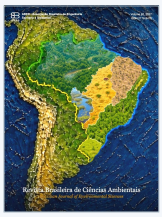
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Anthropogenic marine litter at the Maracá-Jipioca Ecological Station, Brazilian Amazon coast

Lixo antropogênico marinho na Estação Ecológica de Maracá-Jipioca, Costa Amazônica, Brasil

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Abstract

Coastal environments are increasingly threatened by anthropogenic marine litter (AML), especially plastic waste. Such waste can cause substantial ecological damage and compromise ecosystem services. The objective of this study was to quantify and classify AML and to assess its environmental impacts at the *Estação Ecológica de Maracá-Jipioca* (ESECMJ, Maracá-Jipioca Ecological Station). Solid waste items were manually collected around Maracá Island, sorted, and analyzed using environmental impact metrics, including the Clean Coast Index (CCI). A total of 2,067 items were recorded; plastic accounted for 95.4%, followed by smaller proportions of rubber, glass, and metal. According to the CCI, the area was classified as moderately dirty (CCI = 8.3, with an average density of 0.41 items/m^2). Zone I was classified as clean (CCI = 2.6), and Zone II as dirty (CCI = 13.9). AML accumulation differed significantly between zones ($W = 2$, $p = 0.031$), with 84% of the litter found in Zone II. The accumulation of AML may pose serious risks to fishery resources that are essential to local livelihoods and may adversely affect human health, economic activities, and biodiversity. It may also threaten habitat integrity and local biodiversity in this protected coastal ecosystem, although direct measurement of habitat degradation and species loss was beyond the scope of this study. These findings underscore the urgent need for integrated, transboundary solid waste management strategies that encompass waste generation, handling, and disposal. Such strategies should be supported by effective public policies and scientific evidence to mitigate environmental risks and promote the conservation of coastal and marine ecosystems.

Keywords plastic pollution · Clean Coast Index · protected area · transboundary litter · allochthonous litter

Resumo

Ambientes costeiros estão cada vez mais ameaçados pelo lixo antropogênico marinho (LAM), especialmente resíduos plásticos, que podem causar danos ecológicos significativos e comprometer os serviços ecossistêmicos. Este estudo teve como objetivo quantificar e classificar o LAM e avaliar seus impactos ambientais na Estação Ecológica de Maracá-Jipioca (ESECMJ). Os resíduos sólidos foram coletados manualmente *in situ* ao redor da Ilha de Maracá, posteriormente triados e analisados por meio de métricas de impacto ambiental. Foram registrados 2.067 itens, dos quais 95,4% eram plásticos, seguidos por menores proporções de borracha, vidro e metal. De acordo com o Índice de Limpeza Costeira (CCI), a área foi classificada como moderadamente suja (CCI = 8,3; densidade média de 0,41 itens/m^2). A Zona I foi considerada uma costa limpa (CCI = 2,6), enquanto a Zona II foi classificada como suja (CCI = 13,9) e concentrou 84% dos resíduos, com diferença estatisticamente significativa entre as zonas ($W = 2$; $p = 0,031$). O acúmulo de LAM pode representar sérios riscos aos recursos pesqueiros, essenciais para a subsistência local, além de poder afetar negativamente a saúde humana, as atividades econômicas e a biodiversidade. Adicionalmente, representa riscos potenciais à integridade do habitat e à biodiversidade local neste ecossistema costeiro protegido, embora a mensuração direta da degradação do habitat e da perda de espécies estivesse fora do escopo deste estudo. Existe a necessidade urgente de estratégias integradas e transfronteiriças de gestão de resíduos sólidos, abrangendo a geração, o manejo e a disposição final. Tais estratégias devem ser apoiadas por políticas públicas eficazes e pelo conhecimento científico, a fim de mitigar os riscos ambientais e promover a conservação dos ecossistemas costeiros e marinhos.

Palavras-chave poluição plástica · Índice de Limpeza Costeira · área protegida · lixo transfronteiriço · lixo alóctone

1 Introduction

Anthropogenic marine litter (AML), also known as marine debris, refers to persistent solid waste of human origin that has been discarded, lost, or abandoned in coastal and marine environments (NOAA, 2024). Such materials can accumulate in a wide range of environments, including rivers, beaches, islands, and the open ocean, from the surface to the seafloor. Their distribution is influenced by transport mechanisms such as stormwater runoff, sewage discharge, riverine flow, and natural forces, including ocean currents, tidal dynamics, and wind, as well as by direct inputs from human activities (Veiga et al., 2016; Agamuthu et al., 2019; Kanhai et al., 2022).

AML affects millions of people in coastal regions worldwide. In Brazil, 81.6 million metric tons of municipal solid waste were generated in 2024, and more than half of the Brazilian population (54.8%) lives within 150 km of the coast (ABREMA, 2025). This proximity means that a substantial fraction of inadequately managed waste may enter the marine environment, leading to environmental pollution, contamination of aquatic organisms, potential harm to human health, and adverse effects on economic activities such as fishing and tourism (Woods et al., 2021).

The ecological consequences of AML are well documented. AML directly affects at least 267 animal species globally, including 86% of sea turtles, 44% of seabirds, and 43% of marine mammals, through entanglement, ingestion, and habitat degradation (Lima et al., 2020; Mendes et al., 2024). AML can also enter food webs, raising concerns about potential effects on human health, particularly in communities dependent on marine resources for subsistence (Lima et al., 2022; UN, 2023). These cumulative impacts threaten biodiversity, compromise ecosystem services, and undermine the economic and cultural benefits provided by coastal and marine environments to local communities (Fernandes et al., 2021).

In response to the global scale of this problem, international and national governance frameworks have evolved considerably. The United Nations 2030 Agenda for Sustainable Development identifies ocean conservation and the sustainable use of marine resources as Sustainable Development Goal 14 (Life Below Water; UN, 2024). Ongoing negotiations aim to establish a legally binding international instrument on plastic pollution under the auspices of the United Nations Environment Programme (UNEP). Brazil has adopted the *Plano Nacional de Combate ao Lixo no Mar* (PNCLM, National Plan to Combat Marine Litter), developed by the *Ministério do Meio Ambiente* (MMA, Ministry of the Environment; MMA, 2019) and discussed by Castro et al. (2024). The *Ministério da Ciência, Tecnologia e Inovações* (MCTI, Ministry of Science, Technology and Innovation) has been developing a National Strategy for a Plastic-Free Ocean (MCTI, 2022). These frameworks collectively underscore the urgency of generating reliable, site-specific data on the state, composition, and distribution of AML in vulnerable coastal ecosystems.

Marine protected areas (MPAs) and conservation units (unidades de conservação, the protected-area categories established under Brazilian law) are often assumed to be sheltered from anthropogenic pressures. However, their geographic remoteness does not prevent the deposition of allochthonous AML transported by ocean currents, highlighting a paradox of increasing scientific relevance (Grillo et al., 2021; Botterell et al., 2024; Melo et al., 2026). In Brazil, the *Sistema Nacional de Unidades de Conservação da Natureza* (SNUC, National System of Nature Conservation Units; Law No. 9,985/2000) designates Ecological Stations as the most restrictive category of conservation unit, with no permanent human occupation and strictly controlled access. Despite this legal status, the persistence and hydrodynamic mobility of plastic debris allow it to reach even the most remote protected environments, making these areas important sentinels for evaluating the transboundary nature of marine pollution.

The SNUC includes 333 federal conservation units; together with state and municipal units, conservation units cover approximately 18% of the national territory and 26% of Brazil's marine area (MMA, 2024). Monitoring Ecological Stations is particularly challenging because of their strict access restrictions and, in many cases, geographic remoteness, yet these characteristics also make such areas scientifically important for assessing anthropogenic pressures.

In Brazil, systematic research on AML began in 1973 with the first record of polyethylene particles on the coast of Rio Grande do Sul (Ivar do Sul and Costa, 2007). Since then, studies along the Amazon coast have consistently identified plastic as the dominant AML category, with most AML being allochthonous and transported by the North Equatorial Current and the Amazon River outflow rather than generated locally (Lima et al., 2022; Assis et al., 2023; Mendes et al., 2025). The study geographically closest to the *Estação Ecológica de Maracá-Jipioca* (ESECMJ, Maracá-Jipioca Ecological Station), conducted by Assis et al. (2023), confirmed the vulnerability of Amazonian protected areas to transboundary plastic pollution, yet no systematic assessment had previously been conducted at the ESECMJ, a gap the present study addresses.

Based on previous studies of the Amazon coast and the hydrodynamic characteristics of the ESECMJ, two research hypotheses were formulated: (H1) plastic would be the dominant AML category at the ESECMJ, consistent with patterns previously reported for the Amazon coast (Lima et al., 2022; Assis et al., 2023; Mendes et al., 2025); and (H2) AML accumulation would be significantly higher in Zone II (Atlantic-facing, wave-exposed shore) than in Zone I (sheltered inner shore), given Zone II's greater direct exposure to the North Equatorial Current and Atlantic oceanographic forcing.

Environmental impact was assessed using the Clean Coast Index (CCI), originally proposed by Alkalay et al. (2007) and adapted by Rangel-Buitrago et al. (2019) for plastic-specific evaluation of coastal cleanliness. This index has been widely applied across contrasting coastal environments and in AML monitoring studies worldwide (Rangel-Buitrago et al., 2021; Barik et al., 2024; Ilechukwu et al., 2024).

This study provides the first systematic characterization of AML at the ESECMJ, in the state of Amapá, Brazil. The objective was to quantify and classify AML and to assess its environmental impacts across the island's contrasting coastal zones using the CCI and to de-

termine whether AML accumulation differs between zones with contrasting exposure to Atlantic oceanographic forcing. The findings provide an empirical baseline for this previously unassessed protected area and are relevant to ongoing discussions on the integration of remote conservation units into national and international plastic-governance frameworks.

2 Materials and methods

2.1 Study area and sampling design

The Amapá coastal zone encompasses 750 km of coastline and plays a pivotal role in maintaining biodiversity and supporting local communities that rely on fishing and the harvesting of natural resources for their livelihoods (Santos et al., 2016; Silva Junior et al., 2022). The region is the best-preserved and least densely populated coastal zone in Brazil, with population densities along the Amapá-to-Piauí coastal segment below 50 inhabitants/km² (MMA, 2008) and 62% of the state's territory under some form of conservation status within 20 officially designated conservation units (MMA, 2019; Brito and Drummond, 2022).

The present study was conducted at the ESECMJ, which comprises two islands with a total area of approximately 59,000 ha (Carvalho, 2017; ICMBio, 2022). All sampling was conducted on Maracá Island (Figure 1), hereafter referred to as "the island." The ESECMJ is situated in the muddy-coast region of the Amazon, adjacent to Cabo Norte, within the Atlantic coastal sector of Amapá (lat. 01°59′06″N to 02°13′45″N; long. 49°31′13″W to 50°30′20″W). Fieldwork was authorized by the *Instituto Chico Mendes de Conservação da Biodiversidade* (ICMBio, Chico Mendes Institute for Biodiversity Conservation) under the *Sistema de Autorização e Informação em Biodiversidade* (SISBIO, Biodiversity Authorization and Information System) permit No. 86582.

The geomorphology of the island is shaped by the North Equatorial Current and by substantial sediment input from the Amazon River and its smaller tributaries, including the Flechal, Amapá Grande, and Macarri rivers (IBAMA, 2006; Santos et al., 2009; MMA, 2019) (Figure 1). These oceanographic and sedimentary processes play a crucial role in determining the environmental characteristics and shoreline morphology of the ESECMJ.

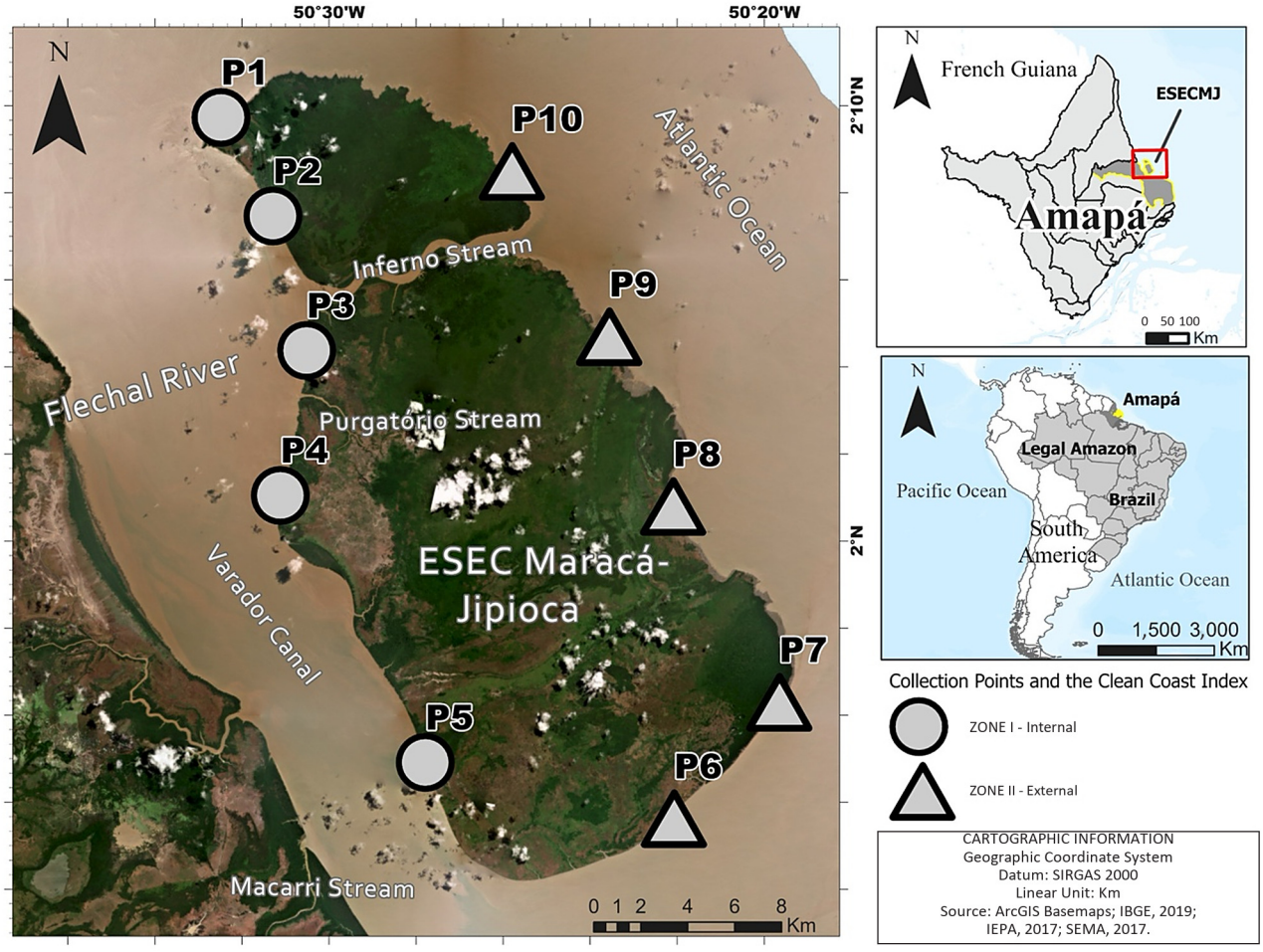


Figure 1. Map of the ESECMJ, Amapá, showing the 10 AML sampling points across Zone I (P1–P5) and Zone II (P6–P10)

2.2 AML collection protocol

AML sampling was conducted in February 2023, during the peak of the rainy season in Amapá, at 10 sampling points distributed around the island, five in each zone (Figure 1). The use of 10 sampling points reflected the logistical constraints associated with accessing a strictly protected, geographically remote island and was consistent with the sampling effort reported in comparable studies of islands and protected coastal environments (Assis et al., 2023; Howlader et al., 2024).

At each sampling point, a 50 m × 10 m transect (500 m²) was established perpendicular to the shoreline, yielding a total sampled area of 2,500 m² in each zone (5,000 m² overall). Each point was sampled by two field technicians for 1 h. A minimum spacing of 10 km between consecutive sampling points was maintained to reduce spatial dependence among observations.

All solid waste items ≥2.5 cm along their longest dimension were collected manually, in accordance with the Marine Strategy Framework Directive (MSFD) marine litter monitoring protocol (Vlachogianni, 2014) and the National Oceanic and Atmospheric Administration (NOAA) Marine Debris Monitoring and Assessment guidelines (Lippiatt et al., 2013). Items below this threshold were not collected, consistent with the definition of macrolitter adopted in these protocols. Collected items were placed in 100-L woven polypropylene bags and labeled by sampling point.

During the sorting and identification process, all items were counted, and AML density was calculated as items per square meter (items/m²). Materials were then classified into the seven categories and corresponding subcategories proposed by Lippiatt et al. (2013): plastic, metal, glass, rubber, processed lumber/paper, cloth/fabric, and others. This classification scheme was selected to facilitate direct comparison with international studies using the same standardized protocol.

Although gravimetric data were not collected in the present study, the abundance and density metrics used were consistent with the MSFD protocol (Vlachogianni, 2014) and the NOAA guidelines (Lippiatt et al., 2013).

2.3 Macrolitter environmental impact assessment: CCI

Coastal cleanliness was assessed using the plastic-specific adaptation of the CCI (Alkalay et al., 2007; Rangel-Buitrago et al., 2019). The CCI classifies coastal cleanliness into five categories based on plastic debris density: very clean (0.0–2.0), clean (2.1–5.0), moderately dirty (5.1–10.0), dirty (10.1–20.0), and extremely dirty (>20.0).

This index quantifies the amount of litter per unit area by relating the number of items to the total sampled area. It is calculated as follows (Equation 1):

$$CCI = \frac{\Sigma n \text{ items in each transect}}{A} \times K \qquad \text{(Equation 1)}$$

where n is the number of litter items collected, A is the sampled area (m²), and K is a correction factor set at 20, as defined in the original methodology of Alkalay et al. (2007). This correction factor normalizes the index to the scale used to classify coastal cleanliness.

2.4 Statistical analysis

Statistical analyses were performed in R (R Core Team, 2023) using RStudio. Prior to between-zone comparisons, normality was assessed using the Kolmogorov–Smirnov test, and homogeneity of variances was evaluated using Levene's test. Because AML item counts did not meet the assumptions required for parametric analysis, the nonparametric Wilcoxon rank-sum test was used to compare AML item counts between Zone I and Zone II. Descriptive results are reported as medians and interquartile ranges (IQRs). Statistical significance was set at $\alpha = 0.05$.

3 Results and discussion

3.1 Abundance and spatial distribution of AML

A total of 2,067 items were collected across the 10 sampling points, with plastic as the dominant category (95.4%), followed by rubber (3.1%), glass (1.2%), metal (0.1%), and other materials (0.1%). AML density ranged from 0.04 to 1.78 items/m², with a mean of 0.41 items/m² (Table 1). The highest AML density was recorded at point P9 (891 items; 1.78 items/m²), located on the Atlantic-facing side of the island (Zone II). Conversely, the lowest density was recorded at point P5 (0.04 items/m²), situated in the sheltered inner zone (Zone I; Figure 2).

Of all the items collected, 84% were found in Zone II, with point P9 alone accounting for 43.1% of all items recorded on the island (891 items), making it the most litter-prone location within the ESECMJ. In contrast, points P2 and P5 in Zone I had the lowest levels of accumulation, representing 1.2% and 1.1% of all items, respectively (Figure 2). Marine plastic pollution occurs throughout the world's oceans, including on remote islands and within protected areas (Monteiro et al., 2018). For comparison, the Colombian islands of Providencia and Santa Catalina, also located within a conservation unit, exhibited AML densities ranging from 0.4 to 1.4 items/m² (Garcés-Ordóñez et al., 2021).

3.2 Composition and typology of AML

Plastic was the predominant AML category across all sampling points, with 1,972 items (95.4% of all items collected), corresponding to a density of 0.39 items/m². No paper or cloth items were recorded at any sampling point (Figure 3). The overwhelming dominance of plastic debris indicates substantial plastic pollution and is consistent with the broader pattern reported across marine environments worldwide (Bolívar-Anillo et al., 2023). Plastic debris is among the primary threats to marine ecosystem health, with documented direct and indirect effects on coastal and oceanic biota (Pauna et al., 2019).

The dominance of plastic at the ESECMJ mirrors findings from international and Brazilian studies. Islands can function as sources, temporary reservoirs, or final sinks for marine plastic debris (Monteiro et al., 2024). Globally, plastic has been consistently identified as the dominant AML category (Rangel-Buitrago et al., 2018; Rakib et al., 2021; Silva et al., 2022; Ribeiro et al., 2025; Rangel-Buitrago, 2025). In Brazil, this pattern has also been documented in various

Table 1. Abundance, density, and CCI of AML at the 10 sampling points across Zones I and II

Sampling Point	Zone	Items (n)	Area (m²)	Density (items/m²)	CCI	Classification
P1	I	28	500	**0.06**	**1.1**	Very clean
P2	I	24	500	**0.05**	**1.0**	Very clean
P3	I	63	500	**0.13**	**2.5**	Clean
P4	I	194	500	**0.39**	**7.8**	Moderately dirty
P5	I	22	500	**0.04**	**0.9**	Very clean
Zone I total		**331**	**2,500**	**0.13**	**3.0**	**Clean**
P6	II	145	500	**0.29**	**5.8**	Moderately dirty
P7	II	376	500	**0.75**	**15.0**	Dirty
P8	II	259	500	**0.52**	**10.4**	Dirty
P9	II	891	500	**1.78**	**35.6**	Extremely dirty
P10	II	65	500	**0.13**	**2.6**	Clean
Zone II total		**1,736**	**2,500**	**0.69**	**14.0**	**Dirty**
ESECMJ total		**2,067**	**5,000**	**0.41**	**8.3**	**Moderately dirty**

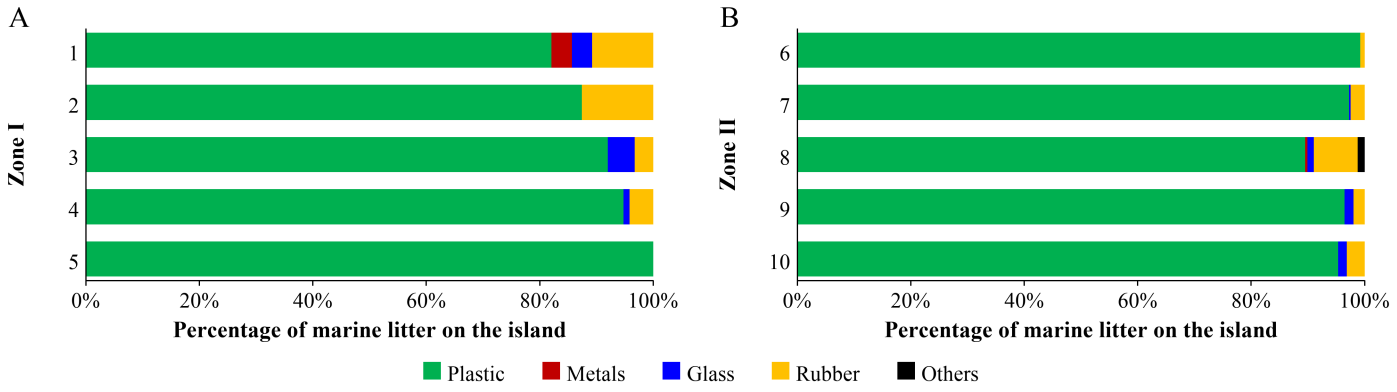


Figure 2. Composition of AML collected at the ESECMJ, Amapá, Brazil. (A) Zone I (P1–P5); (B) Zone II (P6–P10).

coastal environments (Leite et al., 2014; Marin et al., 2019; Lima et al., 2022; Souza et al., 2025).

A diverse range of item types was recorded during the study, with plastic bottles, polystyrene foam floats, plastic lids, food containers, personal hygiene products, glass bottles, and fishing gear among the most prevalent items (Figures 2 and 3). Notably, manufacturing labels indicated nonlocal or international origins for some of the items, including plastic bottles manufactured in Africa, Asia, Europe, South America, and North America (Figure 3B). These observations are consistent with evidence that plastic debris can carry provenance markers from diverse production regions (Ryan et al., 2018). Although this evidence does not allow direct confirmation of transport pathways, it is consistent with the transboundary transport of AML reported elsewhere on the Amazon coast (Onink et al., 2021; Chassignet et al., 2021; Assis et al., 2023) and highlights the relevance of transboundary solid waste governance.

Recent studies indicate that plastic debris is the predominant form of AML in the Amazonian marine ecosystem, largely as a result of inadequate waste management associated with fishing activities (Lima et al., 2022). The ESECMJ is directly influenced by artisanal and commercial fishing (Jimenez et al., 2020), and illegal fishing is one of the main resource-use conflicts within the station. This context may help explain the substantial amount of lost, abandoned, or discarded fishing gear recorded in this study, including polystyrene foam floats, ropes, nets, and fishing buoys (Figure 3A). Improper disposal of fishing materials and single-use plastics increases the litter load in the marine environment. These materials may originate from both local fishing activities and international shipping routes and can be transported over long distances by ocean currents before accumulating on remote islands and in protected coastal areas (Assis et al., 2023).

The rubber category, comprising sandals and other footwear, as well as rubber fragments (Figure 3A), represented 3.1% of all items, consistent with findings from other Amazonian beaches (Praia do Calhau, São Luís: 1.4%; Lima et al., 2022) and other Brazilian coastal environments (Praia Grande, Ilha de São Francisco do Sul: 6.79%; Ilha de Pontal: 6.27%; Praia Brava, Arraial do Cabo: 6.28%; Stelmack et al., 2018).

Glass accounted for 1.2% of all items and consisted primarily of bottles, jars, fragments, light bulbs, and floats (Figure 3), consistent



Figure 3. AML collected at the ESECMJ, Amapá, Brazil: (A) collected litter; (B) examples of items manufactured in different countries

with proportions reported in other AML studies (Araújo and Costa, 2008; Portz et al., 2011; Leite et al., 2014). The presence of glass bottles and light bulbs suggests a possible association with fishing activities in the surrounding waters.

Notably, two glass fishing floats (buoys) were identified in the glass category (detail in Figure 3). Glass floats were first developed in Norway in the mid-19th century and became widely used in Japanese and global fishing fleets as net floats and line markers (Pausch and Hardy, 2015). Beginning in the 1960s, glass was progressively replaced by more durable materials, initially cork and aluminum and subsequently plastic, and glass floats gradually fell out of commercial use. Today, surviving examples are considered rare collectibles (Pausch and Hardy, 2015). Despite their rarity, glass floats continue to be recorded in coastal surveys worldwide, having been transported over long distances by ocean currents before becoming stranded (Mattos, 2016). Their presence at the ESECMJ likely results from long-range transport by surface currents, tidal dynamics, and wind rather than from recent local disposal.

Items classified as "metal" and "other" each represented 0.1% of all collected items (Figure 2). Metal items included aluminum foil, a metal float, and metal cans, and "other" items included human-modified wood fragments. This pattern is consistent with other AML studies (Portz et al., 2011; Stelmack et al., 2018; Coelho, 2020). The low representation of metal items may be attributed to their higher density than plastic, which limits their buoyancy and causes them to sink more rapidly through the water column (Nabilah Adzhar et al., 2023).

3.3 Environmental impact assessment: CCI

The environmental impacts of AML pose an increasing challenge to marine ecosystems and human communities globally, and no environment, including protected areas, is entirely immune to the effects of AML accumulation. Howlader et al. (2024) reported severe AML pollution, particularly plastic pollution, on Sonadia Island, Bangladesh, a biodiversity hotspot, with associated habitat degradation and threats to endemic species. The predominance of plastic reported for Sonadia Island is comparable to that observed at the ESECMJ.

The CCI assessment for the ESECMJ revealed a pronounced spatial contrast between zones. Zone I, the sheltered inner zone, contained 16% of all items and was classified as clean (CCI = 2.6). Zone II, the wave-exposed outer zone, contained 84% of all items and was classified as dirty (CCI = 13.9). The difference between zones was statistically significant (Wilcoxon rank-sum test, $W = 2$, $p = 0.031$; Figure 4). The overall CCI for the ESECMJ was 8.3, which classifies the station as moderately dirty.

An exploratory analysis was developed specifically for this study; it is not part of either the original CCI methodology proposed by Alkalay et al. (2007) or the plastic-specific adaptation by Rangel-Buitrago et al. (2019). In this analysis, the CCI was recalculated after excluding all plastic items to illustrate the relative contribution of plastic to the overall pollution burden at the ESECMJ. Under this scenario, the entire station would be reclassified as very clean: CCI-Zone I = 0.2, CCI-Zone II = 0.6, and CCI-ESECMJ = 0.4. This exploratory recalculation indicates that plastic is the dominant contributor to the ESECMJ's overall CCI classification and that, in its absence, the station would meet the highest cleanliness standard under the CCI classification scheme.

The contrast between zones is consistent with local hydrodynamic patterns: tidal current velocities in the Varador channel, which separates Maracá Island from the Amapá mainland, reach up to 1.53 m/s during spring tides, generating substantial seabed shear stress and sediment redistribution in the region (Farias et al., 2024). Combined with direct exposure to the North Equatorial Current, this hydrodynamic regime likely enhances AML retention and stranding along the Atlantic-facing outer shore (Zone II) compared with the more sheltered, lower-energy inner shore (Zone I).

The consequences of poor solid waste management, particularly of plastics, extend across national boundaries and have substantial global implications (Kanhai et al., 2022; UNEP and ISWA, 2024; Ma et al., 2024). The accumulation of plastics, metals, and rubber in coastal ecosystems such as the ESECMJ can lead to biodiversity loss, habitat degradation, and harm to marine fauna and flora, with cascading consequences for fisheries and local livelihoods, human

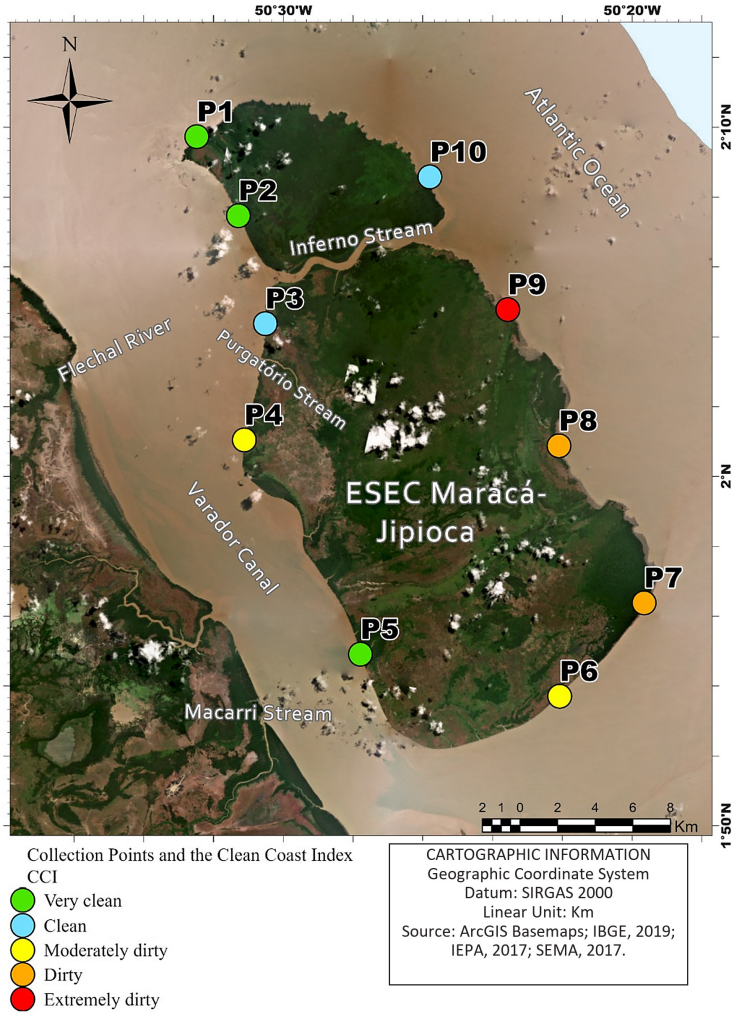


Figure 4. CCI classification of the ESECMJ by zone (Zones I and II)
Source: based on the criteria proposed by Alkalay et al. (2007) and Rangel-Buitrago et al. (2019).

health, and broader environmental sustainability (Bergmann et al., 2015; Mendes et al., 2024).

3.4 Study limitations

This study has several limitations that should be considered when interpreting its findings. Sampling was conducted during a single period (February 2023, corresponding to the peak of the rainy season), which precludes an assessment of potential seasonal variability in AML accumulation and composition at the ESECMJ; AML loads may differ during the dry season, when river discharge and wind and wave patterns change. In line with the standardized protocols adopted, this study focused on macrolitter (≥2.5 cm); microplastics were not surveyed, and their abundance and composition at the ESECMJ remain unknown. In addition, data on item size classes were not recorded during sorting, precluding an assessment of whether item size differed between the sheltered inner zone (Zone I) and the wave-exposed outer zone (Zone II). Finally, inferences regarding AML origins and transport via the North Equatorial Current and from international sources were based on circumstantial evidence, specifically manufacturing labels and provenance markings, rather than direct tracking, drifter data, or oceanographic trajectory modeling.

4 Conclusion

This study was motivated by the need to provide the first systematic assessment of AML at the ESECMJ, a federally protected, geographically remote, and previously unstudied area on the Amapá coast. The research addressed a recognized scientific gap: despite growing evidence that allochthonous AML transported by ocean currents reaches even strictly protected areas, no prior AML assessment had been conducted at the ESECMJ. The study objectives were fully achieved through the systematic characterization of the composition and spatial distribution of AML and the associated environmental quality across two contrasting coastal zones of the island. The results show that this federally protected and geographically remote area is substantially affected by transboundary plastic pollution. These findings provide the first empirical baseline for the ESECMJ and support efforts to integrate remote conservation units into national and international plastic-governance frameworks, including the PNCLM and ongoing UNEP global treaty negotiations.

A total of 2,067 items were recorded, with plastic as the dominant category (95.4%), followed by rubber (3.1%), glass (1.2%), and metal and other materials (0.1% each). Mean AML density was 0.41 items/m^2 (range = 0.04–1.78 items/m^2). The CCI classified the ESECMJ overall as moderately dirty (CCI = 8.3), indicating substantial AML accumulation even within this federally protected and geographically remote area. The composition of the AML was consistent with a predominantly allochthonous origin.

AML accumulation showed a pronounced spatial pattern at the ESECMJ. Zone II, the Atlantic-facing, wave-exposed zone, contained 84% of all items (CCI = 13.9; dirty), whereas the sheltered Zone I contained 16% (CCI = 2.6; clean). The presence of internationally manufactured plastic items is consistent with allochthonous transport by ocean currents, in line with patterns previously reported for the Amazon coast, although this study did not employ trajectory modeling or tracking analyses to directly confirm transport pathways. An exploratory CCI recalculation excluding all plastic items reclassified the entire ESECMJ as very clean (CCI = 0.4), indicating that plastic is the dominant contributor to the station's overall CCI classification and that even strictly protected coastal areas are not shielded from the broader plastic pollution crisis.

Future studies should adopt multiseason sampling designs, incorporate microplastic sampling protocols and polymer identification methods (e.g., Fourier-transform infrared [FTIR] spectroscopy) for source attribution, and apply oceanographic trajectory modeling to reconstruct AML pathways. These findings also underscore the need to formally incorporate remote protected areas such as the ESECMJ into the PNCLM and to strengthen the scientific basis for transboundary plastic governance within ongoing UNEP global treaty negotiations.

Authors' contributions

Santos, J.E.C.: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – original draft; Machado, D.S.: Data curation, Methodology, Visualization, Writing – review & editing; Magalhães, A.P.: Data curation, Investigation, Methodology, Visualization; Pardal, E.C.: Conceptualization, Data curation, Investigation, Visualization, Writing – review & editing; Miranda, Z.P.: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Visualization, Writing – review & editing.

Conflicts of interest

The authors declare no conflicts of interest.

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Declaration on the use of generative artificial intelligence

During the preparation of this work, the authors used generative AI tools (ChatGPT and Claude) for English-language editing and proofreading. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of this publication.

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