantially among sites (Critchell et al., 2019; Rangel and Gracia, 2026). Nevertheless, the objective of this study was not to provide a regional inventory, but to evaluate the analytical performance of a dual-classification framework under real-world conditions.

Because the survey was conducted at a single point in time, the results reflect accumulated deposition under prevailing conditions rather than a temporally resolved accumulation rate. Event-driven variability, including storm-induced pulses or seasonal shifts in transport pathways, may influence short-term density patterns. Longitudinal monitoring would be required to evaluate the temporal stability of convergence dynamics.

Despite these limitations, the combined use of standardized regulatory classification and Anthropocene-based taxonomy provides a robust proof of concept for integrative macrolitter analysis. The approach maintains compatibility with established monitoring frameworks while substantially enhancing interpretative resolution at producer, brand, and product levels. As such, the methodological constraints identified here primarily reflect challenges common to macrolitter research in general, rather than weaknesses of the dual-classification framework itself. Future applications across multiple sites and environmental contexts will further refine its robustness and support broader comparative analyses.

Although ATPL introduces a new perspective for interpreting macrolitter assemblages, its analytical performance in terms of inter-observer consistency and sensitivity has not yet been formally quantified. Like other visual source-attribution methods (i.e., OSPAR), ATPL is limited by item degradation and observer-dependent identification, but it differs from chemical or model-based approaches by enabling direct linkage between litter assemblages and specific producers and products, thereby complementing rather than replacing existing source-attribution techniques.

4. Conclusions

This study documents a high-density macrolitter assemblage on a small, uninhabited Caribbean island, demonstrating that isolated coastal systems can accumulate debris at magnitudes comparable to inhabited island environments. The absence of local waste generation, combined with the island's low-lying morphology and regional hydrodynamic exposure, indicates that the observed accumulation reflects externally driven inputs rather than in situ disposal. While based on a single temporal snapshot, the results are consistent with Isla Arena functioning as a passive recipient of regional marine litter transport.

Standardized classification using the Joint List of Litter Categories confirmed the dominance of plastic items, particularly beverage bottles, revealing strong functional simplification of the assemblage. These findings align with global patterns of consumer-derived plastic prevalence in island and coastal accumulation zones.

Application of the Anthropocene Taxonomy of Plastic Litter provided additional resolution at producer, brand, and product levels within the identifiable subset of items. Although approximately 72% of plastic items lacked sufficient labeling for producer-level attribution, the traceable fraction revealed measurable heterogeneity and concentration among a limited number of corporate actors. These patterns apply only to the identifiable component of the assemblage and should be interpreted considering differential degradation and label persistence. Importantly, the substantial loss of traceability itself represents a key environmental signal, highlighting how exposure processes rapidly erode source information once plastics enter marine systems.

The integration of regulatory classification with ATPL does not replace standardized monitoring frameworks nor provide definitive attribution of proportional responsibility. Rather, it demonstrates how existing datasets can be structured to extract additional producer-level information where identification is possible, thereby enhancing interpretative depth without altering field protocols. In this sense, the dual-classification framework functions as an analytical extension of conventional monitoring rather than an alternative system.

Future applications across multiple sites and temporal scales, combined with formal validation of inter-observer consistency and integration with production or market-share data, will be necessary to evaluate the broader robustness and governance utility of this approach. Nonetheless, the present study illustrates that even within the constraints of partial traceability, hierarchical classification can reveal structural features of marine litter assemblages that remain invisible under material-based categorization alone.

CRediT authorship contribution statement

Nelson Rangel-Buitrago: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alex Paternina-Ramos:** Writing – original draft, Investigation, Data curation. **Lucio Brabo:** Writing – original draft, Investigation. **Francisco Jailton Silva Filho:** Writing – original draft, Investigation. **Tommaso Giarrizzo:** Writing – original draft, Investigation. **Mohamed Ben-Haddad:** Writing – original draft, Investigation. **Leví García-Romero:** Writing – original draft, Investigation. **Carolina Peña-Alonso:** Writing – original draft, Investigation. **Juan Guillermo Martín:** Writing – original draft, Investigation. **J.A.G. Cooper:** Writing – original draft, Investigation. **William J. Neal:** Writing – original draft, Investigation. **Francois Galgani:** Writing – original draft, Investigation.

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.2026.119541.

Data availability

Data will be made available on request.

References

Al-Najjar, T., Al-Shiyab, A., 2011. Marine litter at (Al-Ghandoor area), the most northern part of the Jordanian coast of the Gulf of Aqaba, Red Sea. Nat. Sci. 3, 921–926.

Andrades, R., Santos, R., Joyeux, J.-C., Chelazzi, D., Cincinelli, A., Giarrizzo, T., 2018. Marine debris in Trindade Island, a remote island of the South Atlantic. Mar. Pollut. Bull. 137, 180–184.

Andrady, A.L., 2015. Persistence of plastic litter in the oceans. In: Marine Anthropogenic Litter. Springer International Publishing, Cham, pp. 57–72. https://doi.org/10.1007/978-3-319-16510-3_3.

Andrady, A.L., Barnes, P.W., Bornman, J.F., Gouin, T., Madronich, S., White, C.C., Zepp, R.G., Jansen, M.A.K., 2022. Oxidation and fragmentation of plastics in a changing environment; from UV-radiation to biological degradation. Sci. Total Environ. 851, 158022. https://doi.org/10.1016/j.scitotenv.2022.158022.

Andriolo, U., Gonçalves, G., 2022. Is coastal erosion a source of marine litter pollution? Evidence of coastal dunes being a reservoir of plastics. Mar. Pollut. Bull. 174, 113307. https://doi.org/10.1016/j.marpolbul.2021.113307.

Andriolo, U., Gonçalves, G., Bessa, F., Sobral, P., 2020. Mapping marine litter on coastal dunes with unmanned aerial systems: a showcase on the Atlantic Coast. Sci. Total Environ. 736, 139632. https://doi.org/10.1016/j.scitotenv.2020.139632.

Andriolo, U., Gonçalves, G., Sobral, P., Bessa, F., 2021. Spatial and size distribution of macro-litter on coastal dunes from drone images: a case study on the Atlantic coast. Mar. Pollut. Bull. 169, 112490. https://doi.org/10.1016/j.marpolbul.2021.112490.

Anfuso, G., Rangel-Buitrago, N., Correa Arango, I.D., 2015. Evolution of Sandspits Along the Caribbean Coast of Colombia: Natural and Human Influences, pp. 1–19. https://doi.org/10.1007/978-3-319-13716-2_1.

Arcangeli, A., Pasanisi, E., Santini, E., Crosti, R., 2025. A systematic monitoring approach to assess floating marine macro litter in Italian waters: baseline, thresholds, good environmental status, and mitigation priorities under the EU MSFD. Mar. Pollut. Bull. 212, 117477. https://doi.org/10.1016/j.marpolbul.2024.117477.

Bosence, D., 2005. A genetic classification of carbonate platforms based on their basinal and tectonic settings in the Cenozoic. Sediment. Geol. 175, 49–72. https://doi.org/10.1016/j.sedgeo.2004.12.030.

Brabo, L., Martins, L.L., Andrades, R., Teixeira, C.E.P., do Nascimento, A.P., de Azevedo, R.N.A., Bezerra, L.E.A., Cavalcante, R.M., Cottens, K.F., Soares, R.A., de Oliveira Sousa, P.H.G., Mont'Alverne, T.F., Soares, M.O., Giarrizzo, T., 2024. A transcontinental threat: plastic waste from Africa invades Brazil's coast. Sci. Total Environ. 954, 176599. https://doi.org/10.1016/j.scitotenv.2024.176599.

Canals, M., Pham, C.K., Bergmann, M., Gutow, L., Hanke, G., van Sebille, E., Angiolillo, M., Buhl-Mortensen, L., Cau, A., Ioakeimidis, C., Kammann, U., Lundsten, L., Papatheodorou, G., Purser, A., Sanchez-Vidal, A., Schulz, M., Vinci, M., Chiba, S., Galgani, F., Langenkämper, D., Möller, T., Nattkemper, T.W., Ruiz, M., Suikkanen, S., Woodall, L., Fakiris, E., Molina Jack, M.E., Giorgetti, A., 2020. The quest for seafloor macrolitter: a critical review of background knowledge, current methods and future prospects. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/abc6d4.

Claro, F., Fossi, M.C., Ioakeimidis, C., Baini, M., Lusher, A.L., Mc Fee, W., McIntosh, R.R., Pelamatti, T., Sorce, M., Galgani, F., Hardesty, B.D., 2019. Tools and constraints in monitoring interactions between marine litter and megafauna: insights from case studies around the world. Mar. Pollut. Bull. 141, 147–160. https://doi.org/10.1016/j.marpolbul.2019.01.018.

Compa, M., Wilcox, C., Hardesty, B.D., Alomar, C., March, D., Deudero, S., 2022. Quantifying the risk of plastic ingestion by ichthyofauna in the Balearic Islands (western Mediterranean Sea). Mar. Pollut. Bull. 183, 114075. https://doi.org/10.1016/j.marpolbul.2022.114075.

Critchell, K., Bauer-Civiello, A., Benham, C., Berry, K., Eagle, L., Hamann, M., Hussey, K., Ridgway, T., 2019. Plastic pollution in the coastal environment: current challenges and future solutions. In: Coasts and Estuaries. Elsevier, pp. 595–609. https://doi.org/10.1016/B978-0-12-814003-1.00034-4.

Falk-Andersson, J., Hurley, R., Lusher, A.L., 2025. Including decision makers in development of cost-efficient litter monitoring - a three step process. Environ. Pollut. 373, 126104. https://doi.org/10.1016/j.envpol.2025.126104.

Galgani, F., Lusher, A.L., Strand, J., Haarr, M.L., Vinci, M., Molina Jack, E., Kagi, R., Aliani, S., Herzke, D., Nikiforov, V., Primpke, S., Schmidt, N., Fabres, J., de Witte, B., Solbakken, V.S., van Bavel, B., 2024. Revisiting the strategy for marine litter monitoring within the european marine strategy framework directive (MSFD). Ocean Coast. Manag. 255, 107254. https://doi.org/10.1016/j.ocecoaman.2024.107254.

Garcés-Ordóñez, O., Saldarriaga-Vélez, J.F., Espinosa-Díaz, L.F., 2021. Marine litter pollution in mangrove forests from Providencia and Santa Catalina islands, after Hurricane IOTA path in the Colombian Caribbean. Mar. Pollut. Bull. 168, 112471. https://doi.org/10.1016/j.marpolbul.2021.112471.

Garcés-Ordóñez, O., Ergas, M., Baeza-Álvarez, J., Honorato-Zimmer, D., López-Xalín, N., Vásquez, N., Canals, M., de Veer, D., Aguilera, M.E., Arias, I., Bolaños, S., Aguilar Fallas, D., Cuenca, M., de La Torre León, A.C., Díaz Córdoba, E., Gallardo, M. de los Á., Hernández, S., Marcus, L., Muñoz-Araya, J.M., Pérez-Venegas, D.J., Sánchez, O. A., Segura Estévez, D., Valdivia-Chavez, D., Vélez Tacuri, J., Xajil-Sabán, M., Praet, E., Zambrano, R., Zárate, R., Thiel, M., 2025a. Abundance, provenance, and characteristics of plastic beverage bottles in human settlements and on beaches of the Latin American Pacific region: a citizen science study. J. Clean. Prod. 521, 146234. https://doi.org/10.1016/j.jclepro.2025.146234.

Garcés-Ordóñez, O., Spence, R., Canals, M., Thiel, M., 2025b. Macrolitter contamination in beach, dune, and mangrove ecosystems on a Caribbean island: a comparative analysis. Mar. Pollut. Bull. 213, 117616. https://doi.org/10.1016/j.marpolbul.2025.117616.

González-Fernández, D., Hanke, G., 2017. Toward a harmonized approach for monitoring of riverine floating macro litter inputs to the marine environment. Front. Mar. Sci. 4. https://doi.org/10.3389/fmars.2017.00086.

Gracia, A., Rangel-Buitrago, N., Sellanes, J., 2012. Methane seep molluscs from the Sinú–San Jacinto fold belt in the Caribbean Sea of Colombia. J. Mar. Biol. Assoc. U. K. 92, 1367–1377. https://doi.org/10.1017/S0025315411001421.

Gracia, C.A., Rangel-Buitrago, N., Flórez, P., 2018. Beach litter and woody-debris colonizers on the Atlantico department Caribbean coastline, Colombia. Mar. Pollut. Bull. 128, 185–196. https://doi.org/10.1016/j.marpolbul.2018.01.017.

Guruge, K.P.G.K.P., Bamunuarachchi, B.A.A.D., Bandara, T., Bandara, B.M.C.A., Suwandhahannadi, W.K., Hewathilake, H.P.T.S., Kumara, P.B.T.P., 2026. Spatial patterns of macro-debris and microplastic pollution in Sri Lankan mangrove ecosystems: insights from Rekawa and Negombo. Mar. Pollut. Bull. 225, 119275. https://doi.org/10.1016/j.marpolbul.2026.119275.

Haarr, M.L., Falk-Andersson, J., Fabres, J., 2022. Global marine litter research 2015–2020: geographical and methodological trends. Sci. Total Environ. 820, 153162. https://doi.org/10.1016/j.scitotenv.2022.153162.

Hanke, G., Canals, M., Nakajima, R., Bergmann, M., Galgani, F., Li, D., Papatheodorou, G., Pham, C.K., Amon, D.J., Angiolillo, M., Buhl-Mortensen, L., Cau, A., Consoli, P., Davies, J.S., Dominguez-Carrió, C., Duarte, C.M., Giorgetti, A., Grøsvik, B.E., Gutow, L., Huvenne, V.A.I., Ioakeimidis, C., Komorin, V., Liu, G., Lundsten, L., Makarenko, I., Martynova, A., Jack, M.E.M., Nattkemper, T.W., Palacz, A.P., Palma, M., Pierdomenico, M., Pogojeva, M., Ruiz, M., Ruiz-Orejón, L.F., Russell, J., Shan, X., Valdenegro-Toro, M., Vinci, M., Wei, N., Woodall, L.C., Zhang, S., 2025. Out of sight, but not out of mind: key issues regarding seafloor macrolitter monitoring. Mar. Pollut. Bull. 221, 118500. https://doi.org/10.1016/j.marpolbul.2025.118500.

Hendrawan, I.G., Sudarmawan, A.R., Pamungkas, P.B.P., Julyantoro, P.G.S., Karang, I.W.G.A., Wiyanto, D.B., Raharja, I.M.D., Maharta, I.P.R.F., Lazaren, C.C., Wyatt, A.S.J., 2026. Plastic threats to coral reefs: a strategic management perspective from Bali's marine protected areas. Mar. Pollut. Bull. 226, 119385. https://doi.org/10.1016/j.marpolbul.2026.119385.

Iglesias, I., Lupiac, M., Vieira, L.R., Antunes, S.C., Mira-Veiga, J., Sousa-Pinto, I., Lobo, A., 2023. Socio-economic factors affecting the distribution of marine litter: the Portuguese case study. Mar. Pollut. Bull. 193, 115168. https://doi.org/10.1016/j.marpolbul.2023.115168.

Ilechukwu, I., Stoeltje, M., Conn, E., Reimer, J.D., 2025. Marine litter on remote islands: case study of beaches in Ishigaki and Taketomi Islands, Japan. Mar. Pollut. Bull. 214, 117797. https://doi.org/10.1016/j.marpolbul.2025.117797.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 1979 (347), 768–771. https://doi.org/10.1126/science.1260352.

Kasa, V.P., Brahmandam, A.K.S.V., Samal, B., Cheela, V.R.S., Dubey, B.K., Pathak, K., 2025. Assessment of coastal litter trends in tourist vs. non-tourist beaches: a case study from Indian coastal smart city. Sci. Total Environ. 959, 178339. https://doi.org/10.1016/j.scitotenv.2024.178339.

Krelling, A.P., Souza, M.M., Williams, A.T., Turra, A., 2017. Transboundary movement of marine litter in an estuarine gradient: evaluating sources and sinks using hydrodynamic modelling and ground truthing estimates. Mar. Pollut. Bull. 119, 48–63. https://doi.org/10.1016/j.marpolbul.2017.03.034.

Lavers, J.L., Dicks, L., Finger, A., 2019. Significant plastic accumulation on the Cocos (Keeling) Islands, Australia. Sci. Rep. 9, 7102.

Lavers, J.L., Cook, H., Woodward, C., Tait, H.L., Rivers-Auty, J., 2026. Wind speed and direction influence beach plastic accumulation patterns on remote Christmas Island. Mar. Pollut. Bull. 222, 118883. https://doi.org/10.1016/j.marpolbul.2025.118883.

Macias, D., Stips, A., Hanke, G., 2022. Model based estimate of transboundary litter pollution on Mediterranean coasts. Mar. Pollut. Bull. 175, 113121. https://doi.org/10.1016/j.marpolbul.2021.113121.

Markić, A., Iveša, N., Budiša, A., Kovačić, I., Burić, P., Pustijanac, E., Buršić, M., Banai, B., Legin, D.P., Palatinus, A., Tutman, P., 2024. Fragmented marine plastics as the prevalent litter type on a small island beach in the Adriatic. Mar. Pollut. Bull. 203, 116467. https://doi.org/10.1016/j.marpolbul.2024.116467.

Martinez-Mirambell, C., García-Taibo, O., Ferriz-Valero, A., Baena-Morales, S., 2025. Plogging improves environmental awareness in high school physical education students. J. Adventure Educ. Outdoor Learn. 25, 333–343. https://doi.org/10.1080/14729679.2023.2235705.

Nisanth, H.P., Punnakkal, H.P., Sukumarapillai, A., Kumar, A.B., 2025. Marine litter pollution in inhabited and uninhabited Lakshadweep islands, Indian Ocean. Mar Pollut Bull 217, 118062. https://doi.org/10.1016/j.marpolbul.2025.118062.

Ocean Conservancy, 2010. Trash Travels – 2010 Annual Report. Ocean Conservancy, Washington, DC. https://oceanconservancy.org/wp-content/uploads/2017/04/2010-Ocean-Conservancy-ICC-Report.pdf.

Ocean Conservancy, 2018. International Coastal Cleanup: Past Results. https://oceanconservancy.org/trash-free-seas/international-coastal-cleanup/past-results.

OSPAR, 2009. Marine Litter in the North-East Atlantic Region: Assessment and Priorities for Response. OSPAR Commission, London.

OSPAR, 2010. Guideline for Monitoring Marine Litter on the Beaches in the OSPAR Maritime Area. OSPAR Commission, London.

Ponmani, M., Padmavathy, P., Manimekalai, D., Shalini, R., Ravikumar, T., Hariharan, G., Manickavasagam, S., 2026. Ecological risk and source attribution of macro litter in the biodiverse blue carbon mangrove ecosystem along the Gulf of Mannar. Mar. Pollut. Bull. 223, 119015. https://doi.org/10.1016/j.marpolbul.2025.119015.

Rangel-Buitrago, N., Gracia, C.A., 2026. Remote beaches as plastic hotspots: pollution patterns and management implications. Mar. Pollut. Bull. 223, 119017. https://doi.org/10.1016/j.marpolbul.2025.119017.

Rangel-Buitrago, Nelson., 2025. Plastics in Coastal and Marine Environments. Elsevier.

Rangel-Buitrago, N., Ben-Haddad, M., 2024. A 20-year review of the coastal scenery evaluation system. Ocean Coast. Manag. 257, 107341. https://doi.org/10.1016/j.ocecoaman.2024.107341.

Rangel-Buitrago, N., Galgani, F., 2026. Plastic pollution along the Caribbean coast of Colombia. Mar. Pollut. Bull. 222, 118864. https://doi.org/10.1016/j.marpolbul.2025.118864.

Rangel-Buitrago, N., Correa, I.D., Anfuso, G., Ergin, A., Williams, A.T., 2013. Assessing and managing scenery of the Caribbean Coast of Colombia. Tour. Manag. 35, 41–58. https://doi.org/10.1016/j.tourman.2012.05.008.

Rangel-Buitrago, N., Williams, A., Anfuso, G., Arias, M., Gracia C., A., 2017. Magnitudes, sources, and management of beach litter along the Atlantico department coastline, Caribbean coast of Colombia. Ocean Coast. Manag. 138, 142–157. https://doi.org/10.1016/j.ocecoaman.2017.01.021.

Rangel-Buitrago, N., Williams, A., Anfuso, G., 2018. Killing the goose with the golden eggs: litter effects on scenic quality of the Caribbean coast of Colombia. Mar. Pollut. Bull. 127, 22–38. https://doi.org/10.1016/j.marpolbul.2017.11.023.

Rangel-Buitrago, N., Gracia C., A., Velez-Mendoza, A., Carvajal-Florián, A., Mojica-Martinez, L., Neal, W.J., 2019. Where did this refuse come from? Marine anthropogenic litter on a remote island of the Colombian Caribbean Sea. Mar. Pollut. Bull. 149, 110611. https://doi.org/10.1016/j.marpolbul.2019.110611.

Rangel-Buitrago, N., Brabo, L., Silva Filho, F.J., Ben-Haddad, M., García-Romero, L., Peña-Alonso, C., Martín, J.G., Cooper, J.A.G., Neal, W.J., Galgani, F., Giarrizzo, T., 2026. The Anthropocene Taxonomy of Plastic Litter (Under Review).

Ratter, B.M.W., 2018. Geography of Small Islands. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-63869-0.

Rees, G., Pond, K., 1995. Marine litter monitoring programmes—a review of methods with special reference to national surveys. Mar. Pollut. Bull. 30, 103–108. https://doi.org/10.1016/0025-326X(94)00192-C.

Rhodes, Andy, 2018. Abundance, density, and influencing indicators of solid waste accumulation and mitigation solutions along coastlines on Isla Colón in Bocas del Toro Province, Panamá. In: Independent Study Project (ISP) Collection, p. 2942. https://digitalcollections.sit.edu/isp_collection/2942.

Ríos, N., Frias, J.P.G.L., Rodríguez, Y., Carriço, R., Garcia, S.M., Juliano, M., Pham, C.K., 2018. Spatio-temporal variability of beached macro-litter on remote islands of the North Atlantic. Mar. Pollut. Bull. 133, 304–311.

Roome, E., Robins, P., Walton, M., Taboada, E., Neill, S., 2026. Dispersal of marine plastic litter during tropical cyclones. Mar. Pollut. Bull. 222, 118522. https://doi.org/10.1016/j.marpolbul.2025.118522.

Ryan, P.G., Dilley, B.J., Ronconi, R.A., Connan, M., 2019. Rapid increase in Asian bottles in the South Atlantic Ocean indicates major debris inputs from ships. Proc. Natl. Acad. Sci. 116, 20892–20897. https://doi.org/10.1073/pnas.1909816116.

Ryan, P.G., Pichegru, L., Connan, M., 2024. Tracing beach litter sources: drink lids tell a different story from their bottles. Mar. Pollut. Bull. 201, 116186. https://doi.org/10.1016/j.marpolbul.2024.116186.

Savage, J., Chamberlain, A., Fellows, M., Jones, R., Letessier, T.B., Llewellyn, F., Morritt, D., Rowcliffe, M., Koldewey, H., 2024. Big brands impact small islands: sources of plastic pollution in a remote and protected archipelago. Mar. Pollut. Bull. 203, 116476. https://doi.org/10.1016/j.marpolbul.2024.116476.

Schoeppe, S., Bryson, E., Williams, R., Symons, S., Hall, T., 2025. Picking up litter when walking outdoors: people engage in physical activity for planetary health. Sustain. Environ. 11. https://doi.org/10.1080/27658511.2025.2518796.

Schreyers, L.J., Erismann, R., Erismann, S., Ludwig, C., Patel, B., Filella, M., van Emmerik, T.H.M., 2024. Revealing the role of land-use features on macrolitter distribution in Swiss freshwaters. Environ. Pollut. 362, 124911. https://doi.org/10.1016/j.envpol.2024.124911.

Shankar, V.S., Purti, N., Ramakrishnan, S., Kaviarasan, T., Satyakeerthy, T.R., Jacob, S., 2023. A new hotspot of macro-litter in the Rutland Island, South Andaman, India: menace from IORC. Environ. Sci. Pollut. Res. 30, 82107–82123. https://doi.org/10.1007/s11356-023-28024-8.

Shankar, V.S., De, K., Mandal, S., Jacob, S., Satyakeerthy, T.R., 2024. Assessment of transboundary macro-litter on the remote island of Andaman and Nicobar: unveiling the governing factors and risk assessment. Mar. Pollut. Bull. 209, 117145. https://doi.org/10.1016/j.marpolbul.2024.117145.

Shankar, V.S., De, K., Jacob, S., Satyakeerthy, T.R., 2025. Unveiling the risk of marine litter and derelict fishing gear in remote coral reefs of the Andaman and Nicobar Islands, North Indian Ocean. Mar. Pollut. Bull. 212, 117591. https://doi.org/10.1016/j.marpolbul.2025.117591.

Shumway, S.E., Ward, J.Evan., 2025. Plastics in the Sea: Occurrence and Impacts. Academic Press, an imprint of Elsevier.

van Duinen, B., Kaandorp, M.L.A., van Sebille, E., 2022. Identifying marine sources of beached plastics through a Bayesian Framework: application to Southwest Netherlands. Geophys. Res. Lett. 49. https://doi.org/10.1029/2021GL097214.

van Nguyen, N., Ba Le, L., Ta, T.Y., Tien Nguyen, T.H., Bui, T.-K.L., 2026. A photographic framework for the rapid assessment of macro-litter pollution in mangrove ecosystems: a citizen science-ready approach and a case study in a UNESCO biosphere reserve. Reg. Stud. Mar. Sci. 93, 104697. https://doi.org/10.1016/j.rsma.2025.104697.

van Rheenen, D., Naria, O., Melo, R., Sobry, C., 2024. Small Island States or Territories, pp. 15–33. https://doi.org/10.1007/978-3-031-51705-1_2.

Vriend, P., Roebroek, C.T.J., van Emmerik, T., 2020. Same but different: a framework to design and compare riverbank plastic monitoring strategies. Front. Water 2. https://doi.org/10.3389/frwa.2020.563791.

Weidlich, S., Lenz, M., 2022. Abundance, composition and sources of beach litter on the Cape Verdean island São Vicente. Mar. Pollut. Bull. 185, 114258. https://doi.org/10.1016/j.marpolbul.2022.114258.

Williams, A.T., Micallef, Anton., 2009. Beach Management: Principles and Practice. Earthscan.

Williams, A.T., Rangel-Buitrago, N., 2019. Marine litter: solutions for a major environmental problem. J. Coast. Res. 35, 648. https://doi.org/10.2112/JCOASTRES-D-18-00096.18/.

Williams, A.T., Rangel-Buitrago, N., 2022. The past, present, and future of plastic pollution. Mar. Pollut. Bull. 176, 113429. https://doi.org/10.1016/j.marpolbul.2022.113429.