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Programa de Pós-Graduação em Ecologia, Conservação e Biodiversidade

Poluição por microplásticos em Patrimônios Naturais da UNESCO: do cenário global às primeiras evidências nos Lençóis Maranhenses.

Élida Priscila Bogéa Carvalho

Uberlândia (MG)

Julho, 2025

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Tese apresentada à Universidade Federal de Uberlândia, como parte das exigências do Programa de Pós- Graduação em Ecologia, Conservação e Biodiversidade para a obtenção do título de doutora.

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Av. Pará, 1720, Bloco 2D, Sala 26 - Bairro Umuarama, Uberlândia-MG, CEP 38405-320
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“Que mar é esse
que inunda meus guizos?
que arcabouço alçará
minhas ramas de luz?”

[Salgado Maranhão - Lacre 2]

À minha Tiêta,
meu bichinho de amar.
Dádiva.

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Introdução geral

A poluição por microplásticos (MPs) emergiu nas últimas décadas como um dos maiores desafios ambientais globais, dada a sua ubiquidade, persistência e potencial de causar impactos adversos em diferentes níveis da biodiversidade e dos ecossistemas. Considerados partículas sólidas sintéticas ou matrizes poliméricas com tamanhos inferiores a 5 mm, os MPs podem ser oriundos de fontes primárias (produzidos intencionalmente em pequena escala) ou secundárias (fragmentação de plásticos maiores), apresentando elevada capacidade de dispersão e acúmulo em compartimentos diversos, inclusive em regiões remotas e protegidas (Andrades et al., 2020; Silva-Cavalcanti et al., 2017). Nesse cenário, áreas reconhecidas como Patrimônio Natural da Humanidade pela UNESCO, caracterizadas por sua relevância ecológica e valor universal excepcional, estão cada vez mais expostas à contaminação por MPs, ameaçando não apenas sua integridade ambiental, mas também o simbolismo e os modos de vida que nelas se inserem (Thompson et al., 2024; Osipova et al., 2020).

A presente tese investiga a presença, caracterização e impactos de MPs no Parque Nacional dos Lençóis Maranhenses (PNLM), uma das mais icônicas áreas naturais brasileiras, recém-reconhecida como Patrimônio Natural Mundial (UNESCO, 2025). Embora o PNLM seja amplamente estudado sob a perspectiva da biodiversidade, ecologia de dunas e hidrologia, não há registros anteriores sistemáticos sobre a ocorrência de MPs nesse ecossistema. A escolha da região como foco desta tese não é arbitrária: além de seu valor ambiental intrínseco, o parque é alvo de crescente pressão antrópica devido à intensificação do turismo, da urbanização das bordas e da vulnerabilidade aos fluxos de resíduos transportados por vento e água (Andrades et al., 2020).

O problema central que esta pesquisa buscou investigar foi: “Qual é a extensão e a natureza da contaminação por microplásticos no Parque Nacional dos Lençóis Maranhenses e como ela se distribui em função de fatores ambientais e antrópicos?”.

Para responder a essa questão, esta pesquisa teve como objetivo geral avaliar a presença, a distribuição espacial, as características físico-químicas e os fatores associados à contaminação por microplásticos no PNLM e em áreas adjacentes.

Especificamente, pretendeu-se: quantificar e caracterizar os MPs em amostras de água e sedimento ao longo de três áreas distintas (interna ao PNLM, suas bordas e regiões

urbanas costeiras próximas); investigar a relação entre os padrões de contaminação e variáveis ambientais, como correntes, ventos e configuração geográfica; analisar a composição polimérica dos MPs encontrados, a fim de inferir suas possíveis fontes de origem; e, por fim, propor recomendações técnicas para o monitoramento e a gestão da poluição por microplásticos em unidades de conservação de proteção integral.

A relevância desta tese está ancorada em três pilares: (i) o ineditismo de um estudo sistemático de MPs em uma área brasileira recém-reconhecida como Patrimônio Natural da Humanidade; (ii) a contribuição para o avanço da compreensão sobre a dinâmica de poluentes invisíveis em ecossistemas costeiros sensíveis; e (iii) o potencial de subsidiar políticas públicas e estratégias de conservação. Em consonância com os Objetivos de Desenvolvimento Sustentável (ODS 14 e ODS 15) e com a Década da Ciência Oceânica da ONU, esta pesquisa fornece evidências empíricas que podem apoiar a implementação de ações concretas voltadas à proteção dos ecossistemas e à segurança socioambiental (Udhayakumar et al., 2025; Silva et al., 2021).

Além disso, pesquisas recentes em áreas costeiras tropicais, como as realizadas por Ribeiro-Brasil et al. (2023), evidenciam que a contaminação por MPs está fortemente associada a fontes urbanas e à gestão deficiente de resíduos sólidos, o que reforça a importância de estudos focados em regiões que, embora protegidas, estejam submetidas a pressões antrópicas crescentes. Estudos como os de Azevedo-Santos et al. (2022) também indicam que a caracterização físico-química dos MPs pode ser utilizada como ferramenta para rastreamento de fontes e rotas de transporte desses poluentes, permitindo inferências mais precisas sobre sua dinâmica nos ambientes estudados.

Um dos principais desdobramentos deste trabalho é a possibilidade de propor recomendações futuras e estratégias de mitigação baseadas em evidências empíricas. A análise detalhada da composição, distribuição e possíveis fontes de MPs no PNLN permite não apenas o aprimoramento de políticas públicas, mas também a formulação de intervenções locais direcionadas, como planos de gestão integrada de resíduos, campanhas de educação ambiental e monitoramento participativo em unidades de conservação (Ribeiro-Brasil et al., 2023; Azevedo-Santos et al., 2022; Silva-Cavalcanti et al., 2017). Essas recomendações, além de reforçarem a dimensão aplicada da pesquisa, contribuem diretamente para o desenvolvimento de estratégias preventivas que podem ser adaptadas a outros contextos de vulnerabilidade ambiental semelhantes.

Este trabalho está estruturado em dois capítulos independentes, mas complementares, conforme descrito sucintamente a seguir:

Capítulo 1 - “Microplastic pollution in UNESCO natural world heritage sites: a global review”

Neste primeira capítulo, uma revisão sistemática de literatura, discute a presença e os impactos dos MPs em Patrimônios Naturais da Humanidade reconhecidos pela UNESCO, oferecendo uma perspectiva global sobre a extensão e gravidade dessa forma de poluição. O trabalho foi conduzido com base em protocolos rigorosos de busca e seleção de estudos em bases científicas internacionais, considerando diferentes tipos de microplásticos, matrizes ambientais e organismos-alvo. A revisão contempla pesquisas realizadas em áreas oficialmente classificadas como patrimônios naturais ou mistos, abordando aspectos como fontes, vias de dispersão, riscos ecotoxicológicos e estratégias de monitoramento e mitigação. Além disso, o trabalho também identifica lacunas metodológicas a serem superadas. Assim, a partir dessa abordagem ampla e crítica, em que integramos dados sobre distribuição, fontes, efeitos ecotoxicológicos e estratégias de mitigação, o capítulo busca consolidar o conhecimento atual sobre a contaminação por MPs em regiões de alto valor ecológico e cultural, fornecendo subsídios teóricos e metodológicos para a formulação de políticas públicas e ações de conservação ambiental mais eficazes e integradas.

Capítulo 2 - “Tracking microplastics in paradise: first evidence of pollution in Lençóis Maranhenses National Park (Maranhão, Brazil), a UNESCO world heritage site”

O segundo capítulo apresenta os resultados originais da análise empírica conduzida no PNLM, incluindo a distribuição espacial, características e possíveis fontes dos MPs identificados. O estudo foi desenvolvido a partir de um delineamento amostral abrangente que contemplou áreas protegidas e regiões adjacentes do Parque Nacional dos Lençóis Maranhenses (PNLM), no Brasil. A investigação envolveu coleta e processamento de amostras de areia, com posterior análise físico-química dos microplásticos por meio de técnicas como espectroscopia RAMAN. A pesquisa também considerou variáveis ambientais e antrópicas para compreender os padrões de dispersão e acúmulo de MPs na região. O trabalho se propôs a avaliar a contaminação por microplásticos em um dos mais recentes Patrimônios Naturais da Humanidade, contribuindo com dados inéditos sobre este tipo de poluição em ambientes de dunas e lagoas sazonais. Ao integrar aspectos

ecológicos, metodológicos e de gestão, o capítulo também se destina a subsidiar estratégias de monitoramento e conservação voltadas à proteção de ecossistemas costeiros sensíveis.

Juntos, os dois capítulos fornecem uma visão integrada e abrangente sobre a problemática da poluição por microplásticos em ecossistemas costeiros protegidos, em uma escala variando entre a global e a específica, mas que se complementam.

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1. “Microplastic pollution in UNESCO natural world heritage sites: a global review”

Élida Priscila Bogéa Carvalho^{1,2}, Guilherme Malafaia^{1,2,3,4#}

¹Post-Graduation Program in Ecology, Conservation, and Biodiversity, Federal University of Uberlândia, Uberlândia 38408144, MG, Brazil.

²Laboratory of Toxicology Applied to the Environment, Goiano Federal Institute – Urutaí Campus. Rodovia Geraldo Silva Nascimento, 2,5 km, Zona Rural, Urutaí 75790-000, GO, Brazil

³Post-Graduation Program in Conservation of Cerrado Natural Resources, Goiano Federal Institute, Urutaí 75790-000, GO, Brazil.

⁴Post-Graduation Program in Biotechnology and Biodiversity, Goiano Federal Institute, GO, Brazil.

#Dr. Guilherme Malafaia. Laboratory of Toxicology Applied to the Environment, Goiano Federal Institute – Urutaí Campus. Rodovia Geraldo Silva Nascimento, 2,5 km, Zona Rural, Urutaí, GO, Brazil. CEP: 75790-000. Phone: +55 64 3465 1995. Email: guilhermeifgoiano@gmail.com

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1.1. Abstract

Microplastic (MP) pollution has emerged as one of the primary threats to aquatic and terrestrial ecosystems, including globally recognized protected areas. This review critically evaluates MPs' presence, distribution, and impacts in regions classified as UNESCO World Natural Heritage Sites. The analysis encompasses 60 studies published up to December 2024, highlighting temporal trends and geographic gaps. Findings reveal that of the 312 UNESCO-recognized areas, only 26 have been the focus of MP-related studies, primarily in coastal and aquatic ecosystems. Notable sites include the Galápagos Islands, the Great Barrier Reef, and the Fernando de Noronha Archipelago. MPs, predominantly synthetic fibers composed of polyethylene (PE) and polypropylene (PP), were detected across various environmental matrices and organisms, including sediments, surface waters, and marine and freshwater species. Furthermore, human activities such as unregulated tourism and improper waste disposal exacerbate MP dispersion, compromising the ecological integrity of these regions. This review identifies methodological gaps and proposes more integrated approaches to enhance monitoring and mitigation efforts, emphasizing the importance of global and regional public policies. By contributing to a broader understanding of the impacts of MPs in areas of high ecological and cultural value, this study underscores the urgency of coordinated actions that balance environmental conservation with economic sustainability.

Keywords: Natural heritage, plastic particles, microplastic pollution, protected areas, environmental conservation.

1.2. Introduction

The growing concern for the conservation of ecosystems on a global scale has strengthened the relevance of international environmental protection policies (Wuepper et al., 2024) and emphasized the importance of areas designated as UNESCO World Natural Heritage Sites. Established in 1972, the UNESCO World Heritage Convention aims to safeguard properties of outstanding universal value, fostering international cooperation to preserve sites with invaluable historical, cultural, and environmental significance (UNESCO, 2025). As highlighted by Osipova et al. (2020), these regions encompass tropical forests, coral reefs, mountains, lakes, islands, and deserts, which harbor unique biodiversity and perform essential ecosystem functions such as climate regulation and freshwater purification. Beyond their ecological role, these heritage sites hold strong cultural and aesthetic appeal, serving as key elements of local identities and supporting nature-based tourism, which drives sustainable economies (Ramón-Cardona et al., 2021; Matušíková et al., 2024; Echeverri et al., 2024). However, even with international protection status, these areas are not immune to human activities' multiple and interconnected threats. Recent studies reveal that pressures such as resource exploitation, infrastructure expansion, unregulated tourism, mining, and illegal activities often co-occur, further complicating effective conservation efforts (Qin et al., 2019; Reddiar & Osti, 2022; Falk & Hagsten, 2023; Selcuk et al., 2023; Falk & Hagsten, 2024; Potvin et al., 2024). Additionally, the impacts of various types of pollution also pose significant threats to the ecological integrity of World Heritage Sites, affecting biodiversity, ecosystem services, and local communities reliant on these resources (Esteban- Cantillo et al., 2024; Meskell, 2024; Dos-Santos et al., 2024; Morais et al., 2024).

While various pollutants represent serious threats to natural heritage sites, microplastics (MPs) have emerged as one of the most concerning due to their persistence, capacity for long-distance transport, and widespread dispersion across different environmental compartments (Pal et al., 2024; Thompson et al., 2024; Udhayakumar et al., 2025). Recent studies have shown that MPs are ubiquitous, being detected even in remote and uninhabited regions (Tan et al., 2020; Dai et al., 2024; Niu et al., 2024), demonstrating that pollution by these materials transcends urban and industrial boundaries, reaching areas previously considered untouched by human activity. This massive spread raises concerns about ecological impacts and the degradation of areas classified as World Natural Heritage Sites, essential for biodiversity conservation and maintaining global ecosystem balance. As highlighted by Frias & Nash (2019), MPs are defined as “any synthetic solid particle or polymeric matrix, with regular or irregular shape and with size ranging from 1 μm to 5 mm, of either primary or secondary manufacturing origin, which are insoluble in water.” While primary MPs refer to particles intentionally produced in small dimensions for use in products such as cosmetics,

pharmaceuticals, personal hygiene items, and textiles (Gani et al., 2024), secondary MPs result from the fragmentation of larger plastic materials, a process influenced by factors such as ultraviolet radiation, laundry washing, and other sources of mechanical abrasion. Under prolonged exposure to sunlight, large plastic debris undergoes photo-thermal degradation. At the same time, actions like friction with water, wind, and hard surfaces contribute to the fragmentation of these structures, compromising their integrity (Mahapatra et al., 2024). Once introduced into ecosystems, MPs can be transported by winds (Pham et al., 2025), ocean currents (Jiang et al., 2024), and waterways (Wang et al., 2024), expanding their dispersion on regional and global scales. This transport facilitates their presence in remote areas, where they can accumulate in various environmental matrices (Ali et al., 2024), contributing to their incorporation into food chains (Singh et al., 2024).

In this context, the presence of MPs in protected areas poses a significant challenge to environmental management and biodiversity conservation. Beyond affecting local biodiversity, MPs can also impact these territories' symbolic and ecological value, underscoring the need for integrated global policies to monitor and mitigate this invisible but highly impactful form of pollution. Studies demonstrate that in addition to physical effects such as gastrointestinal tract blockage (Jovanović, 2017; Chen et al., 2022) and a false sense of satiety (Pastorino et al., 2022; Sharma et al., 2024), MPs can also carry toxic substances, including heavy metals and persistent organic compounds, amplifying their ecotoxicological impacts (Rafa et al., 2024). Furthermore, many natural heritage sites are located in regions economically reliant on ecotourism and artisanal fishing, activities that can be severely affected by environmental degradation. The presence of MPs can thus compromise the visual integrity and biological functionality of these regions, directly impacting their ability to sustain local communities and attract visitors. Additionally, studies conducted in various areas have shown that MPs can disrupt biogeochemical cycles (Zhang et al., 2024), interfere with the photosynthetic processes of marine organisms (Huang et al., 2024), and reduce water filtration efficiency by filter-feeding organisms such as mollusks and sponges (Shalom et al., 2022).

Considering these aspects, the present review not only complements but also extends the scope of recent reviews on the subject (Napper et al., 2023; Liza et al., 2024; Fernandes et al., 2024; Dahms & Greenfield, 2024; Ghanadi et al., 2024; Li et al., 2025; Ansari et al., 2025) by providing a critical and comparative analysis of MP contamination in UNESCO World Natural Heritage Sites. This study examines the evolution of publications, methodologies employed, and key findings, highlighting existing gaps and proposing more integrated and multidisciplinary approaches to improve monitoring and mitigate impacts. Additionally, practical recommendations are offered for implementing management strategies that account for these globally significant ecosystems' local and regional particularities. With this approach, we believe the present study contributes

to a broader understanding of the challenges posed by MP pollution and guides the development of more effective public policies and conservation strategies.

1.3. Search and selection procedures

A comprehensive strategy was adopted to conduct the search and selection of articles, following recognized guidelines for literature reviews. The article search was performed across scientific databases, including Web of Science, Scopus, and Google Scholar, using a variety of descriptors such as *“microplastics,” “microplastic particles,” “plastic microparticles,” “microscopic plastic fragments,” “micro-sized plastic debris,” “synthetic microfibers,” “microbeads,” “plastic microfibers,” “plastic microfragments,” “secondary microplastics,” “primary microplastics,” “plastic micro-residues,” “polymer microparticles,” “microplastic pollutants,” “nanoplastics,” “microplastic debris,” “aquatic ecosystems,” “biodiversity impact,” “pollution mitigation”*. Specific combinations of terms were also employed, including: *“microplastics in UNESCO World Heritage Sites,” “microplastic pollution in natural heritage areas,” “microplastics in tropical and subtropical ecosystems,” “impacts of microplastics in marine and terrestrial World Heritage Sites,” “plastic waste and conservation in World Heritage environments,” “environmental impacts of microplastics in protected natural areas,” “microplastic contamination in biodiversity hotspots,” “management of microplastic pollution in heritage-protected areas,” “case studies of microplastic pollution in UNESCO-listed regions,”* and *“sustainable approaches to mitigate microplastics in heritage ecosystems.”* The descriptors were applied both individually and in combination with Boolean operators ("AND," "OR," and "NOT") to refine results and ensure the identification of relevant studies.

No specific temporal restriction was applied for study selection; all articles meeting the inclusion criteria were analyzed, regardless of publication year. These criteria included:

- i. original articles, baseline studies, short communications, and technical notes published and indexed in the databases by December 30, 2024;
- ii. studies published in English;
- iii. articles accessible after up to three access attempts;

- iv. studies involving Mps of any nature, including research on quantification, typification, physicochemical characterization, ecotoxicological analyses, and environmental impact assessments;
- v. studies addressing different matrices such as sediments, surface waters, and animal or plant species; and
- vi. research on mitigation methods, dispersion modeling, and MP transport dynamics.

Additionally, studies conducted at least partially in UNESCO recognized natural heritage sites, classified as "natural" or "mixed," were included, even if the research also covered adjacent or geographically influential areas.

Exclusion criteria included duplicate works, conference abstracts, books, reviews, restricted-access publications without complete data, and studies lacking clear scientific evidence related to the investigated theme. The study screening process was conducted in three stages: (i) title screening to initially exclude irrelevant articles; (ii) detailed analysis of abstracts to select studies with the highest potential contribution; and (iii) full-text reading for final inclusion. To ensure accurate classification of the areas mentioned in the studies as World Heritage Sites, the official UNESCO World Heritage List website (<https://whc.unesco.org/en/list/>) was consulted, using the names of regions and areas described in the articles.

From the eligible articles, we extracted information on the year of publication, the number of authors, and the reported mean concentrations or ranges of MP concentrations (for studies involving identification and quantification). Other data, such as the scope of sampling areas, the number of collected samples, MP characteristics (e.g., size, shape, polymer composition), organisms and biological samples analyzed, and methodological and analytical procedures employed, were gathered to enrich the discussion and provide a critical and comparative analysis of the reviewed studies. Only data related to collection points within these areas were considered for studies that included areas outside UNESCO-recognized Natural Heritage Sites.

1.4. Results

1.4.1. Evolution of publications and geographical distribution of studies

After applying the inclusion criteria, 60 full-text articles were selected and analyzed. As shown in Figure 1A, there was a marked increase in publications over time. Between 2003 and 2018, the number of articles remained stable, with only one publication per year. However, starting in 2019, a gradual growth was observed, reaching an average of 13.6 articles per year from 2022 to 2024, with a predicted linear growth trend, as shown in the analysis (Figure 1A). Additionally, Figure 1B highlights a linear upward trend in the average number of authors per article over the years. In 2020, the average number of authors was 5.16 per publication, increasing to 8.33 authors per article in 2024, representing a 61.4% increase.

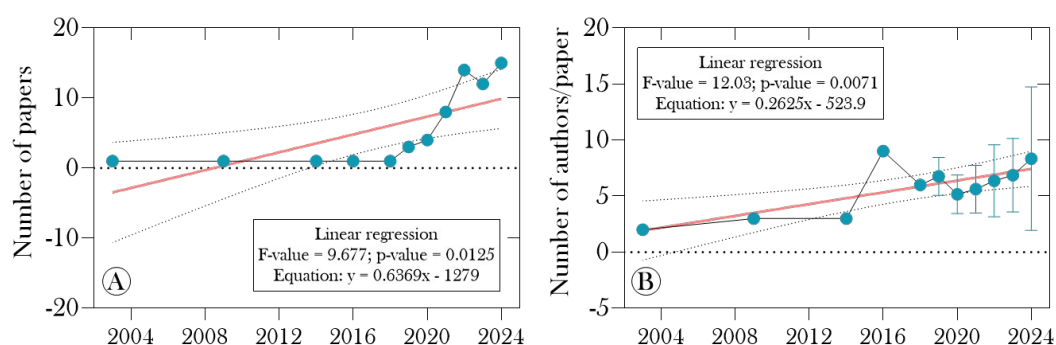


Figure 1. Temporal evolution of studies on microplastics in UNESCO World Heritage Sites, showing (A) the number of articles published over the years and (B) the average number of authors per article over time, with linear trend lines and corresponding p-values demonstrating significant growth in both cases.

On the other hand, the number of areas investigated for MP-related topics is significantly lower than the total number of UNESCO World Natural Heritage Sites. Of the 312 areas classified by UNESCO as "natural" or "mixed" heritage, the studies reviewed in this analysis covered only 26 areas (Figure 2 and Table 1), with the most prevalent being the Galapagos Islands (Ecuador), The Sundarbans (India-Bangladesh), Lake Baikal (Russia), the Great Barrier Reef (Australia), and the Fernando de Noronha Archipelago (Brazil) (Table 1), distributed across 20 countries out of the 114 that have areas with these designations. Furthermore, we observed that among the countries with protected areas where studies were conducted, most investigated fewer than half of their designated sites (Table 1).

Table 1. UNESCO Natural World Heritage Sites investigated for microplastic pollution: geographical distribution and research frequency

UNESCO Natural World Heritage Sites studied	Países	Number papers/site	Number of UNESCO Natural World Heritage Sites in the studied	Number of UNESCO Natural World Heritage Sites in the countries	Natural World Heritage Sites Studied concerning those existing in the country
Macquarie Island ⁽¹⁾	Australia	1	2	16	12,5
Great Barrier Reef ⁽²⁾		6			
The Sundarbans ⁽³⁾	India	4	2	8	25,0
Western Ghats		1			
The Sundarbans ⁽³⁾	Bangladesh	3	1	1	100
Brazilian Atlantic Islands: Fernando de Noronha and Atol das Rocas Reserves ⁽⁴⁾	Brazil	5	4	9	44,4
Atlantic Forest South-East Reserves ⁽⁵⁾		1			
Central Amazon		1			

Conservation Complex ⁽⁶⁾						
Pantanal Conservation Area ⁽⁷⁾		2				
China Danxia ⁽⁸⁾		1				
Jiuzhaigou Valley Scenic ⁽⁹⁾		1 *				
Huanglong Scenic ⁽¹⁰⁾	China	1 *	4	19	21,0	
Three Parallel Rivers of Yunnan Protected Areas ⁽¹¹⁾		1				
Cocos Island National Park ⁽¹²⁾	Costa Rica	1	1	3	33,3	
Ilulissat Icefjord ⁽¹³⁾	Denmark	1	1	3	33,2	
Galapagos Island ⁽¹⁴⁾	Ecuador	9	1	2	50,0	
Lagoons of New Caledonia: Reef Diversity and	France	1	1	9	11,1	

Associated

Ecosystems^(1,5)

Komodo National Park ⁽¹⁶⁾	Indonesia	1	1	4	25,0
Isole Eolie (Aeolian Islands) ⁽¹⁷⁾	Italy	3	1	6	16,6
Shiretoko ⁽¹⁸⁾	Japan	2	1	5	20,0
Revillagigedo Archipelago ⁽¹⁹⁾	Mexico	1	1	8	12,5
Wadden Sea ⁽²⁰⁾	Netherlands	1	1	1	100
Danube Delta ⁽²¹⁾	Romania	2	1	2	50,0
Lake Baikal ⁽²²⁾	Russia	6	1	11	9,0
iSimangaliso Wetland Park ⁽²³⁾	South Africa	1	1	5	20,0
Teide National Park ⁽²⁴⁾	Spain	2	1	6	16,6
Yellowstone National Park ⁽²⁵⁾	United States	1	1	13	7,7
Ichkeul National Park ⁽²⁶⁾	Tunisia	1	1	1	100

⁽¹⁾<https://whc.unesco.org/en/list/629>, ⁽²⁾<https://whc.unesco.org/en/list/154>, ⁽³⁾<https://whc.unesco.org/en/list/798>, ⁽⁴⁾<https://whc.unesco.org/en/list/1000>,

⁽⁵⁾<https://whc.unesco.org/en/list/893>, ⁽⁶⁾<https://whc.unesco.org/en/list/998>, ⁽⁷⁾<https://whc.unesco.org/en/list/999>, ⁽⁸⁾<https://whc.unesco.org/en/list/1335>,

⁽⁹⁾<https://whc.unesco.org/en/list/637>, ⁽¹⁰⁾<https://whc.unesco.org/en/list/638>, ⁽¹¹⁾<https://whc.unesco.org/en/list/1083>, ⁽¹²⁾<https://whc.unesco.org/en/list/820>,
⁽¹³⁾<https://whc.unesco.org/en/list/1149>, ⁽¹⁴⁾<https://whc.unesco.org/en/list/1>, ⁽¹⁵⁾<https://whc.unesco.org/en/list/1115>, ⁽¹⁶⁾<https://whc.unesco.org/en/list/609>,
⁽¹⁷⁾<https://whc.unesco.org/en/list/908>, ⁽¹⁸⁾<https://whc.unesco.org/en/list/1193>, ⁽¹⁹⁾<https://whc.unesco.org/en/list/1510>, ⁽²⁰⁾<https://whc.unesco.org/en/list/1314>, ⁽²¹⁾<https://whc.unesco.org/en/list/588>, ⁽²²⁾<https://whc.unesco.org/en/list/754>, ⁽²³⁾<https://whc.unesco.org/en/list/914>, ⁽²⁴⁾<https://whc.unesco.org/en/list/1258>, ⁽²⁵⁾<https://whc.unesco.org/en/list/28>, and ⁽²⁶⁾<https://whc.unesco.org/en/list/8>.

*Referem-se a um único estudo, em que as duas áreas foram alvo de investigação.

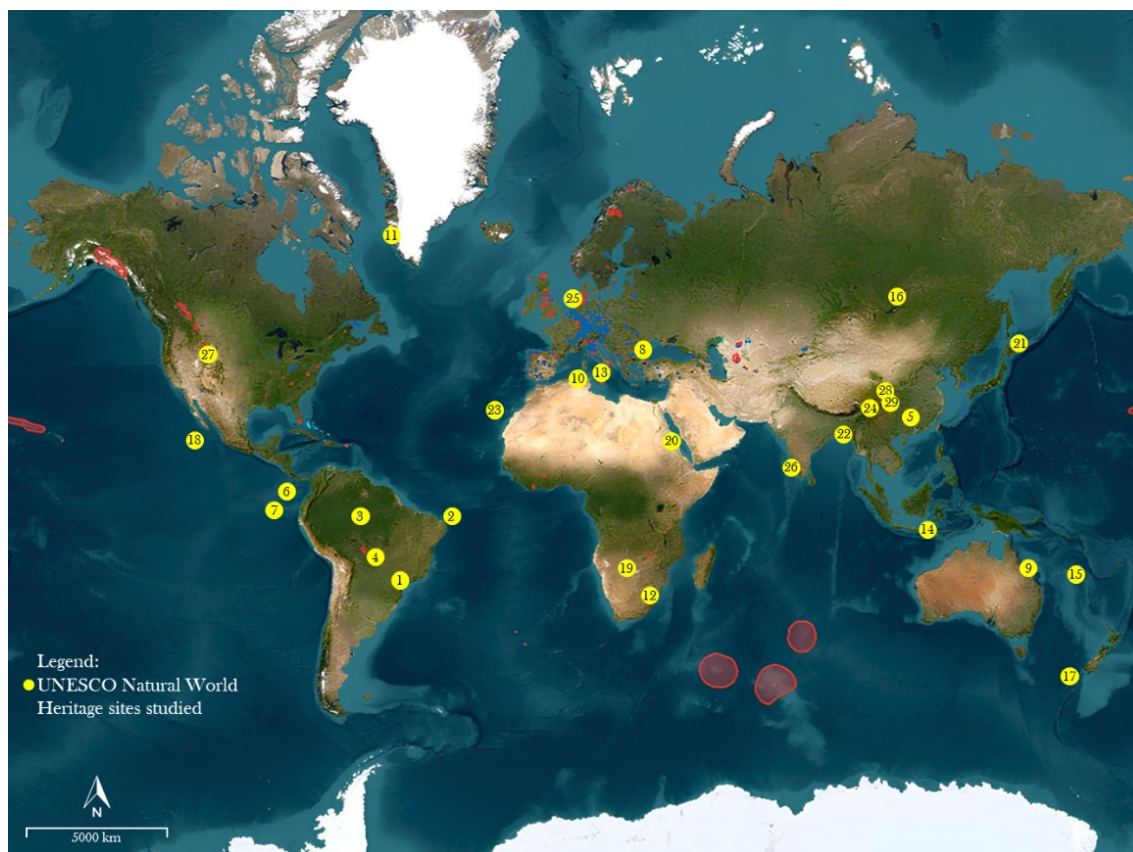


Figure 2. Location of UNESCO World Natural Heritage sites assessed in microplastic pollution studies (up to December 30, 2024).

Note: (1) Atlantic Forest South-East Reserves, Brazil; (2) Brazilian Atlantic Islands: Fernando de Noronha and Atol das Rocas Reserves, Brazil; (3) Central Amazon Conservation Complex, Brazil; (4) Pantanal Conservation Area, Brazil; (5) China Danxia, China; (6) Cocos Island National Park, Costa Rica; (7) Galapagos Island, Ecuador; (8) Danube Delta, Romania; (9) Great Barrier Reef, Australia; (10) Ichkeul National Park, Tunisia; (11) Ilulissat Icefjord, Denmark; (12) iSimangaliso Wetland Park, South Africa; (13) Isole Eolie (Aeolian Islands), Italy; (14) Komodo National Park, Indonesia; (15) Lagoons of New Caledonia: Reef Diversity and Associated Ecosystems, France; (16) Lake Baikal, Russia; (17) Macquarie Island, Australia; (18) Revillagigedo Archipelago, Mexico; (19) Okavango Delta, Botswana; (20) Sanganeb Marine National Park and Dungonab Bay - Mukkawar Island Marine National Park, Sudan; (21) Shiretoko, Japan; (22) The Sundarbans, Bangladesh; (23) Teide National Park, Spain; (24) Three Parallel Rivers of Yunnan Protected Areas, China; (25) Wadden Sea, Netherlands; (26) Western Ghats, India; (27) Yellowstone National Park, United States of America; (28) Jiuzhaigou Valley Scenic and Historic Interest Area, China, and (29) Huanglong Scenic and Historic Interest Area, China.

1.4.2. Focus of investigations in reviewed studies

Regarding the focus of the investigations in the evaluated articles, most studies involved the identification, quantification, and/or typification of MPs in environmental matrices, with a particular emphasis on surface waters and sediments (the most prevalent sample types), whether marine or freshwater. Additionally, 23 studies addressed wildlife contamination by MPs, while three explored aspects related to MP transport and dispersion, employing modeling to trace sources and distribution routes.

1.4.2.1. Studies focused on wildlife contamination by microplastics

Through studies focusing on wildlife, the presence of MPs was identified in a wide range of species, including fish, reptiles, birds, mammals, and a broad spectrum of aquatic invertebrates (marine and freshwater) (Table 2). Among the reviewed studies on fish, Sarker et al. (2022) stands out for their work in the aquatic ecosystem of the Sundarbans mangrove forest, located in the southwestern coastal zone of Bangladesh (Figure 2A). In this environment, the authors collected 40 fish species across eight sampling sites between June and December 2021 (Figure 3A). Notable among the species examined were *Tenualosa ilisha* (Hilsa), an anadromous fish and the national symbol of Bangladesh, essential for local fisheries, and *Channa punctata* (spotted snakehead), a carnivorous species native to India and neighboring countries. In the study by Dithakanyane et al. (2022), the authors evaluated the presence of MPs in the digestive organs of *Tilapia sparrmanii* (Sparman's tilapia) collected in the Okavango Delta (Botswana), demonstrating that the highest concentrations were found in the intestines, followed by the stomach and gills, with a predominance of fragments and fibers in the 1–3 mm range. Furthermore, noteworthy are the studies by Dawson et al. (2022), the only one to assess MP contamination in a species inhabiting coral-rich areas of the Great Barrier Reef (Australia), *Plectropomus leopardus*, and the study by Justino et al. (2023), which investigated the trophic transfer of MPs from prey to predators in *Thunnus albacares* and other pelagic species in the Fernando de Noronha Archipelago (Brazil) (Table 2).

Marine mammals were also the subject of studies evaluating the presence of MPs in fecal samples. Eriksson & Burton (2003) identified plastic particles in the feces of fur seals [*Arctocephalus tropicalis* (subtropical fur seal) and *Arctocephalus gazella* (Antarctic fur seal)] on Macquarie Island (Australia), with a predominance of polyethylene (PE) and polypropylene (PP) fragments resulting from the degradation of larger plastics, likely ingested indirectly via the consumption of pelagic fish. Meanwhile, Moreira-Mendieta et al. (2023) detected MPs in 37% of fecal samples from adult Galápagos sea lions (*Zalophus wollebaekii*) (out of a total of 160 samples) collected along the coast in five significant colonies in the southeastern region of the Galápagos Marine Reserve in August 2021 (Figure 3B). Most identified particles were microfibers associated with residues from textiles, fishing

activities, and packaging. Additionally, studying *Rhinopithecus bieti* (Yunnan snub-nosed monkey) in alpine primary forests of protected areas in the Three Parallel Rivers of Yunnan, China (Figure 3C), Xia et al. (2024) reported the presence of MPs in the feces of this primate (Table 2), a rare and endangered species endemic to China. The research highlighted that human-supplemented feeding significantly increased exposure to MPs, while tourism had a less pronounced impact. Finally, Álvarez-Méndez et al. (2024) investigated anthropogenic particles in the feces of European rabbits (*Oryctolagus cuniculus*) and mouflons (*Ovis gmelini*) in Teide National Park, Canary Islands, detecting PE and PP fragments in 4% of the samples, with an average of 0.79 ± 0.20 particles/g of feces (Table 2). Atmospheric deposition and tourist presence were identified as possible contamination sources.

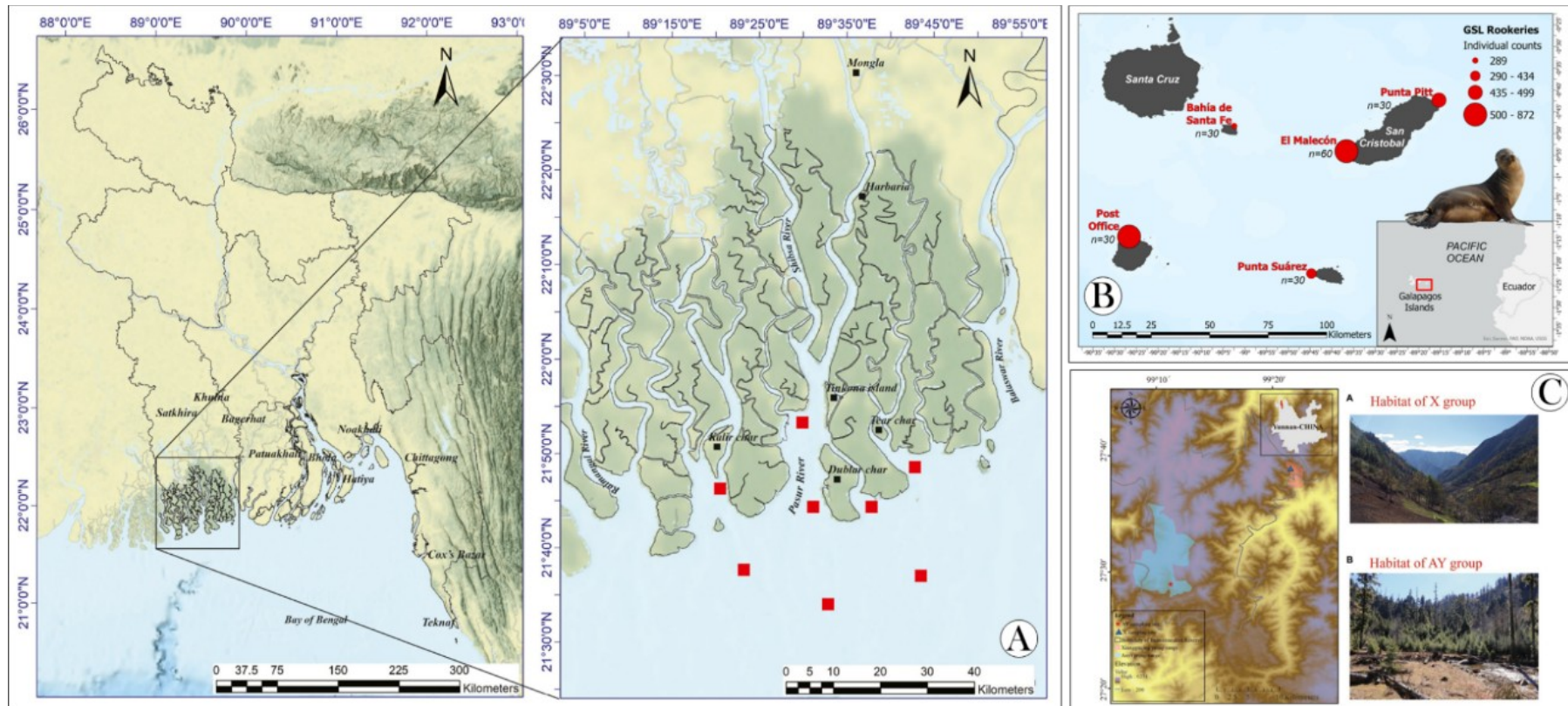


Figure 3. (A) Geographical extent of study area showing the location of Bangladesh in left panel. Black rectangle in left panel indicates the sampling area. Right panel shows the zoom view of sampling area. Red filled rectangles in right panel indicate the sampling locations [reprinted from Sarker et al. (2022), with permission from Elsevier (License ID: 1564907), Copyright © 2022 Elsevier BV]. (B) Study areas showing the locations of Galapagos sea lion rookeries from the southeast Galapagos archipelago, as well as the number of samples collected at each site. Circle sizes are based on animals counted on each rookery during field work [reprinted from Moreira-Mendieta et al. (2023), with permission from Elsevier (License ID: 1564908), Copyright © 2023 Elsevier BV]. (C) Study site and sampling site habitat (reprinted from Xia et al. (2024), licensed under CC BY 4.0).

Among the studies focused on invertebrates, notable works include those by Meyer et al. (2022), Miller et al. (2023), and Yang et al. (2024) (Table 2). In the first study, the authors investigated the impacts of pollutants from domestic sewage on benthic communities in Lake Baikal (Russia), emphasizing how nutrients and micropollutants can alter aquatic ecosystems while providing a robust database of pollution indicators, such as pharmaceuticals, MPs, and fatty acids. In Yang et al. (2024), the authors observed that pelagic copepods also collected in Lake Baikal exhibited an incidence of MP ingestion over 10 times higher than reported in other lakes, primarily associated with high-density particles. Conversely, Miller et al. (2023) evaluated the presence of MPs in a coral reef food web in the Great Barrier Reef (Australia), demonstrating that although MPs are transferred across trophic levels, there was no evidence of bioaccumulation or biomagnification, despite MP concentrations being similar to the surrounding environment. Additionally, the study by Berr et al. (2020) stands out as the only one to evaluate the presence of MPs in seabirds. The authors analyzed the stomach contents of 90 individuals from 12 species collected in New Caledonia, identifying plastic debris in 14.4% of the samples, with notable findings in Procellariidae such as the white-throated petrel (*Pterodroma leucoptera*) (41.2% incidence), the Tahiti petrel (*Pseudobulweria rostrata*) (33.3%), and the wedge-tailed shearwater (*Ardenna pacifica*) (7.7%) (Table 2), indicating a lower prevalence of plastic ingestion compared to other areas in the tropical Pacific.

On the other hand, Caron et al. (2018), Muñoz-Perez et al. (2024), and Ramon-Gomez et al. (2024) focused on analyzing the fecal contents of reptile species. Muñoz-Perez et al. (2024) investigated MP ingestion in juvenile green turtles (*Chelonia mydas*) in Ecuadorian national parks and found MPs in 98% of the samples, with the highest prevalence in the Galápagos Marine Reserve, highlighting polymers such as polyvinyl alcohol (PVOH) and polymethyl methacrylate (PMMA), along with associations to changes in 11 health metrics. Ramon-Gomez et al. (2024) reported that feces from giant tortoises (*Chelonoidis porteri*) collected in the protected area "La Torta" in the Galápagos National Park contained only two fragments of plastic waste. In contrast, feces from tortoises in anthropized areas on Santa Cruz Island—the most populated island in the archipelago—contained 590 fragments (including MPs and macroplastics - Figure 4), with an average of 3.97 plastic items/kg of feces, compared to only 0.08 items/kg in the protected areas.



Figure 4. Plastic pollution and wildlife interactions: evidence from Galapagos Giant Tortoises. (A) A Galapagos giant tortoise (*Chelonoidis porteri*) consuming plastic debris in a human-modified area of Santa Cruz Island. (B) Fecal samples collected from the human-modified area, visibly containing plastic debris. (C) Examples of plastic debris retrieved from tortoise feces, including a sanitary face mask. This figure is reprinted from Ramon-Gomez et al. (2024) with permission from Elsevier (License ID: 1564913, Copyright © 2024 Elsevier BV). These observations highlight the pervasive impact of plastic pollution on wildlife, even within globally significant ecosystems such as the Galapagos Islands.

Table 2. Summary of studies on microplastic contamination in various organisms conducted in UNESCO World Natural Heritage Sites.

UNESCO Natural World Heritage Sites studied	Countries	Organisms studied	Type of sample analyzed	Microplastic concentrations	References
Macquarie Island	Australia	<i>Arctocephalus tropicalis</i> (Antarctic fur seal) and <i>Arctocephalus gazella</i> (the sub-Antarctic fur seal)	Feces	Plastic particles were found in 145 feces, totaling 164 particles, with 1 particle per scat being most frequent (85%)	Eriksson & Burton (2003)
Great Barrier Reef	Australia	<i>Chelonia mydas</i> (Green sea turtle)	Anterior digestive tract content (chyme)	Seven microplastic particles were found (three particles in Turtle A and four in Turtle B), ranging from 0.45 mm to 2.95 mm in size.	Caron et al. (2018)
Great Barrier Reef	Australia	<i>Pomacentrus moluccensis</i>	Gastrointestinal tracts	No significant difference in marine microdebris abundance in damselfish between inshore (median 4.5 items/fish) and offshore reefs (median 4.0 items/fish)	Jensen et al. (2019)
Lagoons of New Caledonia: Reef Diversity and	France	12 seabird species ⁽¹⁾	Stomach contents	Plastic debris was found in the stomach contents of 13 out of 90 seabirds examined (FO = 14.4%), with all three procellariid	Berr et al. (2020)

Associated Ecosystems	species showing plastic ingestion: wedge-tailed shearwater (<i>Ardena pacifica</i> , 0.12 ± 0.06 items per specimen), Gould's petrel (<i>Pterodroma leucoptera</i> , 1.12 ± 0.37), and Tahiti petrel (<i>Pseudobulweria rostrata</i> , 0.5 ± 0.42), while no plastic ingestion was observed in non-procellariid species.			
	Yellowstone National Park	United States	<i>Gammarus lacustris</i> (Amphipods), <i>Oncorhynchus clarkii bouvieri</i> (Yellowstone cutthroat trout), and <i>Salvelinus namaycush</i> (lake trout)	Digestive tracts of amphipods (<i>G. lacustris</i>), and stomach contents of fish (<i>S. namaycush</i> and <i>O. clarkii bouvieri</i>).
	Galapagos Island	Ecuador	<i>Lepas anatifera</i> , <i>Megabalanus peninsularis</i> , <i>Saccostrea palmula</i> , <i>Nerita scabricosta</i> , <i>Chiton sulcatus</i> , <i>Eucidaris galapagensis</i> , and	Entire body of the individuals (<i>L. anatifera</i> , <i>M. peninsularis</i> , <i>S. palmula</i> , <i>N. scabricosta</i> , <i>C. sulcatus</i> , and <i>E. galapagensis</i>) and
				Among the analyzed species, only one of the 32 amphipods (<i>G. lacustris</i>) contained an identifiable non-organic particle. In fish, two lake trout (<i>S. namaycush</i>) diets contained a total of three particles, while one Yellowstone cutthroat trout (<i>O. clarkii bouvieri</i>) diet contained three particles.
				The average MP concentrations/individual were 0.71 ± 0.29 in <i>L. anatifera</i> , 1.17 ± 0.31 in <i>M. peninsularis</i> , 0.67 ± 0.30 in <i>S. palmula</i> (all consisting exclusively of fibers), 0.65 ± 0.19 in <i>N. scabricosta</i> , 0.5 ± 0.5 in <i>C. sulcatus</i> , 0.68 ± 0.18 in <i>E. galapagensis</i> , and 0.99 ± 0.34 in <i>H. kefersteini</i> .
				Driscoll et al. (2021)
				Jones et al. (2021)

The Sundarbans	Bangladesh	<i>Holothuria kefersteini</i>	Gastrointestinal tracts (<i>H. kefersteini</i>)		
		3 zooplankton species, 4 crab species, 3 shark species, 5 molluscs species, 5 shrimp species, 1 turtle species and 40 fish species ⁽²⁾	Entire body of the zooplankton individuals, gastrointestinal tracts (fish, shrimp, turtles, and sharks), and soft tissues (molluscs and crabs)	The abundance of MPs in the aquatic organisms varied between 0.56 ± 0.25 items/individual and 6.06 ± 1.20 items/individual.	Sarker et al. (2022)
Lake Baikal	Russia	Diverse range of macroinvertebrates, predominantly mollusks, amphipods, and isopods ⁽³⁾	Entire body of the individuals	Data on MP concentrations are available in the Environmental Data Initiative repository for detailed consultation and analysis	Meyer et al. (2022)
Cocos Island National Park	Costa Rica	Marine and freshwater fishes, marine lobsters, and freshwater shrimps ⁽⁴⁾	Gastrointestinal tracts (fishes) and entire body of the individuals (lobsters and shrimps)	Marine fishes: 1.37 ± 0.51 MPs/individual; freshwater fishes: 1.16 ± 0.40 MPs/individual; marine lobsters: 1.42 ± 0.75 MPs/organism; and freshwater shrimps: 1.16 ± 0.40 MPs/organism	Pérez et al. (2022)

Okavango Delta	Botswana	<i>Tilapia sarrmanii</i>	Gastrointestinal tracts	≈ 0.8 MPs/intestine, ≈ 0.5 MPs/gills, and ≈ 0.35 MPs/stomach	Ditlhakanyane et al. (2022)
Great Barrier Reef	Australia	<i>Ylistrum balloti</i> (Ballot's Saucer Scallop), <i>Melicerus latisulcatus</i> (Blue-legged King Prawn), <i>Plectropomus leopardus</i> (Common Coral Trout), <i>Lates calcarifer</i> (Barramundi)	Gastrointestinal tract and muscle	Only two coral trout individuals (<i>P. leopardus</i>) had detectable MPs, with 0.19 MP/g in stomach tissue and 0.14 MP/g in intestinal tissue	Dawson et al. (2022)
The Sundarbans	Bangladesh	<i>Tenualosa ilisha</i> , <i>Lates calcarifer</i> , <i>Otolithoides pama</i> , <i>Mystus vittatus</i> , <i>Scatophagus argus</i> , <i>Harpadon nehereus</i> , <i>Pseudapocryptes elongatus</i> , and <i>Awaous grammepomus</i>	Gastrointestinal tract	10.41 ± 7.43 particles/g	Nawar et al. (2023)

Brazilian Atlantic Islands: Fernando de Noronha and Atol das Rocas Reserves	Brazil	Predators: <i>Thunnus albacares</i> (Yellowfin tuna), <i>Thunnus obesus</i> (Bigeye tuna), <i>Sphyraena barracuda</i> (Barracuda), <i>Acanthocybium solandri</i> (Wahoo). Prey: fish and cephalopod⁽⁵⁾	Predators: stomach contents. Prey: digestive tracts of fish and the whole body of cephalopods	Predator (<i>Thunnus albacares</i>): 0.33 ± 14.06 particles/individual. Prey (fish): 0.75 ± 0.95 to 27.4 ± 37.4 particles/individual; prey (cephalopod): 5.0 ± 0.0 to 35 ± 39.5 particles/individual	Justino et al. (2023)
Galapagos Island	Ecuador	<i>Zalophus wollebaeki</i> (Galapagos sea lion)	Feces	0.04 ± 0.05 particles/g in fecal samples	Moreira-Mendieta et al. (2023)
Sundarbans Biosphere Reserve	India	13 fish species ⁽⁶⁾	Gastrointestinal tract	MPs were almost ubiquitous in all fish species (not quantified)	Bhattacharjee et al. (2023)
Great Barrier Reef	Australia	Zooplankton (i.e., copepods), benthic crustaceans (i.e., crabs, lobsters, isopods, amphipods, and shrimps), and a benthic-feeding reef	Copepods and benthic crustaceans: entire body (individual) and fish: gastrointestinal tract (GT)	Copepods: 2.64 ± 2.29 to 4.81 ± 1.90 MPs/g; benthic crustaceans: 0.57 ± 75.93 to 45.68 ± 75.93 MPs/g, and fish: 0.09 ± 0.15 to 0.22 ± 0.26 MPs/g	Miller et al. (2023)

		fish ⁽⁷⁾			
Galapagos Island	Ecuador	<i>Chelonia mydas</i> (Green sea turtle)	Feces	4.4 ± 5.2 MPs/g in fecal samples	Muñoz-Perez et al. (2024)
Galapagos Island	Ecuador	<i>Chelonoidis porteri</i> (Western Santa Cruz giant tortoise)	Feces	3.97 ± 0.48 items/kg in fecal samples (plastic waste was the predominant category in feces within the anthropic - 83.6%)	Ramon-Gomez et al. (2024)
The Sundarbans	India	<i>Boleophthalmus boddarti</i> (Mudskipper) and <i>Oreochromis rubicundus</i> (Redbelly tilapia)	Skin, gills, bucco-opercular cavity and gastrointestinal tract	<i>B. boddarti</i> : 0.84 ± 0.44 MP/fish and <i>O. rubicundus</i> : 2.62 ± 1.21 MP/fish	Chatterjee et al. (2023)
The Sundarbans	India	<i>Clibanarius longitarsus</i> and <i>Telescopium telescopium</i>	Gills and gut tissues	<i>C. longitarsus</i> : 1.94 ± 0.59 MP/crab <i>T. telescopium</i> : 1.69 ± 1.43 MP/L.	Das et al. (2023)
Lake Baikal	Russia	Zooplankton (<i>Epischurella baikalensis</i> and <i>Cyclops kolensis</i>)	Entire body (individual)	0.12 MPs/copepod	Yang et al. (2024)
Three Parallel	China	<i>Rhinopithecus bieti</i>	Feces	75.263 ± 58.141 MPs/g in fecal samples	Xia et al. (2024)

Rivers of Yunnan	(Yunnan snub-nosed			
Protected Areas	monkey)			
	<i>Oryctolagus cuniculus</i>			
Teide National Park	(European rabbit) and	Feces	0.79 ± 0.20 items/g in fecal samples	Álvarez-Méndez et al. (2024)
Spain	<i>Ovis gmelini</i> (Mouflon)			

(1) *Ardenia pacifica* (Wedge-tailed Shearwater), *Pterodroma leucoptera* (Gould's Petrel), *Pseudobulweria rostrata* (Tahiti Petrel), *Anous minutus* (Black Noddy), *Sterna dougallii* (Roseate Tern), *Sula sula* (Red-footed Booby), *Larus novaeollandiae* (Silver Gull), *Anous stolidus* (Brown Noddy), *Onychoprion anaethetus* (Bridled Tern), *Onychoprion fuscatus* (Sooty Tern), *Sternula nereis* (Fairy Tern), and *Thalasseus bergii* (Greater Crested Tern). (2) *Calanus spp.* (copepod), *Pseudodiaptomus spp.* (copepod), *Acartia spp.* (copepod), *Acetes indicus* (Indian prawn), *Penaeus monodon* (giant tiger prawn), *Metapenaeus affinis* (Jinga shrimp), *Penaeus indicus* (Indian white prawn), *Metapenaeus monoceros* (speckled shrimp), *Charybdis hellerii* (yellowline swimming crab), *Ocypode ceratophthalma* (horned ghost crab), *Scylla serrata* (mud crab), *C. rostrata* (likely referring to a crustacean species, potentially *Calappa rostrata*, a box crab), *Telescopium telescopium* (telescope snail), *Nerita articulata* (articulated nerite), *Octopus vulgaris* (common octopus), *Cerithidea obtusa* (mud creeper snail), *Meretrix meretrix* (Asian hard clam), *Rasbora rasbora* (Indian rasbora), *Scatophagus argus* (spotted scat), *Coilia dussumieri* (golden anchovy), *Sardinella fimbriata* (fringescale sardine), *Mugil cephalus* (flathead grey mullet), *Plotosus canius* (grey eel-catfish), *Nemipterus japonicus* (Japanese threadfin bream), *Lates calcarifer* (barramundi or Asian sea bass), *Acanthopagrus berda* (goldsilk seabream), *Rhynchorhamphus georgii* (longbeak halfbeak), *Strongylura leiura* (banded needlefish), *Thryssa hamiltonii* (Hamilton's thryssa), *Nemapteryx nenga* (giant catfish), *Chirocentrus dorab* (Dorab wolf-herring), *Sciades sona* (soldier catfish), *Puntius chola* (swamp barb), *Lepidocephalichthys guntea* (Guntea loach), *Pseudapocryptes elongatus* (elongated mudskipper), *Sardinella gibbosa* (goldstripe sardinella), *Cynoglossus cynoglossus* (Indian tongue sole), *Johnius coitor* (coitor croaker), *Gymnothorax tile* (Indian mud moray), *Harpodon nehereus* (Bombay duck), *Xenentodon cancila* (freshwater garfish), *Channa punctata* (spotted snakehead), *Narcine timlei* (black-spotted electric ray), *Setipinna phasa* (phasa shad), *Alepes kleinii* (scad), *Tenualosa ilisha* (ilish shad), *Plicofollis dussumieri* (Dussumier's catfish), *Exocoetus volitans* (flying fish), *Ailia coila* (Gangetic ailia), *Carangoides armatus* (longfin trevally), *Telatrygon zugei* (pale-edged stingray), *Himantura undulata* (honeycomb stingray), *Gymnura poecilura* (butterfly ray), *Terapon jarbua* (jarbua terapon), *Hilsa kelee* (kelee shad), *Opisthopterus tardoore* (tardoore), *Mustelus mosis* (Arabian smooth-hound shark), *Scoliodon laticaudus* (spadenose shark), and *Rhizoprionodon acutus* (milk shark). (3) Marine fishes (*Lutjanus jordan*), Freshwater fishes (*Dajaus monticola*, *Eleotris picta*, *Gobiesox fulvus*, and *Sicydium cocoensis*), marine lobsters (*Panulirus gracilis* and *Panulirus penicillatus*), and freshwater shrimps (*Macrobrachium sp.*). (4) Acroloxiidae (mollusk family), Asellidae (isopod family), Baicaliidae (mollusk family), Benedictiidae (mollusk family), *Brandtia latissima* (species of macroinvertebrate), *Brandtia parasitica parasitica* (endemic amphipod species), caddisflies (general grouping, not identified to species), *Cryptoropus inflatus* (endemic amphipod species), *Cryptoropus pachytus* (endemic amphipod

species), *Cryptoropus rugosus* (endemic amphipod species), *Eulimnogammarus capreolus* (endemic amphipod species), *Eulimnogammarus cruentus* (endemic amphipod species), *Eulimnogammarus cyaneus* (endemic amphipod species), *Eulimnogammarus grandimanus* (endemic amphipod species), *Eulimnogammarus juveniles* (endemic amphipod species), *Eulimnogammarus maackii* (endemic amphipod species), *Eulimnogammarus maritiji* (endemic amphipod species), *Eulimnogammarus verucosus* (endemic amphipod species), *Eulimnogammarus viridis viridis* (endemic amphipod species), *Eulimnogammarus vittatus* (endemic amphipod species), Maackia (mollusk family), *Pallasea brandtia brandtia* (endemic amphipod species), *Pallasea brandtii tenera* (endemic amphipod species), *Pallasea cancelloides* (endemic amphipod species), *Pallasea cancellus* (endemic amphipod species), *Pallasea viridis* (endemic amphipod species), Planorbidae (mollusk family), *Poekilogammarus crassimus* (endemic amphipod species), *Poekilogammarus ephippiatus* (endemic amphipod species), *Poekilogammarus juveniles* (endemic amphipod species), *Poekilogammarus megonychus perpolitus* (endemic amphipod species), *Poekilogammarus pictus* (endemic amphipod species), and Valvatidae (mollusk family). (5) Prey fish: Bramidae (family), Gempylidae (family), Teleostei n/d, Exocoetidae (family), *Exocoetus volitans*, *Gempylus serpens*, *Acanthurus* sp., *Dactylopterus volitans*, *Dirtemus argenteus*, and *Oxyporhamphus micropterus*. Prey cephalopod: *Abralia veranyi* and *Ornithocheuthis antillarum*. (6) *Harpadon nehereus* (Bombay duck), *Lepturacanthus savala* (Silver ribbon fish), *Bregmaceros maclellandi* (Spotted codlet), *Otolithoide pama* (Pama croaker), *Arius arius* (Threadfin catfish), *Stolephorus indicus* (Indian anchovy), *Cynoglossus lingua* (Tongue sole), *Coilia ramcarati* (Gangetic anchovy), *Pellona ditchella* (Indian shad), *Tetraodon cutcutia* (Pufferfish), *Pisodonophis boro* (Rice-paddy eel), *Panna microdon* (Pomfret), *Coilia dussumieri* (Dussumier's anchovy). (7) Isopod (Cirolanidae family), Shrimp (Caridea infraorder), Amphipod (Amphipoda order), *Galathea australiensis* (Squat lobster), *Etisus frontalis* (Rubble crab), *Thalamita spinimana* (Swimmer crab), Crustacean parts (unknown species).

1.4.2.2. Studies involving the identification, quantification, and/or characterization of microplastics in environmental matrices in UNESCO Natural Heritage Sites

1.4.2.2.1. Studies conducted in the americas

Regarding the studies on the identification, quantification, and/or characterization of MPs in environmental matrices (water, sediment, or sand) in the Americas, Table 3 summarizes the 14 studies identified and evaluated in this review. These studies were conducted in seven UNESCO Natural Heritage Sites (Atlantic Forest South-East Reserves, Fernando de Noronha Archipelago, Cocos Island National Park, Central Amazon Conservation Complex, Galápagos Islands, Pantanal Conservation Area, and Revillagigedo Archipelago). In the Galápagos Archipelago, the study by Sánchez-García et al. (2023) stands out, reporting that the dynamics of MP accumulation in sand samples are strongly associated with predominant ocean currents and human beach usage, revealing MP concentrations comparable to the most contaminated regions globally. One of the main distinguishing features of this study was the inclusion of an analysis of environmental factors influencing the distribution of plastic debris by size. While macro- and mesoplastics showed a strong correlation with the orientation of beaches relative to ocean currents, MPs were more influenced by sediment slope and granulometry, with no significant relationship to proximity to urban areas or recreational beach use. The study also highlighted that in situ fragmentation of larger plastics significantly contributes to the presence of MPs on beaches. In the study by Pelamatti et al. (2021), conducted in various areas of the Revillagigedo Archipelago (Cabo Pierce, Naval Base, and Punta Tosca on Socorro Island; Cañon and Boiler on San Benedicto Island; Clarion on Clarion Island; and Roca Partida on Roca Partida Islet - Figure 5A), the authors identified that 73% of floating plastics were MPs (<5 mm) and emphasized the adsorption of toxic compounds, such as organochlorine pesticides, highlighting the risks to filter-feeding megafauna and threatened endemic species. In the Fernando de Noronha Archipelago, Carvalho et al. (2021) collected sediment samples during the dry season, from October 23 to November 5, 2019, over 13 days. Daily samples were collected from two beaches on the protected side (Cacimba do Padre - L1 and Boldró - L2) and two beaches exposed to winds (Leão - W1 and Sueste - W2), totaling 39 samples per beach, except for Leão (W1), with 36 samples. Additionally, during the days of highest and lowest tidal variation, samples were also collected from Conceição (L3) and Atalaia (W3) beaches, with six samples each (Figure 5B). The authors reported significant spatial variation in MP concentrations, influenced by beach orientation and the dynamics of marine currents and prevailing winds. Beaches facing southeast, such as Sueste (W2) and Leão (W1), showed the highest concentrations due to exposure to the South Equatorial Current, while more protected beaches, such as Cacimba do Padre (L1)

and Boldró (L2), exhibited lower levels of contamination. In the wetlands of the Pantanal, the largest floodplain in the world, Camargo et al. (2022) demonstrated that the highest MP concentrations were observed in urban areas near the cities of Cuiabá and Várzea Grande (Figure 5C), with evidence of contamination by synthetic fibers, possibly from electronic waste. Conversely, in the Paranaguá Estuarine Complex, Mengatto & Nagai (2022) analyzed sediments at various sites (Figure 5D) and found that areas near ports exhibited the highest concentrations of plastic debris. In the Anavilhanas National Park, Rico et al. (2023) demonstrated a heterogeneous distribution of MPs in the samples, with higher concentrations in regions with low water velocity, reinforcing the influence of hydraulic characteristics on MP deposition.

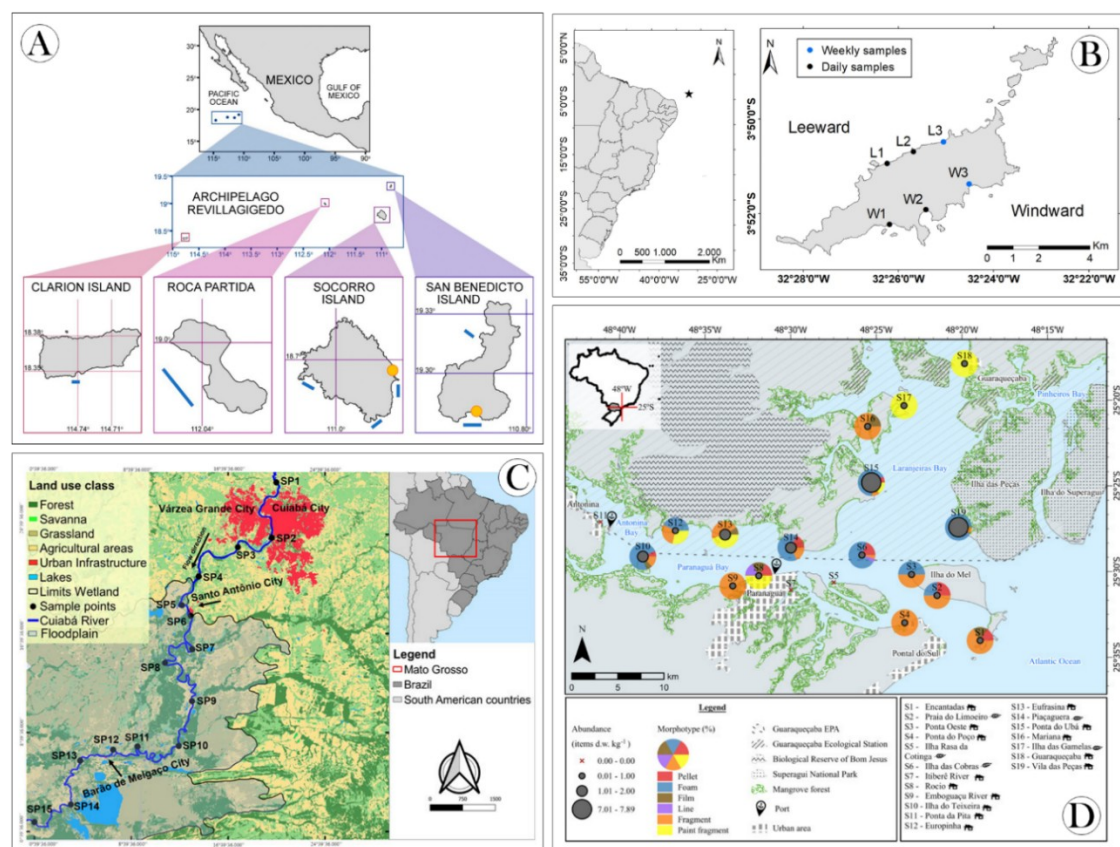


Figure 5. Geographical distribution and sampling sites across diverse ecosystems. (A) Map of the Revillagigedo Archipelago, with yellow dots indicating sampling sites on the beaches. This figure is reprinted from Pelamatti et al. (2021) with permission from Elsevier (License ID: 1564933, Copyright © 2021 Elsevier BV). (B) Location of the Fernando de Noronha Archipelago (black star) in the Western Tropical Atlantic (left panel) and surveyed beaches on the main island (right panel). This figure is reprinted from Carvalho et al. (2021) with permission from Elsevier (License ID: 1564937, Copyright © 2021 Elsevier BV). (C) Map of the Cuiabá River, showing sampling sites and the main land-use patterns. Sites 1 to 4 are situated on the Plateau highlands, while sites 5 to 15 are located on the Pantanal floodplain lowlands. This figure is reprinted from Camargo et al. (2022) and is licensed under CC BY 4.0. (D) Map of the Paranaguá Estuarine Complex, detailing this study's sampling sites along with beach names. This figure is reprinted from Mengatto & Nagai (2022) with permission from Elsevier (License ID: 1564939, Copyright © 2022 Elsevier BV).

Note: In (A), blue lines indicate floating plastics sampling transects. In (B), black and blue dots represent beaches where daily and weekly samples were collected, respectively. In (C), the black line marks the boundary between the Plateau and the Floodplain, with the shaded region to the west representing the floodplain (wetlands). The Cuiabá River flows from northeast to southwest, and sampling sites are denoted as "Sp." In (D), gray circle sizes illustrate microplastic (MP) abundance (items d.w./kg), while pie charts depict the proportions of MP morphotypes. Urban areas are shown as square texture polygons, and the Paranaguá and Antonina ports are indicated by anchor symbols. The Guaraqueçaba Environmental Protected Area is represented by diagonal lines, with stronger diagonal lines denoting the Guaraqueçaba Ecological Station. The Biological Reserve of Bom Jesus is shown as a zigzag polygon, and the Superagui National Park is marked by a dotted polygon. House and leaf symbols differentiate urbanized and non-urbanized beaches, respectively.

Table 3. Summary of studies involving the identification, quantification, and/or characterization of microplastics in environmental matrices conducted in UNESCO Natural Heritage Sites located in the Americas.

UNESCO Natural World Heritage Sites studied	Countries	Type of sample analyzed	Microplastic concentrations	References
Atlantic Forest South-East Reserves	Brazil	Sediments	0 to 7.9 items/kg, 0 to 188.4 items/m ² or 0 to 15074.3 items/m ³	Mengatto & Nagai (2022)
Brazilian Atlantic Islands: Fernando de Noronha and Atol das Rocas Reserves	Brazil	Surface seawater through neustonic plankton samples collected using a manta trawl	0.015 particles/m ³	Ivar do Sul et al. (2014)
Brazilian Atlantic Islands: Fernando de Noronha and Atol das Rocas Reserves	Brazil	Sand	Windward beach: 4.6×10^{-3} g of marine debris/g sand, with 39% being microplastics (2–5 mm), and leeward beach: 0.3×10^{-3} g of marine debris/g sand, with 100% of the debris being plastic fragments, 39% of which were microplastics (2–5 mm)	Ivar do Sul et al. (2009)
Brazilian Atlantic Islands: Fernando de Noronha and Atol das Rocas Reserves	Brazil	Sand	Windward beach: 160.0 ± 137.5 particles/m ² of small microplastics (SMP), predominantly synthetic fibers, and leeward beach: 128.0 ± 84.3 particles/m ² , with no statistical differences in SMP abundance or types between the two groups	Monteiro et al. (2020)

			of beaches		
Brazilian Atlantic Islands: Fernando de Noronha and Atol das Rocas Reserves	Brazil	Sand	0.6 ± 2.5 particles/m ² to 1059.3 ± 1385.6 particles/km ²	Carvalho et al. (2021)	
Cocos Island National Park	Costa Rica	Sediment (marine and freshwater)	3.35 ± 4.30 MPs/sample (marine sediment) and 1.00 ± 1.47 MPs/sample (freshwater sediment)	Pérez et al. (2022)	
Central Amazon Conservation Complex	Brazil	Surface freshwater	Average: 6.5 MPs/m ³ and 0.015 mg/m ³	Rico et al. (2023)	
Galapagos Island	Ecuador	Sand, benthic sediments, and surface seawater	Sand: 0 to 448.8 particles/m ² or 0 to 74.6 particles/kg; benthic sediments: 6.7 to 86.7 particles/kg; and surface seawater: 0.04 to 0.89 particles/m ³	Jones et al. (2021)	
Galapagos Island	Ecuador	Sand	0 to 2524 particles/m ² (average: 381 particles/m ²)	Jones et al. (2022)	
Galapagos Island	Ecuador	Surface seawater	The average concentration was 11.5 ± 1.48 particles/L from grab sampling and 19.8 ± 1.86 particles/L when anthropogenic cellulose particles were included	Deakin et al. (2024)	
Galapagos Island	Ecuador	Sand	5.29 ± 9.16 to 106767.6 ± 127975.9 items/kg	Sánchez-García &	

			(average: 7185.673 items/kg)	Sanz-Lázaro (2023)
Pantanal Conservation Area	Brazil	Sediments	576.8 ± 577.8 items/m ²	Camargo et al. (2022)
Pantanal Conservation Area	Brazil	Surface freshwater	1 to 31 MPs/100L or 0.01 to 0.31 MPs/L (average: 9.6 ± 8.3 MPs/100L or 0.096 ± 0.083 MPs/L)	De-Faria et al. (2021)
Revillagigedo Archipelago	Mexico	Surface seawater	0.031 ± 0.030 plastic pieces/m ³ or 4.768 ± 4.490 plastic pieces/1000 m ² (or 4768000 ± 4490000 plastic pieces/km ²) - 73% of plastic pieces were MPs (<5 mm)	Pelamatti et al. (2021)

1.4.2.2.2. Studies conducted in Europe

In European regions, seven studies were conducted across four UNESCO Natural Heritage Sites, analyzing the identification, quantification, and/or characterization of MPs in various environmental matrices. These areas include the Danube Delta, one of Europe's largest and best-preserved wetlands (Pojar et al., 2021a; Pojar et al., 2021b); the Aeolian Islands in Italy, a volcanic archipelago renowned for its unique geological values and scenic beauty (Sabatino et al., 2024; Fastelli et al., 2016; Coccozza et al., 2024); the Wadden Sea in the Netherlands, the largest continuous tidal area in the world (Materić et al., 2022); and the Ilulissat Icefjord in Greenland (Denmark), a major iceberg calving area and symbol of global climate change (Parga-Martínez et al., 2024) (Table 4).

In the Danube Delta, the studies by Pojar et al. (2021a) and Pojar et al. (2021b) are noteworthy. In the first study, the authors reported MP concentrations ranging from 16.1 to 18.6 particles/m³ in estuarine surface waters collected at two delta locations (samples SU01 and SG01). In the second study, Pojar et al. (2021b) conducted a comprehensive analysis of MP concentrations in sediments across various delta sites, with values ranging from <24 particles/kg in relatively pristine areas, such as the Sf. Gheorghe distributary, to 381 particles/kg in lake- connecting channels, highlighting the role of hydrodynamic processes in MP deposition. In the Wadden Sea, Materić et al. (2022) used laser absorption spectrometry to monitor ultrafine MPs (<10 µm), revealing surface water concentrations ranging from 0.1 to 2.8 µg/L for polyethylene terephthalate (PET) and 0.1 to 0.6 µg/L for polystyrene (PS). The authors also noted the presence of wind-transported MPs and emphasized the contribution of local and regional sources to coastal deposition. In the Aeolian Archipelago, Sabatino et al. (2024) conducted research on the islands of Lipari, Vulcano, Salina, Panarea, and Stromboli, located in the central and western sectors of the archipelago (Figures 6A-G). The authors investigated the distribution and composition of plastic pellets in beach sand samples, using visual inspection and FTIR analysis to identify the physical properties and polymeric composition of the debris. The results revealed high contamination, with 80% of the pellets composed of polyethylene (PE) and 20% of polypropylene (PP). In contrast, the study by Parga-Martínez et al. (2024), conducted in Disko Bay, Greenland (Figure 6H), employed a paleoceanographic approach to reconstruct MP accumulation in glacial sediments over 85 years, based on a sediment core dated to 1930 ± 2. Through Fourier-transform infrared spectroscopy coupled with microscopy (µFTIR), the authors identified concentrations ranging from 987 to 16,645 particles/kg in sizes up to 20 µm, spanning eight polymer types, with PE (47%) and PP (32%) being predominant. Additionally, the study revealed a significant increase in MP accumulation after 1950, coinciding with regional socioeconomic development, suggesting the influence of local anthropogenic pressures.

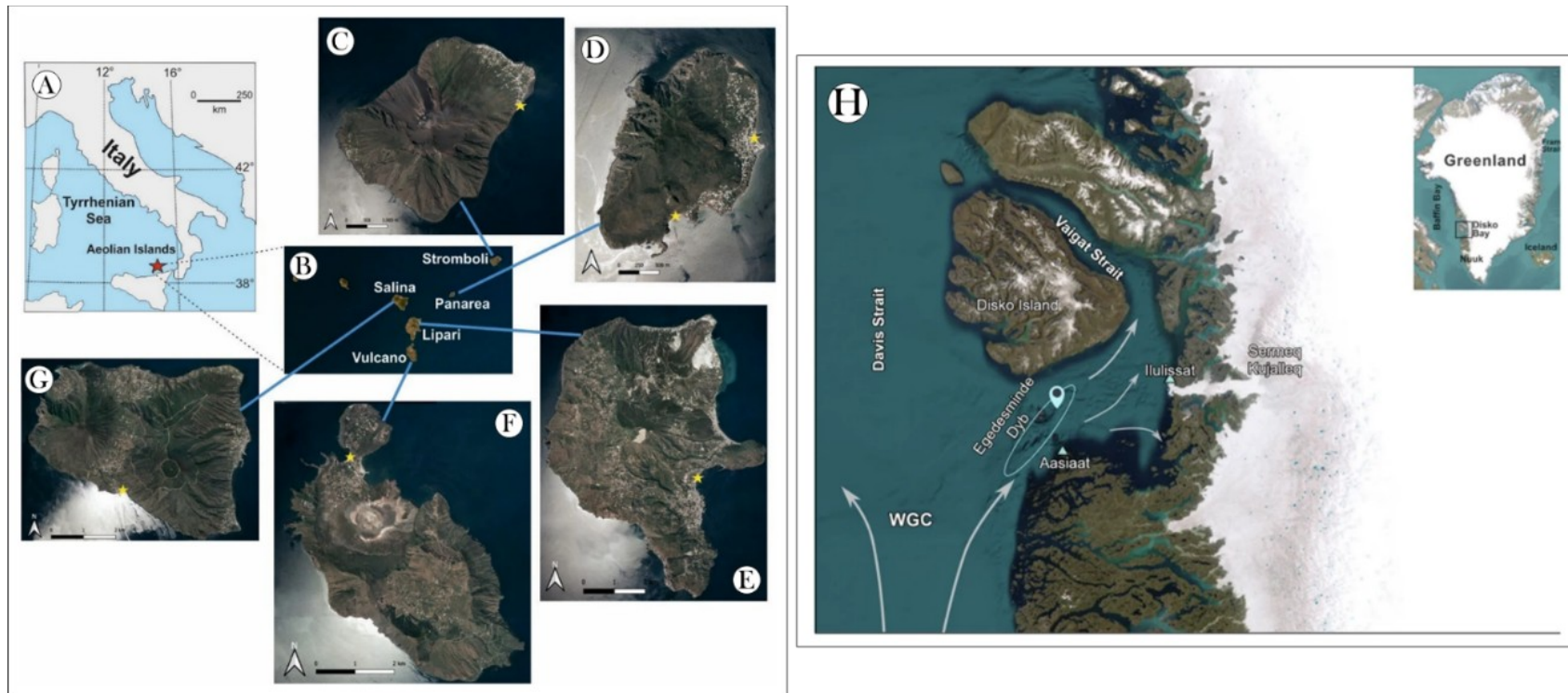


Figure 6. Geographical distribution of sampling sites across the Aeolian Islands and Disko Bay. (A) Map depicting the location of the Aeolian Islands (indicated by the red star) in the Tyrrhenian Sea, Mediterranean. (B) Detailed map of the Aeolian Archipelago with individual islands labeled. (C–G) Specific maps highlighting Stromboli (C), Panarea (D), Lipari (E), Vulcano (F), and Salina (G). These figures are reprinted from Sabatino et al. (2024) and are licensed under CC BY 4.0. (H) Map of Disko Bay, indicating the sampling site at Egedesminde Dyb. Two major settlements in Greenland, Aasiaat and Ilulissat, are marked with blue triangles. This figure is reprinted from Parga-Martínez et al. (2024) and is licensed under CC BY 4.0.

Note: In (A to G), yellow stars on the island maps denote the sampling sites for plastic pellets analyzed in this study. In (H), the fast-flowing glacier *Sermeq Kujalleq* channels meltwater from the Greenland Ice Sheet through the Ilulissat Icefjord. The schematic route of the West Greenland Current (WGC) is depicted with gray arrows.

Table 4. Summary of studies involving the identification, quantification, and/or characterization of microplastics in environmental matrices conducted in UNESCO Natural Heritage Sites located in Europe.

UNESCO Natural World Heritage Sites studied	Countries	Type of sample analyzed	Microplastic concentrations	References
Danube Delta	Romania and Ukraine	Surface estuarine water	16.1 to 18.6 MPs/m ³	Pojar et al. (2021a)
Danube Delta	Romania and Ukraine	Sediments	Microplastic concentrations ranged from ~165 particles/kg at the bifurcation of the Sulina and Sf. Gheorghe distributaries, <24 particles/kg in the Sf. Gheorghe distributary and Rosu Lake, 381 particles/kg in the channel to Rosu Lake (highest concentration), <59 particles/kg upstream of Sulina town, 148 particles/kg in lake sediments north of the Sulina distributary, and <40 particles/kg in the channel to Fortuna Lake.	Pojar et al. (2021b)
Aeolian Islands	Italy	Sand	Panarea-Porto: 30 pellets/m ² ; Vulcano: 40 pellets/m ² ; Salina, Stromboli, and Lipari: 20, 30, and 40 pellets/m ² , respectively	Sabatino et al. (2024)
Aeolian Islands	Italy	Sand	151.0 ± 34.0 to 678.7 ± 345.8 particles/kg (average: 371.7 particles/kg)	Fastelli et al. (2016)
Aeolian Islands	Italy	Sand	0.27 particles/kg to 1.35 particles/kg	Cocozza et al. (2024)

Wadden Sea	Netherlands	Surface seawater	PET: 0.1 to 2.8 µg/L and OS: 0.1 to 0.6 µg/L (ultrafine microplastics)	Materić et al. (2022)
Ilulissat Icefjord	Denmark	Glacimarine sediment	987.4 and 16645 particles/kg (average: 4272.3 ± 3854.4 particles/kg) and the estimated mass ranged between 0.03 and 0.685 mg/kg	Parga-Martínez et al. (2024)

1.4.2.2.3. Studies conducted in Africa

In Africa, only four studies have been conducted in UNESCO Natural Heritage Sites (Table 5). In the iSimangaliso Wetland Park, particularly in the St. Lucia Estuary, Govender et al. (2020) evaluated MP concentrations in estuarine water and mangrove sediments. The average concentration of MPs in surface water was 11.9 ± 11.2 particles per 10,000 liters, while in sediments it was 18.5 ± 34.4 MPs per 500 g, with smaller particles (20 to 100 μm) comprising 45% of the MPs found in sediments. The St. Lucia system was the least impacted among the four estuaries studied, with a total disturbance score (TDS) of 10, compared to other urban estuaries where TDS ranged from 18 to 23. In Tunisia's Ichkeul National Park, Jaouani et al. (2022) investigated the distribution of macro-, meso-, and MPs in sediments across a continuum that included the beach, lagoon, and lake. Their findings revealed that Lake Ichkeul had an average of 130.55 ± 65.61 items/kg of sediment across all seasons (Table 5). Chemical analysis identified fragments of common polymers such as PE, PP, and PET, all $<300 \mu\text{m}$, indicating a predominance of secondary particles. The study also highlighted that contamination levels showed no significant variation between seasons, suggesting continuous pollution.

On the other hand, Dithlakanyane et al. (2022), while evaluating surface water samples at 156 collection points across five sites in the river system of the Okavango Delta, observed that MP loads ranged from $138.18 \mu\text{g}/\text{m}^3$ to $381.67 \mu\text{g}/\text{m}^3$, while abundance fluctuated between 10.18 and 22.67 particles/L. The highest MP weight was recorded at site 4, located in the Moremi Reserve, an area with intense tourist activity, whereas the lowest load was observed at the end of the Panhandle channel (site 2) (Figure 7A). Meanwhile, in Teide National Park, Villanova-Solano et al. (2023) conducted a study on MP contamination in snow samples collected after two intense storms that hit the Canary Islands in 2021. The collections were carried out in three types of areas: “accessible” sites, characterized by high visitor traffic and intense recreational activity; “pristine” areas, showing no recent signs of human activity; and “climbing” zones, located at altitudes above 3,000 m, with access restricted to mountaineers (Figure 7B). A total of 63 samples were analyzed, revealing the presence of MPs in all locations. In pristine areas, the average concentration was 51 ± 72 items/L, while areas with prior anthropogenic activity showed higher concentrations, with 167 ± 104 items/L in accessible areas and 188 ± 164 items/L in climbing zones.

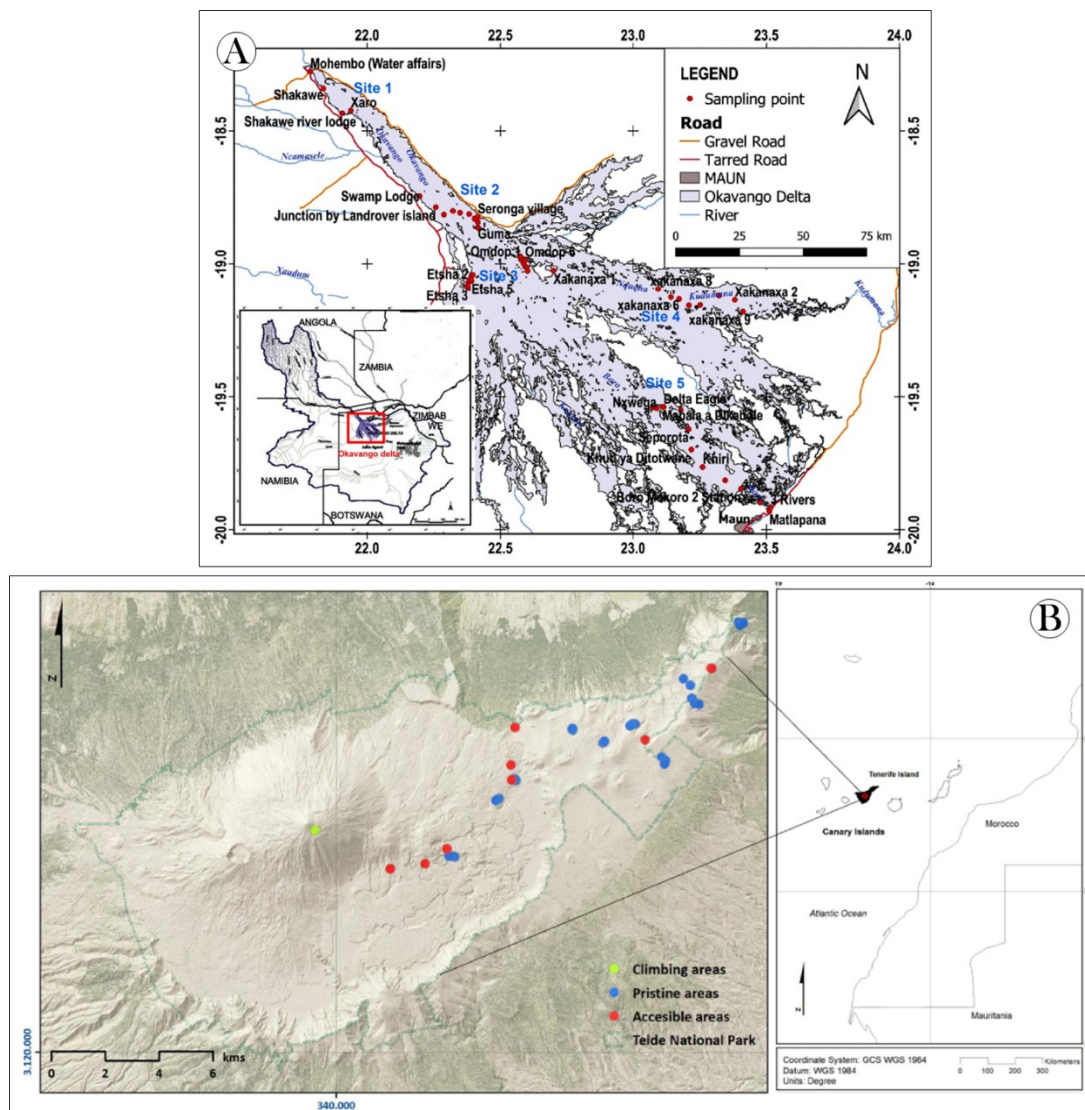


Figure 7. Geographical locations of sampling areas in the Okavango Delta and Teide National Park. (A) Map of the study area showing the location of sampling points across different sites within the river system of the Okavango Delta, Botswana. This figure is reprinted from Ditlhakanyane et al. (2022) and is licensed under CC BY 4.0. (B) Map indicating the snow sampling zones within Teide National Park (Tenerife, Canary Islands, Spain) following the two snowfalls of 2021. Snow samples were collected exclusively from areas where snow was present, limited to the highlighted zones. Certain points on the map represent multiple sampling locations. This figure is reprinted from Villanova-Solano et al. (2023) and is licensed under CC BY 4.0.

1.4.2.2.4. Studies conducted in Oceania

In Oceania, three studies were conducted to identify, quantify, and classify MPs in marine surface water samples from various areas of the Great Barrier Reef (GBR), Australia (Table 5). The study by Jensen et al. (2019) revealed widespread contamination in the surface waters of the central GBR, with microfibers accounting for 86% of the marine debris detected. Additionally, the authors investigated potential sources and transport routes of marine microdebris through numerical simulations using passive tracers and virtual trajectories. In a six-month simulation (up to August 1, 2016), which included

22 sampling points, the plumes of seven rivers discharging into the central GBR remained confined to the coastal zone and did not reach the offshore reefs, including the 11 oceanic sampling points (Figure 8A). According to the authors, this suggests that the microdebris detected in the coastal reefs may originate from coastal rivers, whereas those found in offshore areas have no direct association with these fluvial sources during the study period. A 30-day transport simulation using "virtual drogues" released at inshore and offshore points (Figures 8B-D) supported this hypothesis. Particles simulated at inshore points exhibited cohesive advection northward, while those released at offshore points dispersed more chaotically and broadly. At no point did the trajectories of inshore particles cross the central lagoon to reach offshore points, indicating that the microdebris detected in oceanic areas does not originate from coastal waters during the simulated period, highlighting the complexity of pollutant transport dynamics in the central GBR region.

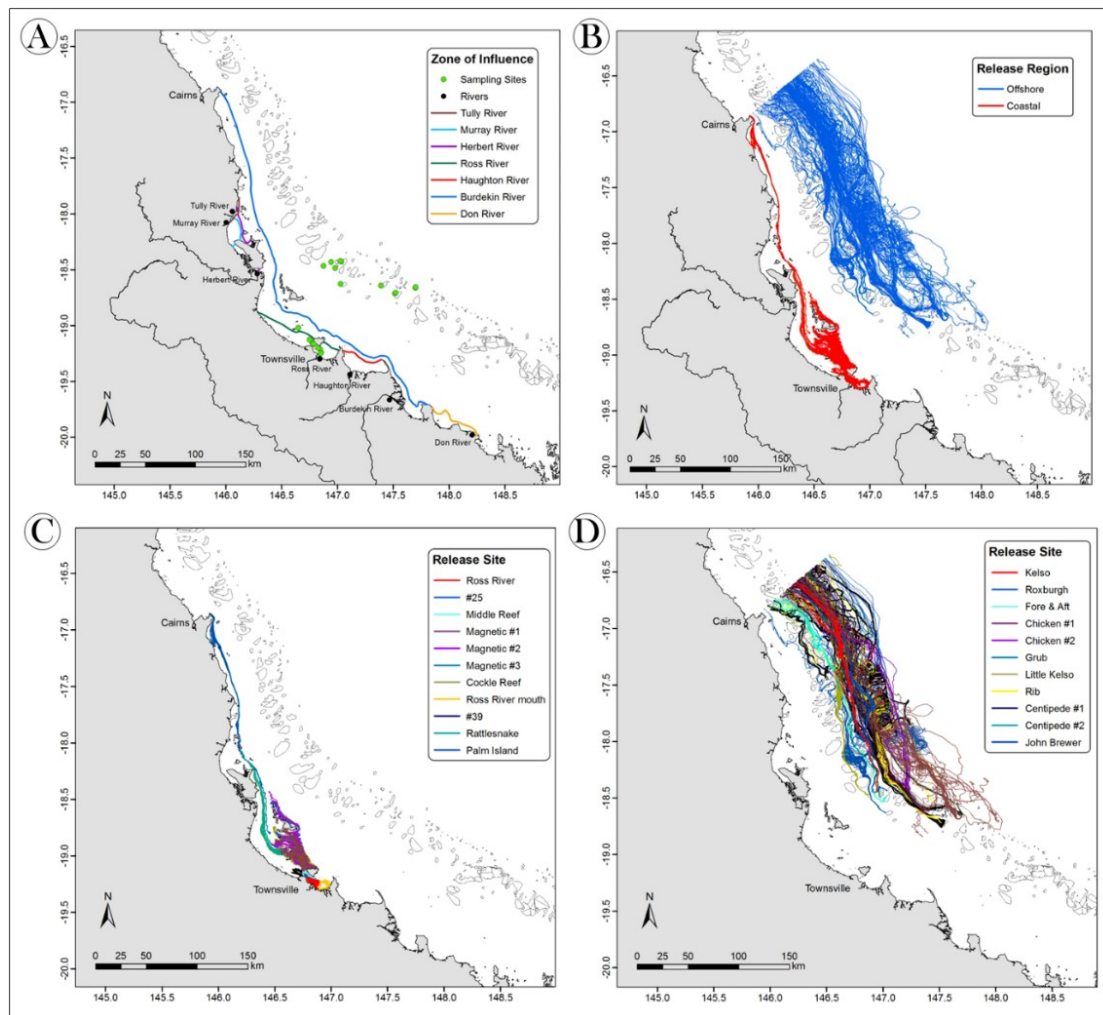


Figure 8. Numerical simulations and virtual drogue trajectories of floating marine microdebris. **(A-B)** Numerical simulations of the source, transport, and fate of floating marine microdebris. Panel **(A)** illustrates river discharge as a potential source of floating marine microdebris detected at the 22 sampling locations, using passive tracers. Panel **(B)** demonstrates potential transport pathways and the fate of microdebris using virtual drogues. In **(A)**, black circles mark the discharge points of seven individual rivers, and green circles represent the 22 sampling locations. Different colors depict the

flood plume extents of individual rivers over a six-month simulation period ending on 01 August 2016. In **(B)**, red trajectories correspond to virtual drogues released at 11 inshore reef locations, while blue trajectories represent those released at 11 offshore reef locations. To enhance visual clarity, only every second release (i.e., every two minutes) is shown. The cessation of trajectories (depicted as a straight line) indicates when the drogues leave the numerical domain. **(C-D)** Thirty-day trajectories of virtual drogues released at the 22 sampling locations within the central Great Barrier Reef. Panel **(C)** represents inshore regions ($n=11$), while panel **(D)** depicts offshore regions ($n=11$). Similar to **(B)**, only every second release is displayed to prevent overexposure and enhance visual definition. The cessation of trajectories, observed as straight lines, signifies the departure of drogues from the numerical domain. Reprinted from Jensen et al. (2019), licensed under CC BY 4.0.

Miller et al. (2022) conducted a pioneering temporal assessment of plastic contamination in the surface waters of the SS Yongala shipwreck (central GBR) between 2016 and 2019, recording the presence of MPs in nearly all trawls, with an average concentration of 0.13 ± 0.17 particles/ m^3 . Polymers such as PP and PE were predominant, and contamination peaks occurred every three months, influenced by factors such as wind speed and river discharges, but not by sea surface temperature. The study emphasized the importance of continuous monitoring to understand the variations and impacts of this type of pollution over time. Similarly, Carbery et al. (2022) focused on analyzing MPs ranging in size from $50 \mu m$ to $300 \mu m$ in the waters surrounding the Whitsunday Islands, demonstrating that MPs were present in all samples, with an average concentration of 0.23 ± 0.03 particles/ m^3 (Figure 9). The most abundant MPs were fibers and fragments in blue, transparent, and black colors, primarily composed of PET, high-density polyethylene (HDPE), and polypropylene (PP). Additionally, the authors identified tourism and recreational activities as major sources of MPs in the region, highlighting the urgency of mitigation policies to protect this globally significant ecosystem.

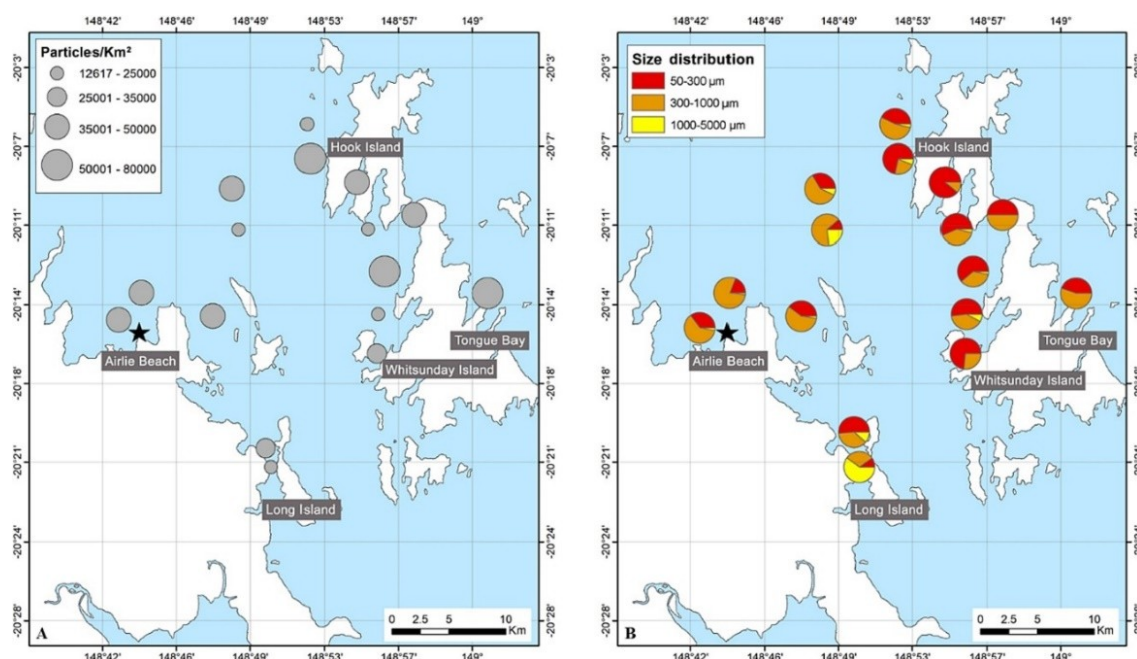


Figure 9. Abundance, distribution, and size variation of microdebris in surface waters of the Whitsunday Islands. (A) Map illustrating the abundance and distribution of microdebris across the sampling sites. **(B)** Map detailing the size distribution of microdebris observed in the collected samples. These maps provide critical insights into the spatial variability of microdebris pollution, highlighting the extent and characteristics of contamination within the study region. Reprinted from Carbery et al. (2022), with permission from Elsevier (License ID: 1565006, Copyright © 2022 Elsevier BV).

Table5. Summary of studies involving the identification, quantification, and/or characterization of microplastics in environmental matrices conducted in UNESCO Natural Heritage Sites located in Africa and Oceania.

UNESCO Natural World Heritage Sites studied	Countries	Type of sample analyzed	Microplastic concentrations	References
iSimangaliso Wetland Park	South Africa	Surface estuarine water and sediments	Surface estuarine water: 11.9 ± 11.2 MPs/10000L or 0.00119 ± 0.00112 MPs/L. Sediments: 18.5 ± 34.4 MPs/500 g or $37 \pm 68,8$ MPs/kg	Govender et al. (2020)
Ichkeul National Park	Tunisia	Sediments	134.16 ± 68.88 items/kg	Jaouani et al. (2022)
Teide National Park	Spain	Snow	Samples collected in pristine areas: 51 ± 72 items/L; previous anthropogenic activity: 167 ± 104 and 188 ± 164 items/L in “accessible areas” and “climbing areas”, respectively	Villanova-Solano et al. (2023)
Okavango Delta	Botswana	Surface water	138.18 to 381.67 $\mu\text{g}/\text{m}^3$	Ditlhakanyane et al. (2022)
Great Barrier Reef	Australia	Surface seawater	0.13 ± 0.17 plastics/ m^3 or 0.005 ± 0.004 plastics/km)	Miller et al. (2022)
Great Barrier Reef	Australia	Surface seawater	0.23 ± 0.03 particles/ m^3	Carbery et al.

				(2022)
Great Barrier Reef	Australia	Surface seawater	For surface waters, median concentration of total marine microdebris (fibres and particles) was almost double around offshore reefs (median = 0.25/m ³ , range 0.05–0.47/m ³) compared to inshore reefs (median = 0.12/ m ³ , range 0.04–0.26/m ³)	Jensen et al. (2019)

1.4.2.2.5. Studies conducted in Asia

In Asian regions, several studies were conducted across eight UNESCO Natural Heritage Sites, addressing the identification, quantification, and characterization of MPs in various environmental compartments (Table 6). These areas include Komodo National Park in Indonesia, known for its marine ecosystems rich in biodiversity (Germanov et al., 2019); the Sundarbans, spanning Bangladesh and India, the world's largest mangrove forest and an important nursery for numerous species (Nawar et al., 2023; Das et al., 2023; Neelavannan et al., 2023; Fatema et al., 2023); Lake Baikal in Russia, the largest freshwater lake by volume and a unique ecosystem (Karnaukhov et al., 2020; Il'ina et al., 2021; Moore et al., 2022; Karnaukhov et al., 2022); the Western Ghats in India, recognized as a biodiversity hotspot (Amrutha et al., 2023); Shiretoko in Japan, home to rare and endangered species in its marine and terrestrial ecosystems (Ohno & Iizuka, 2023; Ohno & Iizuka, 2024); the China Danxia region in China, famed for its unique geological formations (Li et al., 2024); and the scenic valleys of Jiuzhaigou and Huanglong in China, renowned for their mountainous landscapes, crystal-clear lakes, and stunning waterfalls (Zeng et al., 2024).

In the study by Germanov et al. (2019), the abundance and characterization of plastics were assessed in feeding areas of large filter feeders, such as reef manta rays (*Mobula alfredi*) and whale sharks (*Rhincodon typus*), across three coastal sites in Indonesia: Nusa Penida Marine Protected Area, Komodo National Park, and Pantai Bentar in East Java. MP concentrations ranged from 0.04 to 0.90 particles/m³ in plankton net collections and from 210 to 40,440 particles/km² in visual observations, with marked seasonality and greater abundance during the wet season. Furthermore, using theoretical calculations, the authors estimated ingestion rates of up to 63 particles/hour for manta rays and 137 particles/hour for whale sharks. In contrast, Ohno and Iizuka (2023) investigated MPs in snow samples from conservation areas and urban environments in Hokkaido, Japan, recording concentrations of 1.5×10^2 to 4.2×10^3 particles/L, predominantly fragmented particles measuring 30–60 µm, with polymer compositions attributed to long-distance atmospheric transport and local sources. In their subsequent study, Ohno and Iizuka (2024) analyzed sea ice cores from the southern Sea of Okhotsk, detecting MPs at concentrations ranging from 0 to 60 particles/L, with an average of 21 particles/L. Small fragments (<120 µm) were predominant, while fibers (>210 µm) were less frequent. The higher concentration in the lower ice layers was associated with more intense contamination in the underlying waters, highlighting the importance of investigating freezing and MP transport dynamics in polar and cold environments.

Among the studies conducted in The Sundarbans, the work by Neelavannan et al. (2023) stands out, investigating the sources, types, and pathways of MPs in water and sediment samples collected along the Hooghly River to the Sundarbans Biosphere Reserve (Figure 10). The results showed average concentrations of 718 ± 244 items/m³ in water and 428 ± 266 items/kg in sediment, with a predominance of polymers such as high-density polyethylene (33%), polyoxymethylene or

polyacetal (18%), polyphenylene sulfide (18%), and polyacrylamide (13%). These MPs were primarily sized between 0.3 mm and 90 μm in sediment and between 1 mm and 0.3 mm in water, suggesting a high degradation rate and identifying transport via the Hooghly River as a significant ecological risk factor for the region. In Lake Baikal, Karnaukhov et al. (2020) reported elevated MP concentrations in the water, reaching 1.065 billion particles/ km^3 , with fibers (53.08%) and fragments (43.39%) being the predominant forms. The study linked increased pollution levels to tourism in villages lacking waste treatment infrastructure, emphasizing the importance of control measures to preserve this natural heritage. Similarly, the study by Amrutha et al. (2023), conducted in the Western Ghats, India, explored spatial and temporal variations of MPs in sediments from the Sharavathi River, a region of high biodiversity. Concentrations ranged from 2.5 to 57.5 particles/kg during the pre-monsoon period and from 0 to 15 particles/kg post-monsoon, with fragments, films, foams, and fibers as the main categories. The study highlighted that the reduction of MPs after the monsoon is due to sediment transport to the Arabian Sea. Furthermore, the authors reported that the predominant polymers were PE, PET, and PP, and environmental risk indices (Load Index [PLI], Polymer Hazard Index [PHI], and Potential Ecological Risk Index [PERI]) indicated contamination levels ranging from moderate to high risk, underlining the need for mitigation actions given the ecological vulnerability of the area. Meanwhile, Li et al. (2024) investigated MP contamination in the Danxia formations of China, analyzing surface water, sediment, and groundwater in six cities and six counties. The results indicated a moderate level of MPs in urban rivers, with anthropogenic activities such as tourism and urban effluent discharge identified as major sources of pollution. Additionally, the authors observed a trend of MP accumulation in sediments along the river flow gradient, and cluster analysis suggested that MPs in groundwater are influenced by hydraulic interactions between surface and groundwater. The study revealed a high ecological risk in counties and a moderate risk in cities, reinforcing the importance of environmental preservation strategies in the urbanized landscapes of Danxia.

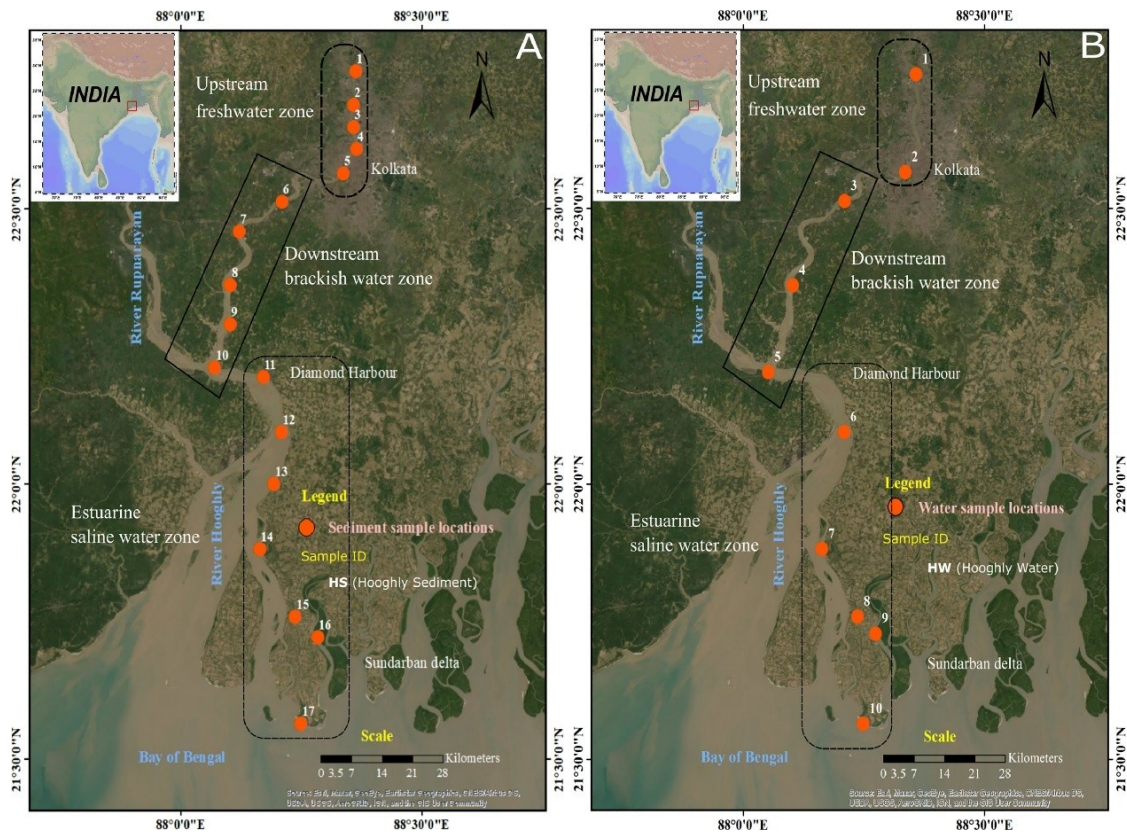


Figure 10. Sampling locations of sediments and water along the Hooghly River. (A) Map showing the sediment sampling locations. **(B)** Map depicting the water sampling locations. The black boxes indicate the different zones within the study area: the upstream freshwater zone (densely populated), the downstream brackish water zone, and the estuarine saline water zone (moderately populated). These zones reflect varying environmental and anthropogenic influences along the river continuum. Reprinted from Neelavannan et al. (2023), licensed under CC BY 4.0.

Table 6. Summary of studies involving identifying, quantifying, and/or characterizing microplastics in environmental matrices conducted in UNESCO Natural Heritage Sites in Asia.

UNESCO Natural World Heritage Sites studied	Countries	Type of sample analyzed	Microplastic concentrations	References
Komodo National Park	Indonesia	Surface water	0.04 to 0.90 pieces/m (trawl survey) and 210 to 40844 pieces/km ² (visual survey)	Germanov et al. (2019)
The Sundarbans	Bangladesh	Surface water and sediment	Surface water: 2.66×10^3 particles/L and sediment: 1.57×10^5 particles/kg.	Nawar et al. (2023)
The Sundarbans	India	Surface seawater, sand, and sediment	Seawater (0.175 ± 0.145 MP/L), sand (42 ± 15.03 MP/kg), sediment 67.63 ± 24.13 MP/kg)	Das et al. (2023)
Jiuzhaigou Valley Scenic	China	Microplastics	Huanglong and Jiuzhaigou regions: no quantification of microplastic concentrations; microbial community composition on MPs was evaluated.	Zeng et al. (2024)
Huanglong Scenic	China			
The Sundarbans	India	Surface water and sediments	Water (718 ± 244 items/m ³) and sediments (428 ± 266 items/kg)	Neelavannan et al. (2023)
The Sundarbans	Bangladesh	Surface water and sediments	Pre-monsoon sampling period (surface water: $81,056 \pm 808.5$ items/km ² , sediments: 47 ± 11 items/kg) and post-monsoon	Fatema et al. (2023)

			(surface water: $73,722 \pm 9096$ items/km ² , sediments: 41 ± 7 items/kg)	
Lake Baikal	Russia	Surface water	19000 to 75000 particles/km ² (average: 42000 particles/km ²)	Il'ina et al. (2021)
Lake Baikal	Russia	Surface water	291 ± 252 MPs/cm ³	Moore et al. (2022)
Lake Baikal	Russia	Surface water	1.065×10^9 partículas/km ³	Karnaukhov et al. (2020)
Lake Baikal	Russia	Surface water	MP fibers - the upper side of the ice: 55.5 particles/L and MPs fragments in the upper samples: 0.3 particles/L, and for the lower samples: 1 particle/L	Karnaukhov et al. (2022)
Western Ghats	India	Riverine sediments	2.5 to 57.5 pieces/kg and 0 to 15 pieces/kg during the pre-monsoon and post-monsoon seasons, respectively	Amrutha et al. (2023)
Shiretoko	Japan	Snow	1.5×10^2 to 4.2×10^3 particles/L	Ohno & Iizuka (2023)
Shiretoko	Japan	Sea-ice cores	0 to 60 particles/L	Ohno & Iizuka (2024)
China Danxia	China	Surface water, sediment, and groundwater	Surface water (averaging 11.2 items/L), sediments (average of 343.9 items/kg), and groundwater (average of 2.2 items/L)	Li et al. (2024)

1.4.3. Studies involving the transport and dispersion of microplastics

In studies investigating the transport and dispersion of MPs, in addition to Jensen et al. (2019), discussed in section 3.3.2.4, two other investigations addressed the dynamics of these particles in marine ecosystems (Van Sebille et al., 2019; McMullen et al., 2024). These studies explored oceanic trajectories of MPs and their bioaccumulation impacts within the marine food web, contributing to the understanding of dispersion routes and ecological implications of this pollution in remote regions. Van Sebille et al. (2019) examined the sources and pathways of MPs arriving at the Galápagos Archipelago using high-resolution numerical models of ocean surface currents and virtual particle tracking. The results revealed that the main contributors to MP pollution in the region are currents originating from Peru, Ecuador, and, to a lesser extent, Colombia, carrying waste from fishing activities and South American coasts. In the "Origin from Galápagos" scenario, particle trajectories primarily concentrated in the eastern tropical Pacific, following the South American coastline and influenced by the Antarctic Circumpolar Current (Figure 11A-B), emphasizing the role of ocean currents in the dispersion of MPs to distant regions.

Conversely, McMullen et al. (2024) employed the Ecopath with Ecosim (EwE) ecosystem modeling tool with the Ecotracer module to simulate the bioaccumulation and biomagnification of MPs in the food web of Galápagos penguins (*Spheniscus mendiculus*). The initial simulation results indicated a rapid increase in MP concentration (g) per biomass (kg) up to approximately the fifth year, followed by slower growth until reaching a steady state around year 60 (Figure 11C). At this equilibrium, the MP concentration in penguins stabilized at 7.6×10^{-5} g/kg, while in plankton-feeding fish, the penguins' primary prey, the steady-state value was 4.93×10^{-8} g/kg. Penguins exhibited the highest MP concentrations per biomass, followed by barracudas, anchovies, sardines, herrings, and salemas, along with predatory zooplankton. In contrast, functional groups at lower trophic levels displayed significantly lower MP concentrations. Additionally, the analysis revealed that the Trophic Magnification Factor (TMF) increased from 7.08 in the first year to 61.7 by the hundredth year (Figure 11D), indicating significant biomagnification throughout the food web.

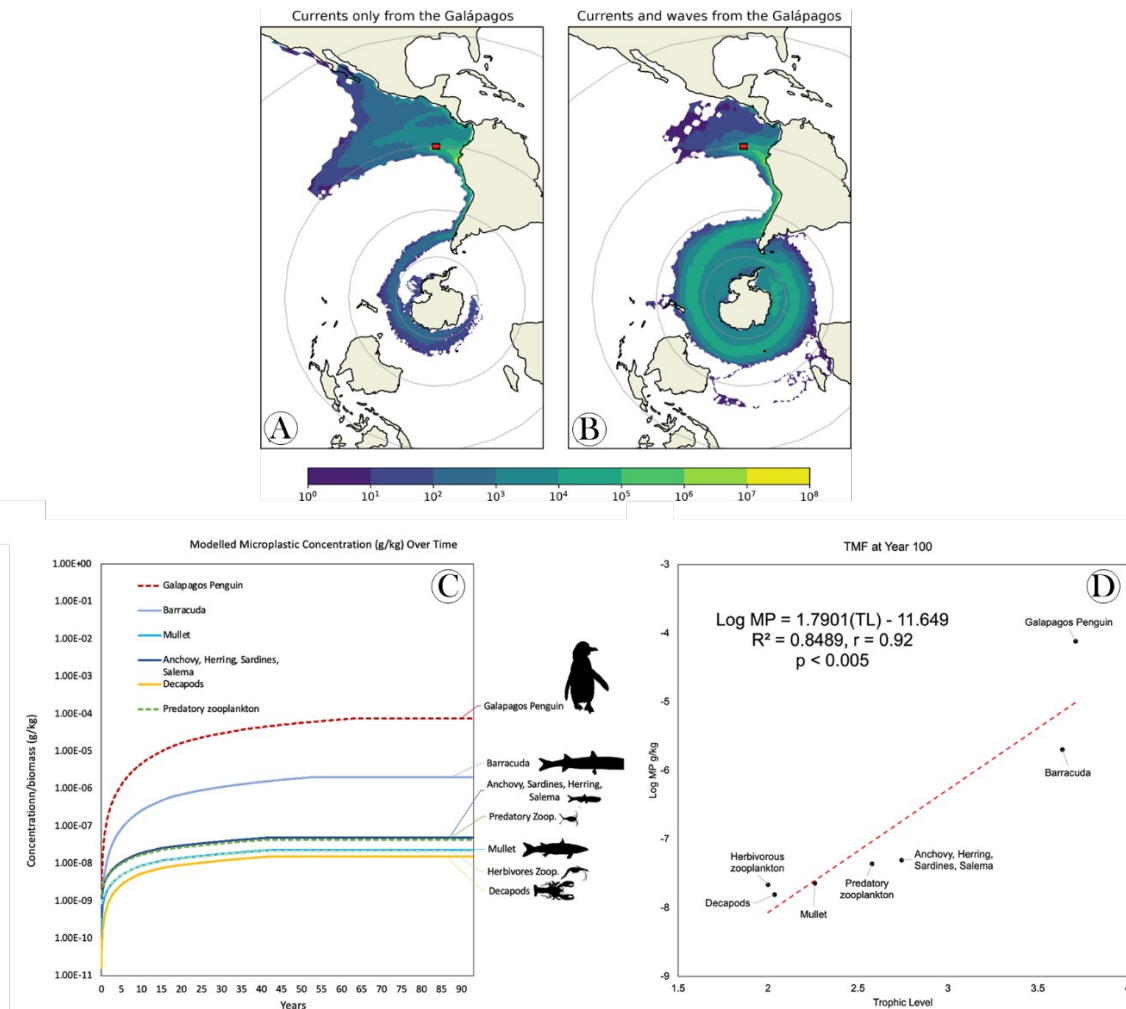


Figure 11. Simulations of particle trajectories and microplastic bioaccumulation in the galápagos region. **(A-B)** Maps from the "Origin from Galápagos" scenario illustrate the density of particle trajectories ending in the Galápagos region (red rectangle). **(A)** shows particle trajectories influenced by currents only, while **(B)** includes the influence of both currents and waves. The scale represents the number of particle crossings per $1^\circ \times 1^\circ$ grid cell on a logarithmic scale. Grey circles denote latitude bands at 60°S , 30°S , the Equator, and 30°N . Beaching is excluded from these simulations, and the maximum trajectory length is 10 years. Most particles remain within the eastern tropical Pacific Ocean or originate from the Southern Ocean. These figures are reprinted from Van Sebille et al. (2019) and licensed under CC BY 4.0. **(C-D)** Projections of microplastic (MP) bioaccumulation in the Galápagos penguin food web model over time and trophic levels. **(C)** Simulations using the Ecotracer routine in Ecopath with Ecosim (EwE) show the progression of MP concentrations under the baseline scenario with initial seawater concentrations of 0.00411 t/km^2 . The simulations incorporate elimination rates based on literature. **(D)** Linear regressions reveal a significant relationship between predicted MP concentrations (log-transformed data) and trophic levels in the Galápagos penguin model at year 100. The antilog of the regression slope was used to calculate the trophic magnification factor (TMF). These figures are reprinted from McMullen et al. (2024) and licensed under CC BY 4.0.

1.5. Discussion

The findings of this review highlight progress in understanding MP contamination in areas recognized as UNESCO World Natural Heritage Sites, emphasizing not only the ecological relevance of these ecosystems but also the growing scientific concern over the extent and impacts of this form of pollution in environments previously considered remote and protected. The increase in studies after 2019 reflects not only greater engagement from the scientific community – as pointed out by recent reviews [e.g., Fernandes et al. (2024) and Thompson et al. (2024)] – but also a response to mounting evidence that MPs can reach unimaginable regions, such as isolated mountains (Padha et al., 2022), polar regions (Mishra et al., 2021), deserts (Du et al., 2024), and inaccessible reefs (Rahman et al., 2023). This phenomenon underscores not just the ubiquity of MPs but also serves as a warning about the fragility of these areas and the complexity of their protection. Additionally, the growing volume of publications has revealed another important trend: a significant increase in the number of coauthors per study, indicating an expansion of interinstitutional and intercontinental collaborations. This movement reflects a push for more integrated and multidisciplinary approaches, aligning with studies conducted in regions beyond those recognized as UNESCO World Natural Heritage Sites [see review by Li et al. (2022)]. This shift is crucial, as investigating the impacts of MPs in ecosystems of high ecological value requires an interdisciplinary approach that brings together experts in oceanography, ecotoxicology, computational modeling, and environmental management, among other fields. Furthermore, the geographical diversity of UNESCO sites, distributed across continents with different socioeconomic realities and technological capacities, underscores the need for global collaborative networks to exchange knowledge, data, and technologies. Such partnerships can enhance the scientific understanding of MPs and support more effective conservation policies tailored to the specificities of each region, promoting integrated monitoring and mitigation strategies (Kumar et al., 2021).

On the other hand, the number of investigations into MP pollution in UNESCO World Natural Heritage Sites remains insufficient, covering only 26 of the 312 recognized sites. This disparity highlights alarming gaps, as many ecosystems of high vulnerability and biodiversity remain unexplored. Among the most studied sites are the Galápagos Archipelago, the Great Barrier Reef, Lake Baikal, and the Fernando de Noronha Archipelago (Table 1) – iconic regions notable not only for their ecological richness but also for their global conservation importance. The Galápagos Archipelago, for example, as highlighted by Hennessy (2018), is one of the world's leading natural laboratories due to its geographical isolation and the presence of endemic species such as the giant tortoise *Chelonoidis porteri* (Hennessy, 2020). However, the growth of tourism and increased maritime traffic have intensified plastic waste accumulation in the region, resulting in high MP concentrations in beach sediments [$106,767.6 \pm 127,975.9$ items/kg (Table 3 – Sánchez-García & Sanz-Lázaro (2023))], exceeding those reported in highly urbanized and anthropized areas such as the Arabian Sea coast and Bay of Bengal (220 ± 50 items/kg) (Tiwari et al., 2019), the southern coast of Brazil (1,000 to 1,500 items/kg) (Pelegrini et al., 2024), or regions with seasonal anthropogenic influence

due to tourism, such as the Datça Peninsula in Turkey ($1,154.4 \pm 700.3$ items/kg) (Yabanlı et al., 2019), where the population can quadruple during the summer.

Similarly, in the Great Barrier Reef, Australia – the largest reef system in the world, which also functions as a crucial climate regulator and nursery for marine species (Richards & Day, 2018) – MP concentrations reported in individuals of *Pomacentrus moluccensis* (median of 4.0 to 4.5 items/fish, Jensen et al., 2019) (Table 2), a keystone species in reef ecosystems (Chaves et al., 2021), were up to four times higher than those recorded in fish caught in the Jamestown region, Ghana. In this area, where large quantities of urban waste are discharged into the sea via the Korle Lagoon, the observed concentrations were significantly lower [*Sardinella maderensis* (1.49 ± 1.48 items/fish), *Pseudupeneus prayensis* (1.26 ± 1.67 items/fish), *Decapterus rhonchus* (0.96 ± 1.05 items/fish), and *Pagellus bellottii* (0.94 ± 1.18 items/fish)] (Pappoe et al., 2022). Conversely, in Lake Baikal, the average concentrations reported in surface waters (42,000 particles/km² - Table 6) (Il'ina et al., 2021) were 677.78% and 106.91% higher, respectively, than those recorded in Lake Superior, in the Great Lakes region of the United States (5,400 particles/km²) (Eriksen et al., 2013), and in Lake Hovsgol, Mongolia (20,300 particles/km²) (Free et al., 2014). Similarly, the concentrations reported by Monteiro et al. (2020) in beach sediments of the Fernando de Noronha Archipelago, Brazil (windward beaches: 160.0 ± 137.5 particles/m²; leeward beaches: 128.0 ± 84.3 particles/m²), were significantly higher than those identified in sediments along the eastern coast of Rio de Janeiro State (20.8 ± 9.73 items/m² in summer and 110.6 ± 144.5 items/m² in winter) (Carvalho et al., 2024), a highly urbanized area with strong anthropogenic influence. These data demonstrate that, although protected and recognized by UNESCO as World Natural Heritage Sites, these areas are not free from MP pollution, underscoring the need to expand research into the vulnerability of these ecosystems to the potential impacts of these pollutants.

On the other hand, while progress is evident, the reviewed studies reveal significant limitations that must be addressed to improve future investigations, particularly in natural areas classified as UNESCO World Heritage Sites, where such gaps may severely compromise accurate assessments of MP pollution and the development of preservation strategies. One of the main barriers is the lack of standardization in collection and analysis methods, which hinders direct comparisons between studies conducted in different regions. Variations in sampling techniques, measurement units (e.g., particles/L, MPs/m², items/m³, MPs/individual, MPs/g of feces or organs, MPs/km² - Tables 2 to 6), and identification methods – ranging from visual identification via stereomicroscopy or optical microscopy [e.g., Carvalho et al. (2021) and Mengatto et al. (2022)], visual identification combined with FT-IR [e.g., Pelamatti et al. (2021) and Sabatino et al. (2024)], visual identification with Raman spectroscopy [e.g., Sánchez-García & Sanz-Lázaro (2023)], or Proton Transfer Reaction-Mass Spectrometry with Thermal Desorption (TD-PTR-MS) alone [e.g., MateriĆ et al. (2022)], to a combination of multiple techniques (optical microscopy, pyrolysis coupled with GC-MS, and FT-IR) [e.g., Pojar et al. (2021a)] – can result in underestimations or overestimations of MP

concentrations, making it impossible to identify global and regional patterns. This lack of uniformity becomes even more critical in remote and hard-to-reach areas, as it prevents data integration into long-term monitoring networks.

Moreover, except for the study by Materić et al. (2022), most of the reviewed studies focused on larger MPs, which, according to the guidelines of ISO/TR 21960:2020 (ISO, 2020), include particles between 100 and 5000 μm . This emphasis neglects smaller particles, which possess a greater capacity for penetration into biological tissues and can traverse physiological barriers, inducing even more severe biological effects in different species (Menichetti et al., 2024). Consequently, the lack of data on these smaller fractions limits understanding of the actual risks posed by contamination. Another challenge is the scarcity of longitudinal studies tracking seasonal variations and accumulation trends over the years, particularly in tropical and polar regions where climatic cycles directly influence the transport and deposition of MPs. Parga-Martínez et al. (2024) observed a more temporally focused approach, which reconstructed MP accumulation in glacial sediments over 85 years using a pioneering paleoceanographic approach, the first of its kind in studies involving UNESCO World Natural Heritage Sites. Without consistent temporal data, predicting long-term impacts and understanding cumulative effects on key species that perform critical functions in these ecosystems becomes unfeasible. Therefore, addressing these methodological and temporal gaps is essential for future studies to go beyond isolated descriptions and provide robust scientific evidence to support public policies and management actions aimed at conserving globally recognized areas of high ecological value.

Another important aspect missing from the reviewed studies concerns the investigation of potential anthropogenic sources and environmental factors often associated with plastic pollution patterns in protected natural environments. These factors include hydrodynamic and oceanographic conditions, water quality, morphological characteristics of different ecosystems (e.g., beaches, estuaries, lagoons, and rivers), population density, waste management practices, land use, and proximity to urban and industrial infrastructure. Such factors can influence the fragmentation, transport dynamics, and deposition of MPs in different environmental compartments, from water bodies to sediments and biota. Furthermore, these interactions may affect the spatial and temporal distribution of MPs and their degradation and toxicity potential, impacting fragile ecosystems of high global conservation significance. Among the analyzed works, the one that adopted an approach closest to a multidimensional perspective was Carvalho et al. (2021). In this study, the authors considered hydrodynamic and oceanographic factors, such as wind direction, wave height, and tidal regimes, in addition to the morphological characteristics of beaches, evaluating their influence on the distribution and deposition of MPs on protected and exposed beaches. However, the authors did not assess water quality, population density, and waste management aspects, which would have been important to understand better the contribution of local and remote anthropogenic sources to MP pollution in the Fernando de Noronha Archipelago.

Moreover, there is a critical lack of investigations into the association between MPs and emerging pollutants such as persistent organic pollutants (POPs) and heavy metals, which, as highlighted by Rafa et al. (2024), can be adsorbed onto MP surfaces, forming toxic complexes capable of amplifying ecotoxicological risks. The study by Pelamatti et al. (2021), conducted in various areas of the Revillagigedo Archipelago, was the only one to demonstrate the adsorption of organochlorine pesticides on plastic fragments, highlighting potential risks to filter-feeding megafauna and vulnerable endemic species. Research with this integrated approach is essential in any natural environment. However, it becomes even more critical in UNESCO World Heritage Sites due to emblematic species and unique ecosystem services. This underscores the urgency of expanding studies that combine environmental monitoring with field experimentation, providing a more comprehensive understanding of contamination processes and their impacts on protected areas where maintaining ecological integrity is a global priority.

Specifically regarding studies on wildlife contamination, although the reviewed works demonstrate assessments across a wide range of species, many exhibit critical gaps that compromise the robustness of their findings and limit a deeper understanding of MP contamination patterns. Among the main weaknesses are the small number of individuals collected, the concentration of sampling in a limited number of locations, and the absence of analyses that account for variations related to the size, sex, life stage, and ecological niche of the investigated species. For instance, in the study by Dithlakanyane et al. (2022), only 15 specimens of *Tilapia sparamanii* were analyzed across five sampling points in the Okavango Delta, an area covering approximately 2 million hectares (UNESCO, 2024), highlighting a limited sampling effort relative to the vast extent of the ecosystem. In Berr et al. (2020), although the authors investigated 90 seabird specimens in New Caledonia, South Pacific, distributed across 12 species, stomach content was analyzed in only a single individual in seven of these species, significantly constraining the analysis of intraspecific variability. Similarly, in the study by Dawson et al. (2022), conducted in the Great Barrier Reef, the average number of gastrointestinal tract samples evaluated across the four analyzed species—*Y. balloti*, *M. latisulcatus*, *P. leopardos*, and *L. calcarifer*—was less than 10. Furthermore, in Nawar et al. (2023), the authors assessed, on average, only 3.25 individuals per species among the eight species investigated. Additionally, our review highlights the need to expand evaluations that link the accumulation of MPs in organisms to potential biological damage, as exemplified by the approach in the study by Muñoz-Perez et al. (2024). In this study, conducted with 46 juvenile green turtles (*C. mydas*) in two Ecuadorian national parks (Galápagos and Machalilla), various health biomarkers were analyzed in association with MP accumulation in feces. Although 98% of the turtles evaluated were exposed to plastic pollution with vital signs within normal ranges, lymphocytes, monocytes, hematocrit, total protein, urea, glucose, and anion gap were significantly higher in turtles at greater risk of plastic contamination.

Finally, in the absence of biological evaluations combined with the identification and quantification of MPs, it would be important for future studies to broaden their analyses using assessment indices such as the Potential Ecological Risk Index (PERI), which was calculated only in the study by Amrutha et al. (2023). While this study did not evaluate MP contamination in organisms, determining the PERI was essential in identifying contamination hotspots and inferring potential ecotoxicological impacts in the river sediments of the Western Ghats. As discussed by Ni et al. (2025), such an index can quantify the potential risk of MPs with different polymeric compositions and toxicity levels, aiding in the prioritization of critical areas for mitigation and management. For this reason, the PERI has been widely used in various other studies that explore different environmental contexts and ecosystems, such as those by Wang et al. (2024), Suyamud et al. (2024), Bhaduri et al. (2025), Li et al. (2025), Go et al. (2025), and

Estherrani et al. (2025), reaffirming its relevance in the integrated analysis of ecological risks associated with MPs.

1.6. Final remarks: future directions and potential mitigation strategies

Aligned with the objectives of this review, the studies analyzed that demonstrate the presence of microplastics (MPs) in various UNESCO World Heritage Sites highlight a significant contradiction. Protected areas, renowned for their biodiversity and global ecological importance, are not immune to pollution by these contaminants. The presented evidence reveals that, despite formal protection, many of these sites are under considerable pressure due to atmospheric and maritime transport of MPs, intensive tourism activities, fishing practices, and riverine discharges. To ensure the conservation of these ecosystems, it is crucial to deepen investigations in already studied areas and to expand research into ecologically critical yet understudied regions, such as Sagarmatha National Park (Nepal), Lençóis Maranhenses (Brazil), the Grand Canyon (USA), Aldabra Atoll (Seychelles), Te Wāhipounamu (New Zealand), and the Serengeti (Tanzania). Like the sites discussed in the reviewed studies, these regions may reveal important patterns of MP contamination and specific vulnerabilities associated with environmental and anthropogenic pressures. Equally important is directing research efforts toward areas listed as UNESCO World Heritage Sites in Danger, which face critical environmental pressures but play a pivotal role in global biodiversity conservation. Notable examples include Manovo-Gounda St Floris National Park (Central African Republic), the Mount Nimba Strict Nature Reserve, spanning Guinea, Liberia, and Côte d'Ivoire, and Virunga National Park (Democratic Republic of the Congo). MP pollution may be an additional stressor in these regions, exacerbating existing degradation conditions. By prioritizing research in these areas, it is possible to obtain essential data to support conservation and restoration strategies and to gain a broader understanding of the factors compromising the integrity of these ecosystems.

In this context, integrated management guidelines that align science, public policies, and community engagement are essential to protect natural heritage sites. Innovative technologies and continuous monitoring are critical for identifying MP accumulation hotspots and directing more effective actions. Strategies tailored to local specificities can minimize the impacts of MP pollution and strengthen the resilience of these ecosystems. Creating management models that integrate various societal and scientific spheres is recommended to achieve this, as demonstrated by successful initiatives in different regions. In oceanic areas, such as islands and archipelagos with high visitation rates, it is imperative to adopt oceanic dispersion modeling programs to trace pollution sources and identify critical entry points, such as ports and inhabited zones. Developing management plans that account for the dynamics of plastic waste accumulation and implementing community monitoring programs are essential strategies. Local environmental education, combined with extended producer responsibility, can make a significant difference in reducing pollution. Furthermore, rigorous enforcement policies, such as implementing vessel tracking systems, are indispensable to prevent illegal waste disposal.

For highly visited continental beaches, especially in urban areas, installing retention barriers and automated waste collection systems, as demonstrated by projects like Ocean Cleanup, is necessary. In addition, cleanup drives and educational campaigns should be expanded, involving NGOs and local communities. These actions must be accompanied by waste monitoring programs to generate data that support waste management at local, national, and global levels. For mangroves, estuaries, and deltas, the installation of containment barriers to reduce MP entry and the promotion of reforestation programs to enhance the natural filtration capacity of these ecosystems are recommended. Public policies for urban waste management and regulating activities such as fishing and navigation during critical periods are fundamental measures to mitigate impacts. Developing integrated management policies and environmental education should also be prioritized in riparian communities, encouraging sustainable waste management practices.

In inland lakes, installing MP filtration systems in urban effluents and conducting awareness campaigns to prevent the improper disposal of microfibers are imperative. Establishing riparian vegetation zones can act as ecological barriers, helping reduce MP transport into inland waters. The implementation of effluent control models and continuous monitoring is essential for the preservation of these ecosystems. Conversely, monitoring MPs in snow and meltwater in glacial and mountainous regions is crucial, alongside selective cleaning methods with minimal ecological interference. For these areas, controlling tourism and establishing sustainable trails with waste collection points are necessary measures to reduce plastic pollution. Additionally, planting native vegetation in vulnerable areas can mitigate MP transport and conserve these fragile environments. Finally, it is essential to strengthen global research networks to promote comparative studies on MPs involving protected area managers, government agencies, and international organizations. Integrating various stakeholders is fundamental for developing collaborative strategies to conserve and restore these

unique ecosystems. Implementing these recommendations, with the commitment of governments, international organizations, and the engagement of local communities, is a critical step toward mitigating the impacts of MP pollution and promoting the ecological resilience of these natural heritage sites.

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2. “Tracking microplastics in paradise: first evidence of pollution in lençóis maranhenses national park (Maranhão, Brazil), a Unesco World Heritage Site.”

Élida Priscila Bogéa Carvalhoa,^b, Wesley Rodrigues Soares^{b,c}, Rafaela Ribeiro de Brito^{b,c}, Bárbara Beatriz da Silva Nunesa,^{a,b}, Aline Sueli de Lima Rodrigues^{b,c}, Ariane Guimarães^b, Giuliano Buzá Jacobucci^a, Letícia Paiva de Matos^b, Abraão Tiago Batista Guimarães^b, Alex Rodrigues Gomes^b, Neuciane Dias Barbosa^d, Estefan Monteiro da Fonseca^e, Thiarlen Marinho da Luza,^{b,f}, Guilherme Malafaia^{b,c,f*}

^aPost-Graduation Program in Ecology, Conservation, and Biodiversity, Federal University of Uberlândia, Uberlândia 38408144, MG, Brazil.

^bLaboratory of Toxicology Applied to the Environment, Goiano Federal Institute – Urutaí Campus. Rodovia Geraldo Silva Nascimento, 2,5 km, Zona Rural, Urutaí 75790-000, GO, Brazil

^cPost-Graduation Program in Conservation of Cerrado Natural Resources, Goiano Federal Institute, Urutaí 75790-000, GO, Brazil.

^dState University of Amapá, Macapá, AP, Brazil

^eAEQUOR-Laboratory of Environmental Intelligence, 24901-040 Maricá, RJ, Brazil. Department of Geology and Geophysics, Institute of Geosciences, Federal Fluminense University, 4210-340 Niterói, RJ, Brazil

^fPost-Graduation Program in Biotechnology and Biodiversity, Goiano Federal Institute, GO, Brazil.

*Email: guilherme.malafaia@ifgoiano.edu.br

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2.1. Abstract

Microplastic (MP) pollution is a growing environmental threat to vulnerable ecosystems, including the *Lençóis Maranhenses* National Park (LMNP), a UNESCO Natural World Heritage Site. This study fills a key data gap by providing the first quantitative assessment of MP presence, characteristics, and potential sources in the region. A total of 92 sand sediment samples were collected along 95.3 km of beaches across three areas: within the LMNP (area 1), the adjacent region (area 2), and a more distant coastal zone (area 3). Samples underwent flotation, filtration, and chemical digestion, and MPs were characterized. Principal component analysis (PCA) was used to explore associations between environmental variables and MP levels, while dispersion modeling based on ocean currents and winds identified likely transport pathways. MPs from the LMNP showed high diversity in size, color, and chemical composition, including uncommon polymers such as PEEK. PCA results indicated a strong influence of anthropogenic factors, particularly proximity to urban areas and tourism. Area 2 was identified as a major MP source. Spectral analyses revealed chemical similarities between MPs from areas 1 and 2, supporting the modeled transport links. These findings highlight the complexity of MP pollution in the LMNP and provide baseline data for conservation and waste management strategies.

Synopsis statement

The first evidence of microplastic pollution in *Lençóis Maranhenses* National Park reveals both anthropogenic and natural influences, informing conservation strategies for tropical coastal ecosystems.

Keywords: marine pollution, plastic waste, tropical ecosystem, Raman spectroscopy, multivariate analysis, coastal conservation.

2.2. Introduction

Plastic pollution has become one of the leading global environmental problems, significantly affecting marine and terrestrial biota and ecosystems (1,2). The mass production of plastic, which exceeds 300 million tons globally per year (3), has become a major environmental concern due to its subsequent improper disposal. Despite advances in environmental awareness, the growing demand for plastics continues to outpace global efforts to recycle and reduce waste, exacerbating the problem. Much of the plastic used in short-term applications, such as packaging, quickly become waste that, without proper management, is discarded into terrestrial and aquatic environments (4). As discussed by Browning et al. (5), insufficient recycling infrastructure and the lack of effective waste management policies, especially in developing countries, result in large quantities of plastics being transported through river and stormwater systems to the oceans. In marine environments, this waste, which ranges from large items to microplastics (MPs), is subjected to ocean currents, winds, and drift actions, facilitating its global dispersion and leading to accumulation in remote and ecologically sensitive areas (6,7). Consequently, this phenomenon pollutes the waters and can hurt marine life, coastal ecosystems, and human health. Furthermore, the cumulative effect of plastic pollution on ecosystem services and coastal economies has drawn attention as a multifaceted environmental crisis (8). This context has motivated several studies with a broad scope, from highly anthropized areas (9-11) to remote natural regions (12-14), which indicate the extent and severity of MP contamination in different ecosystems. However, research on MP pollution and its impacts on tropical ecosystems is still scarce (15-17). Tropical regions are home to numerous ecosystems, some of which exhibit exceptional biodiversity characteristics, unique ecological and biological processes, or natural formations of high aesthetic and scientific value and are even recognized as part of the Natural Heritage of Humanity by UNESCO. Due to these peculiarities, these environments are highly vulnerable to plastic pollution, primarily because of the inadequate waste management infrastructure, which often fails to mitigate human impact. Reports and studies by the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) – a collaboration between IMO/FAO/Unesco-IOC/WMO/IAEA/UN/UNEP (18) – highlight that the sum of these characteristics increases the sensitivity of these locations to polluting agents, requiring continuous monitoring and specific conservation measures that take into account both their ecological importance and their cultural and socioeconomic value. In addition, the fragility of these ecosystems is aggravated by the coexistence of anthropogenic pressures and climate change, which increase the challenges for conservation and sustainable management.

Although recent studies have reported aspects related to MP pollution in these environments, such as the Amazon (Brazil, Colombia, Ecuador, Venezuela) (19), Galápagos Islands (Ecuador) (20), Belize Mesoamerican Barrier Reef System (MBRS, Belize) (21), Komodo National Park (Indonesia) (22) and Great Barrier Reef Marine Park (Australia) (23), our knowledge about the impact and distribution of MP in tropical and subtropical ecosystems is still very limited. In Brazil, in

particular, several sites are recognized by UNESCO as Natural World Heritage Sites (24); however, the vast majority of the few studies involving aspects of MP pollution in these environments have focused only on the Amazon biome [see reviews by Morais et al. (19) and Dos-Santos-Silva et al. (25)] and the Fernando de Noronha Archipelago (26-33). This knowledge gap is even more worrying when considering that several coastal ecosystems in Brazil have intense interaction with human populations that directly depend on their natural resources. Therefore, this scenario underscores the urgent need to expand research in this area, as the expansion of knowledge is essential for developing appropriate monitoring, mitigation, and conservation strategies to protect these vulnerable ecosystems against the growing threat of MP pollution. The most recent Brazilian site recognized by UNESCO in 2024 is the *Lençóis Maranhenses* National Park (LMNP) (24), located in the Northeast region, on the eastern coast of the state of Maranhão, in a transition zone between the Cerrado, Caatinga, and Amazon biomes. More than half of its area is formed by successive chains of dunes interspersed with temporary and permanent lagoons (35,36), and it is considered the largest dune field in Latin America, covering an area of 155 thousand hectares and approximately 80 km of coastline (37). In addition to its essential role in biodiversity conservation, the park boasts aesthetic and geological/geomorphological values of global relevance, standing out as a unique environment of great beauty and scientific importance (38,39). Despite this, no study focused on the identification, characterization, and distribution of MPs has been carried out in the LMNP, with the work of Palombini et al. (40) being the closest to this approach, having characterized and analyzed the possibilities of recovering small polymeric fragments found in the sediments of a beach in a fishing village near the LMNP.

In this context, we conducted a comprehensive study that involved the identification, typing, and chemical characterization of MPs, as well as determining the pollution load and identifying factors influencing pollution in sand sediments collected along beaches within the boundaries of the LMNP, as well as in areas of park influence. As the first study of its kind in the region, our data provide a crucial scientific foundation for understanding MP pollution in one of the most unique ecosystems on the planet, thereby contributing to the development or enhancement of effective monitoring and conservation strategies. The work represents a milestone in understanding the impacts of MPs in tropical areas, aligning with global demands for integrated solutions based on scientific evidence. The relevance of this study extends beyond its local scope, providing a valuable reference for future studies in other natural heritage sites and underscoring the need for a global response to the growing threat of MPs in sensitive and highly biodiverse ecosystems.

2.3. Material and Method

2.3.1. Study area

Located in the eastern portion of the state of Maranhão, in northeastern Brazil, the *Lençóis Maranhenses* National Park (LMNP) occupies an ecotonal area that connects the Amazon, Caatinga, and Cerrado biomes (41). The LMNP extends partially through the municipalities of Barreirinhas, Santo Amaro do Maranhão, and Primeira Cruz, located between the coordinates 02°19' and 2°45' S; 42°44' and 43°29' W (Figure 1). The climate is equatorial, with two well-defined seasons: a rainy season, from March to June, and a dry season that predominates for the rest of the year. The average annual precipitation reaches 1800 mm, and the average temperature is 28.5°C, with a seasonal variation of 1.5°C (42). The soils of the LMNP are sandy and rich in quartz, formed from Quaternary sediments. Since the Pleistocene, marine transgression and regression events have accumulated sediments along the coast, resulting in the formation of successive dune fields over the past 100,000 years (43). Without vegetation, the current field of mobile dunes rests on ancient Pleistocene paleodunes, now stabilized by coastal vegetation (36).

2.3.2. Sampling procedures

Considering the wide range of sampling methods described in the literature, for collecting sand on beaches we adopted a protocol developed based on guidance documents (44-48), as well as previous studies developed in different locations (49). Specifically, the collection campaigns were carried out between November 25 and 27, 2023, during the dry season in the region and collections were directed to the surface sediment, using the upper high tide line as a reference, according to Besley et al. (50). Three areas were selected for sampling. Area 1 encompassed the entire stretch of beach within the LMNP limits, measuring 65 km in length and including parts of the municipalities of Primeira Cruz, Santo Amaro do Maranhão, and Barreirinhas, with 50 samples collected (Figure 1). Area 2 encompassed stretches of beaches in the municipalities of Barreirinhas and Paulino Neves, located outside the LMNP limits, spanning 17.5 km and yielding 20 samples. Finally, Area 3 covered the entire coastal area of the municipality of Tutóia, with 12.8 km of beaches, from which 22 samples were collected. Thus, the sampling extended 95.3 km, with 92 samples collected (Figure 1). See more details in Text S1 of Supporting Information.

In each area (1, 2, and 3), samples were distributed along the entire beach length using a systematic sampling approach, with approximately equal spacing. However, local adjustments were made to account for site-specific heterogeneity, such as changes in geomorphology, river mouths, or other natural features, ensuring spatial representativeness without compromising sampling consistency. Sand samples were collected using a 50 cm × 50 cm aluminum square positioned at the

high tide line. Visible plastic particles were collected across the entire surface within the quadrant, and sand was collected from five specific points: one in each corner of the quadrant and one in the center, at a depth of 5 cm, with an approximate weight of 70-90 g, similar to Besley et al. (50).



Figure 1.

Distribution of sampling points along the shoreline of the *Lençóis Maranhenses* National Park (Maranhão, Northeastern Brazil) (Area 1) and adjacent areas. Area 2 encompassed sections of beaches in the municipalities of Barreirinhas and Paulino Neves, while Area 3 covered the entire coastal extent of the municipality of Tutóia, Maranhão, Northeastern Brazil.

2.3.3. Sample processing and microplastic extraction

Samples were divided into two aliquots, and visible MPs were manually separated. Each subsample underwent flotation in saturated ZnCl_2 (1.7 g/cm^3), followed by centrifugation, filtration (400 mesh), drying, and stereomicroscopic inspection. Only particles with specific visual and thermal properties (hot needle test) were selected. Large MPs ($300 \mu\text{m}$ to 5 mm) were digested in 30% H_2O_2 , washed, dried, and stored for analysis. Sand was dried and weighed to express MPs per kg, and all residues were properly disposed of. Full methodological details are provided in Text S2 of the Supporting Information.

2.3.4. Anti-contamination procedures

Strict contamination control protocols were applied during sampling and laboratory procedures. All materials were sanitized, heated, and protected with pre-heated aluminum foil. Environmental and procedural blanks were used to detect airborne or handling contamination, and all steps occurred under controlled conditions inside a laminar flow hood. No MPs ($300 \mu\text{m}$ – 5 mm) were detected in blanks. Further details are provided in Text S3 of the Supporting Information.

2.3.5. Characterization of microplastics

All extracted MPs were classified by color and type, photographed, and analyzed in ImageJ for size and shape descriptors. Raman spectroscopy was used to determine polymer composition ($n = 317$), with spectra processed and compared to custom and external libraries. Only spectra with sufficient quality indices were accepted. Full methodological details are provided in Text S4 of the Supporting Information.

2.3.6. Distribution maps, polymer hazard index, and pollution load index

MP concentrations (MPs/kg) were corrected for sampling density by dividing the number of samples by the sampled beach length (km), using the highest correction factor as a reference. Each concentration was adjusted accordingly, resulting in data expressed as “(MPs/kg)/km.” These values,

combined with the chemical composition, were used to calculate the contamination factor (CF) and polymer hazard index (PHI), following Das et al. (51) and Lithner et al. (52). CF was calculated using the lowest observed concentration as the background due to lack of prior data. Spatial distribution maps were created in QGIS (v3.38.3) with heatmap rendering to visualize CF and PHI gradients across 255 classes. Details are provided in Text S5 of the Supporting Information.

2.3.7. Assessment of contributing anthropogenic and environmental factors

A comprehensive survey of various variables was conducted in the investigated areas to identify potential sources related to human activities and determine contributing factors associated with environmental vectors frequently linked to MP pollution patterns. This survey included demographic and development characteristics, environmental attributes, land use and occupation, beach characteristics, oceanographic, climatic, and meteorological variables, as well as the proximity of sampling points to urban infrastructure (see details in Table S1 of Supporting Information). Additionally, aliquots of each sand sample were subjected to granulometric analysis based on images analyzed using ImageJ software, according to the procedures proposed by Vandel et al. (53).

2.3.8. Assessment of contamination sources and routes

2.3.8.1. Spectral comparison

To assess the possible similarity between the MPs identified in Area 1 (LMNP) and those in the area immediately adjacent to the park (Area 2), and to infer the distribution dynamics and influence of contamination between the sampling regions, a spectral comparison was performed using data obtained by Raman spectroscopy. The MPs from different areas were grouped based on color patterns, type, size, and shape and then subjected again to spectral analysis according to the procedures described in Text S4 of the Supporting Information. In this reanalysis, different spectra were obtained from various points on the particles, and spectral comparison was performed using Spectragryphy v1.2.16.1 software, with overlapping of the spectra to identify possible correspondences between the samples qualitatively. The spectral data were then subjected to statistical analysis (see item “2.9”) to infer the potential influence of MP pollution in area 2 on contamination in the coastal region of the LMNP.

2.3.8.2. Dispersion simulation

To assess the potential role of ocean currents and winds in MP dispersion between Areas 1 and 2, we reviewed oceanographic and meteorological data and used the Plastic Tracker model to simulate dispersion trajectories. The consistency between modeled routes and regional patterns supported the plausibility of MP transport. Full details are provided in Text S6 of the Supporting Information.

2.3.9. Statistical analyses

A tailored statistical approach was applied to address each objective. ANOVA or Kruskal-Wallis tests were used for comparisons between areas, depending on data distribution. Principal Component Analysis (PCA) and cluster analyses were conducted to identify environmental, geographic, and polymeric variables influencing MP pollution. Spectral similarities between areas were evaluated using correlation analysis and multivariate techniques. Detailed procedures are available in Text S7 of the Supporting Information.

2.4. Results

Initially, our data indicated the presence of MPs along the evaluated stretches of all investigated areas (Figure 2). The LMNP presented 88% of the contaminated samples with a lower CF than that of area 2, including beaches in the municipalities of Barreirinhas and Paulino Neves, located outside the park boundaries (Figure 2A). In contrast, area 3 recorded the lowest pollution levels by MPs and the lowest percentage of contaminated samples (54.5%). We also observed a diversity of MPs in terms of size, color, type, and chemical composition across all areas. In terms of size, the MPs from LMNP had a larger average diameter than those from area 3, although the particle shape was similar between the areas (Figure 3A). Regarding the type and color, transparent fragments and those in the colors blue, white, and green predominated, especially in the LMNP (area 1) and area 2, which presented a greater diversity of colors, also including yellow, red, orange, gray, purple, and brown MPs (Figures 3B-F). Regarding the polymeric composition, we found that the majority of particles in the three areas were composed of polyethylene (PE), polypropylene (PP), propylene-ethylene random copolymer (PEC), and ethylene-vinyl acetate (EVA) (Figures S1 of Supporting Information). Areas 1 and 2, however, also presented particles of polyvinyl chloride (PVC), polystyrene (PS), and ethylene-methyl acrylate (EMA), evidencing a greater diversity of polymers and, consequently, higher PHI values (Figures 2B and 2D). In areas 2 and 3, polyethylene terephthalate (PET) and expanded polystyrene (EPS) were found, indicating specific variations in the composition. On the other hand, LMNP stood out as the only location where polyetheretherketone (PEEK) MPs were identified, indicating a unique polymer composition in this area (see Figure S1 of Supporting Information).

The PCA results complement the observations described above, summarizing the relationships between the MPs' characteristics and the investigated areas' CF (see Figure S2A of

Supporting Information). PC1, which explained 68.5% of the total variance, stood out for capturing variations related to the diversity of polymers and coloration of the MPs, while PC2, responsible for 31.5% of the variance, reflected differences associated with the size and type of particles. Area 3 presented the highest positive value for PC1 (PC score: 5.0248), reflecting lower polymer diversity and more homogeneous colorations, which corroborates the lower CF values observed in this area. In contrast, area 2 exhibited the lowest PC1 value (PC score: -3.7935), indicating a greater diversity of polymers and fragments of less common colors, such as red, brown, and violet, which contributed significantly to the multivariate separation. The LMNP (area 1), with negative values for both PC1 (-1.2313) and PC2 (-3.4451), stood out for grouping larger diameter MPs with notable polymeric diversity, aligning with the high PHI value, together with area 2 (see Figure S2B of Supporting Information), and the presence of exclusive polymers, such as PEEK (see Figure S1 of Supporting Information). Table S2 - available in the Supporting Information - presents the PCA loading values for the two main components (PC1 and PC2).

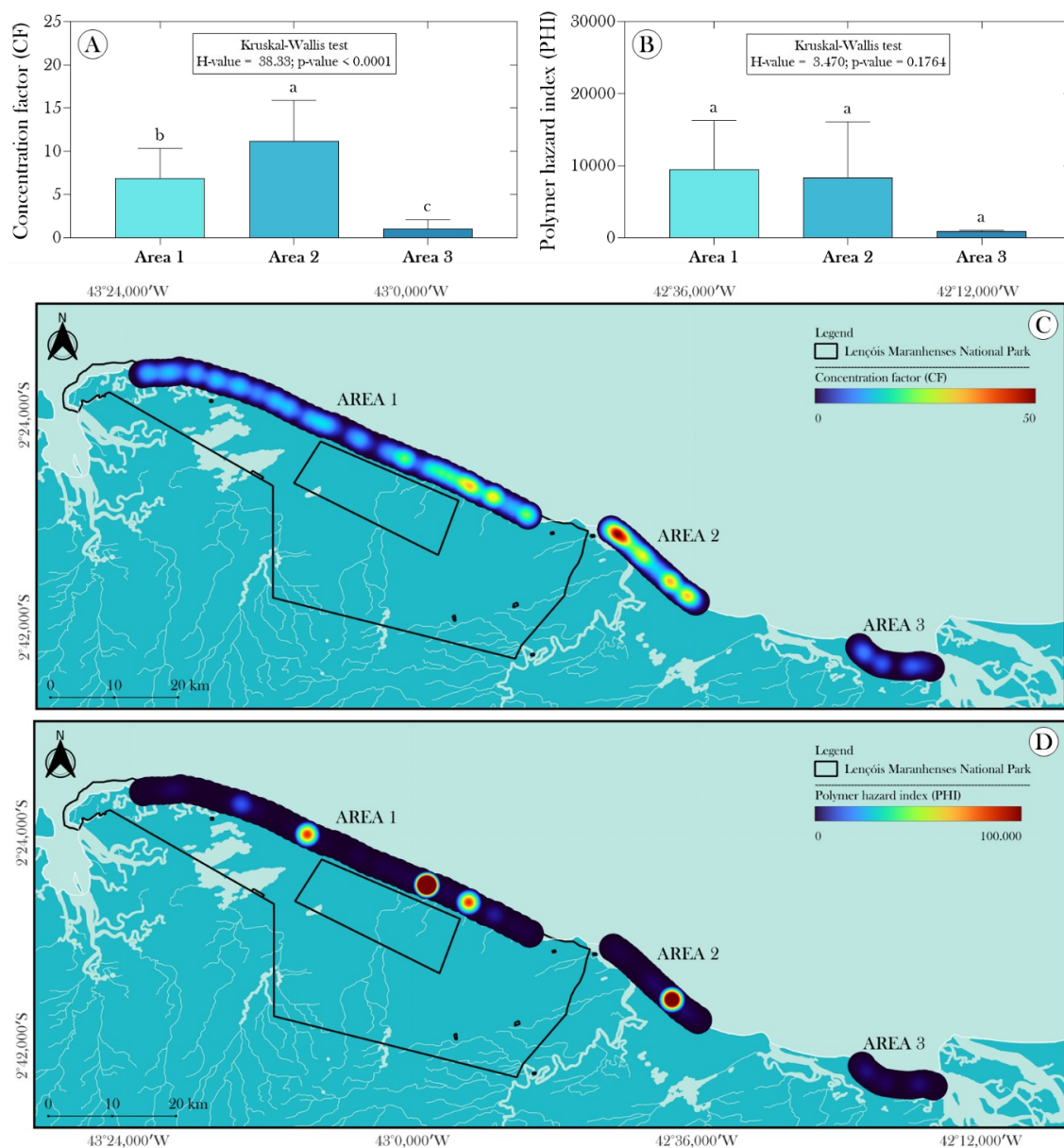


Figure 2. (A) Contamination Factor (CF), (B) Polymer Hazard Index (PHI), (C) distribution map of CFs, and (D) PHI across the investigated areas. Area 1 encompassed the entire beach extension within the boundaries of the *Lençóis Maranhenses* National Park (LMNP); Area 2 included beach sections in the municipalities of Barreirinhas and Paulino Neves, located outside the LMNP boundaries; and Area 3 covered the entire coastal extent of the municipality of Tutóia (State of Maranhão, Northeastern Brazil). In panels “A” and “B,” the bars represent the median and interquartile range, with the statistical analysis summary at the top of the graph. Distinct lowercase letters indicate significant differences between areas.

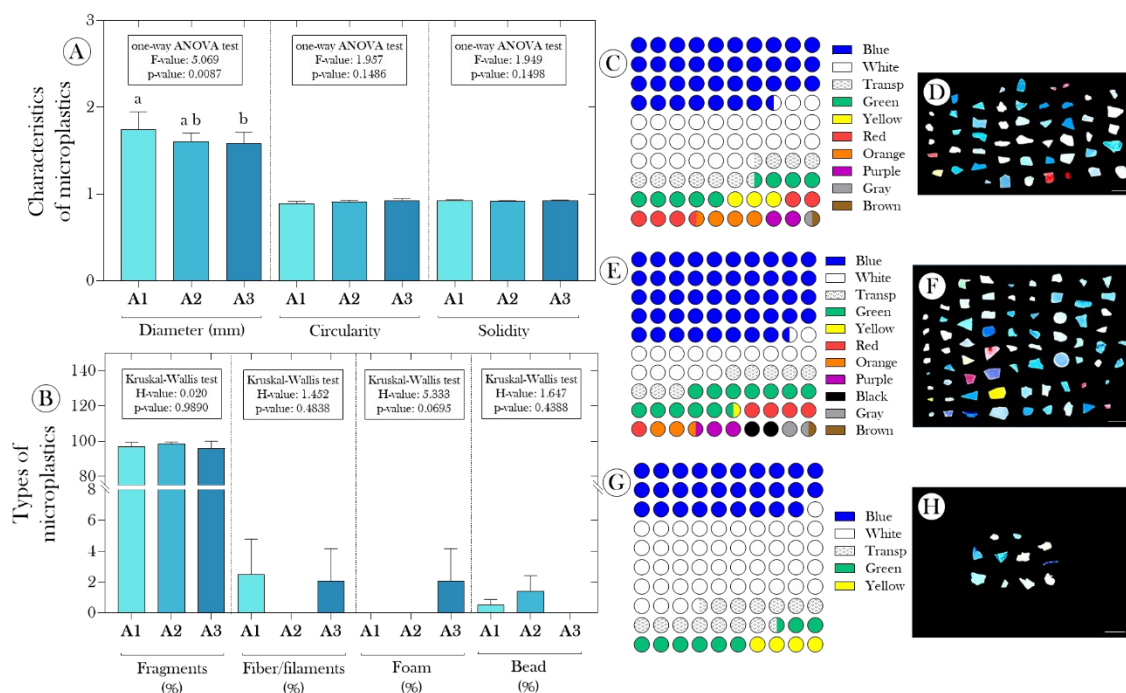


Figure 3. Characteristics of microplastics (MPs) identified in the different investigated areas. (A) Size and shape parameters of MPs, including diameter, circularity, and solidity. (B) Percentage distribution of various types of MPs identified: fragments, fibers/filaments, foam, and spheres. (C-H) Proportion of MP colors in the studied areas: Area 1 (C-D), Area 2 (E-F), and Area 3 (G-H), accompanied by representative images of MPs observed in the respective areas. In “A” and “B,” the bars represent the mean + standard deviation for data analyzed using one-way ANOVA and the median with interquartile range for data analyzed using the Kruskal-Wallis test. Summaries of the statistical analyses are presented at the top of the graph. Distinct lowercase letters indicate significant differences between areas in multiple comparisons. Area 1 encompassed the entire beach extension within the boundaries of the *Lençóis Maranhenses* National Park (LMNP); Area 2 included beach sections in the municipalities of Barreirinhas and Paulino Neves, located outside the LMNP boundaries; and Area 3 covered the entire coastal extent of the municipality of Tutóia (State of Maranhão, Northeastern Brazil).

To determine which environmental, geographic, and land use variables most influence MP pollution levels, we performed a PCA using the collected data. PC1 and PC2 explained 100% of the total variance (Figure S2B), revealing clear separation among the three areas. Area 1 (LMNP) was associated with negative loadings, reflecting reduced urban-industrial influence and predominance of natural features such as longer coastlines, higher sand granulometry, and stronger oceanographic dynamics. Area 2 showed high MP contamination (100% of samples), associated with positive PC2 loadings linked to anthropogenic pressure, including tourism, road proximity, and plastic consumption. Area 3, with lower contamination (54.5%), was associated with positive PC1 loadings such as higher waste collection coverage, mangrove extent, and forest area. We also performed a focused PCA within LMNP, grouping CF values into three subgroups (low, medium, high). The PCA revealed that higher contamination was positively associated with tourism, population density, beach width, and plastic spill risk, while marine peat and finer sand grains (negatively correlated with

CF) may contribute to MP accumulation (Figures 4A–E). Details are provided in Text S9 of Supporting Information.

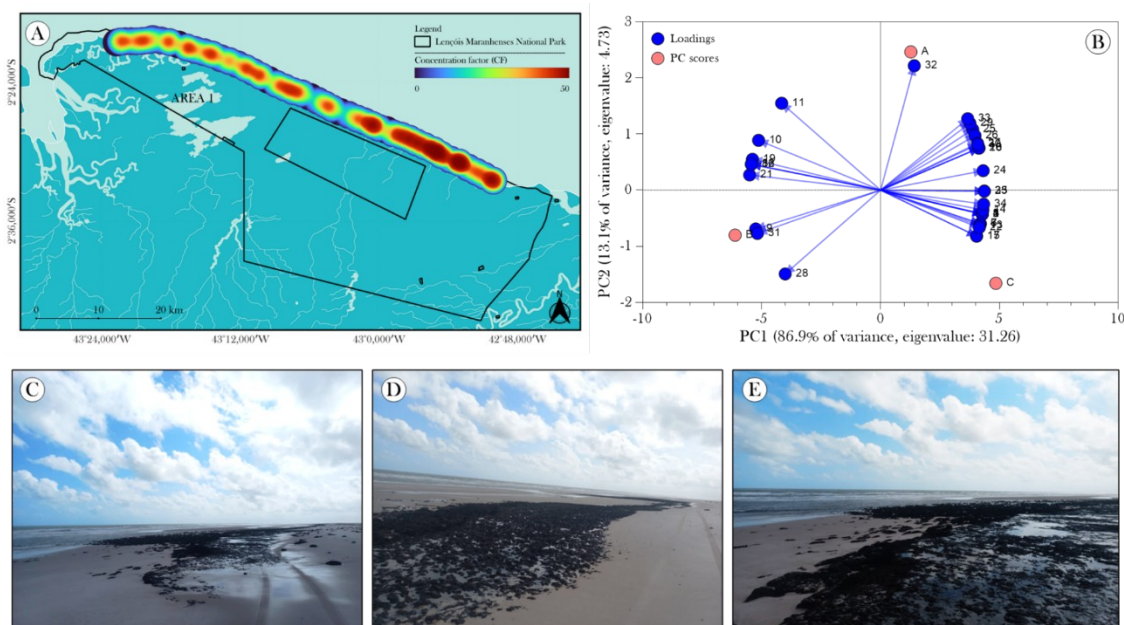


Figure 4. (A) Spatial distribution of the concentration factor (CF) of microplastics (MPs) in the *Lencóis Maranhenses* National Park (LMNP) (State of Maranhão, Northeastern Brazil). (B) Principal Component Analysis (PCA) associating contamination subgroups (SA, SB, and SC) with environmental and anthropogenic variables. (C–E) Field photographs show the presence of marine peat in areas with higher concentrations of MPs within the LMNP. In (B), blue vectors represent the variable loadings contributing to the principal components (PC1 and PC2), and pink circles indicate the PC scores for each study subarea (SA, SB, and SC), illustrating their positioning based on the principal components.

Given that the samples most polluted by MPs from the LMNP are correlated with anthropogenic pressure variables, similar to what was observed in the samples from area 2 – adjacent to the park and with higher pollution levels (Figure 2A) –, we assume that pollution in the park is not exclusively endogenous but potentially intensified by MPs from area 2. To investigate this hypothesis, we initially grouped the MP fragments common between the two areas into color categories: light blue, dark blue, white, transparent, orange, purple, and red. These fragments were reanalyzed, and the chemical composition results of the particles that coincided in terms of color between the areas are presented in Table S5 of Supporting Information. The Raman spectra of particles with matching color and chemical composition between areas were then subjected to spectral analysis to identify structural similarities and degradation patterns that could indicate that the MPs found in the park may also have come from area 2. As expected, the analyses performed – Including visual inspection of the spectra (Figures 5A–G), the positive and significant correlation

between the fragments (see Figures S3A-G of Supporting Information), as well as PCA and cluster analysis (see Table S4A-P of Supporting Information – revealed high similarity between the MPs from areas 1 and 2, especially between PE-MPs (light blue, white, and transparent), PEC-MPs (white, orange, and purple), and PP-MPs (red) (Figures 5, S3, and S4). This similarity extends not only to the chemical composition, characterized by the same type of polymer but also to specific aspects of the Raman spectra that indicate signs of degradation, evidenced by changes in characteristic peaks, such as in the 500–1500 cm^{-1} region, which reflect similar oxidation and molecular fragmentation patterns between the MPs from the two areas.

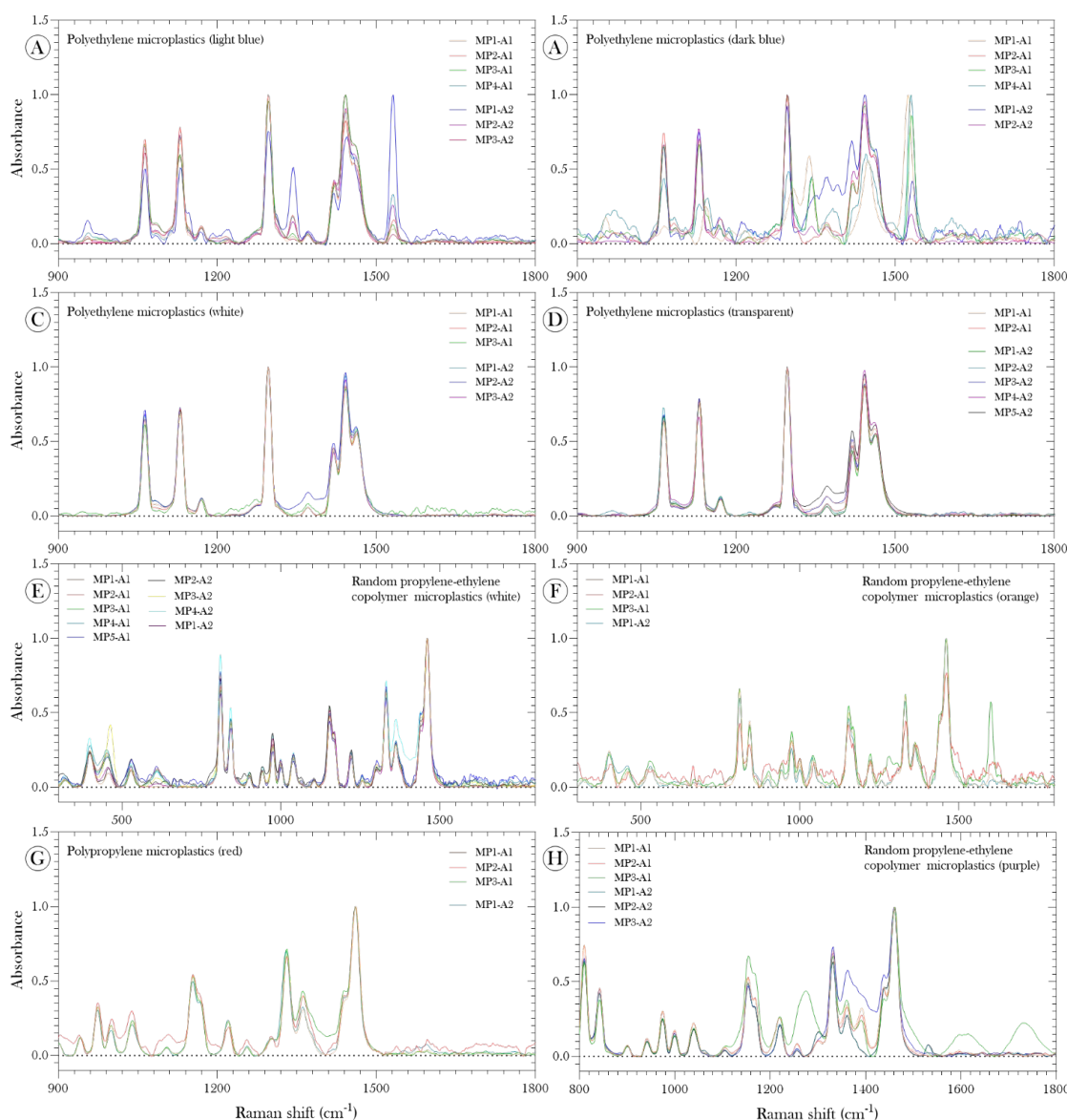


Figure 5. Raman spectra of various microplastics (MPs) categorized by polymer type and color: (A) Polyethylene (light blue), (B) Polyethylene (dark blue), (C) Polyethylene (white), (D) Polyethylene (transparent), (E) Random polypropylene-ethylene copolymer (white), (F) Random polypropylene-ethylene copolymer (orange), (G)

Polypropylene (red), (H) Random polypropylene-ethylene copolymer (purple). Each spectrum represents MPs from different sample areas (MP1, MP2, MP3), with the corresponding lines indicating specific sample groups (A1, A2, etc.).

Furthermore, the dispersion simulation performed by PlasticTracker (see Figures S5A-B of Supporting Information) revealed particle trajectories originating from the municipalities of Barreirinhas and Paulino Neves (which cover area 2), similar to the predominant flow of the North Brazil Current (NBC), which moves from southeast to northwest along the Brazilian coast, transporting warm waters from the equator towards the north (Figures S5 and 6). This coastal current pattern is potentially reinforced by the existence of wind routes with similar orientation, as indicated in the wind frequency rose (Figure 6B), with an average speed of 5.85 m/s at a height of 100 meters. Additionally, during the summer, the Atlantic Equatorial Air Mass (AEAm) exhibits a circulation branch with flow directed northwest along the coast, partially aligning with the NBC (Figures 7A-B). This convergence between ocean current flow and wind patterns, including the seasonal influence of AEAm, suggests a synergy in particle transport processes between the studied areas, facilitating the potential displacement of MPs from area 2 to area 1 along the coast.

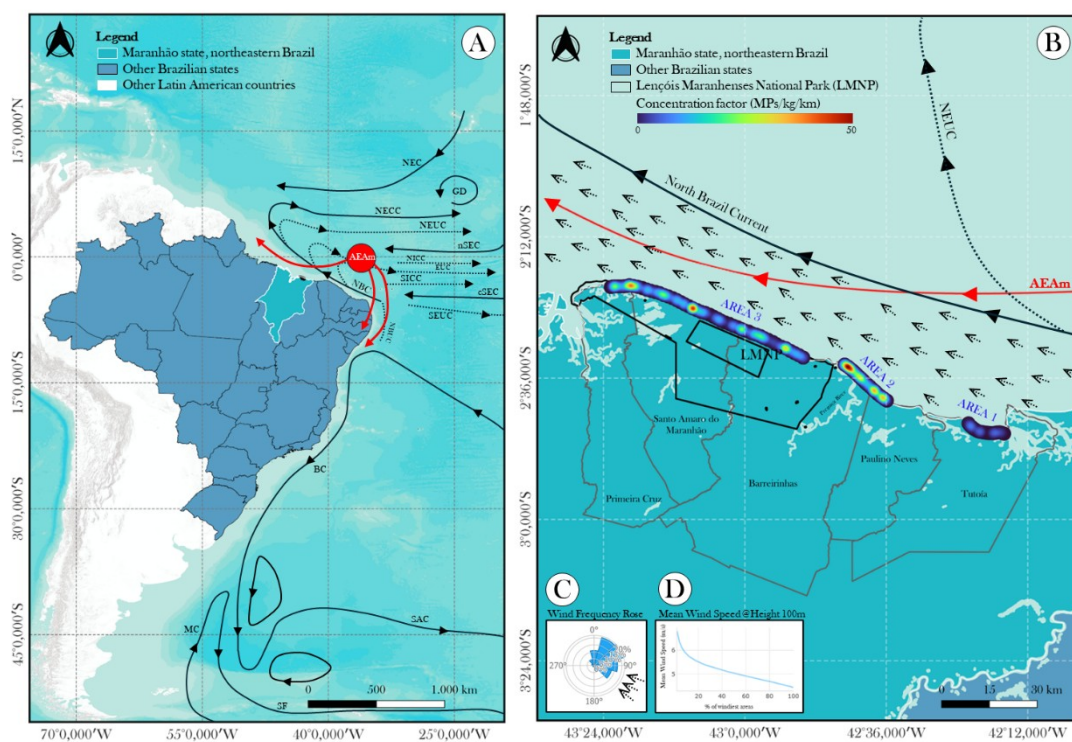


Figure 6. Interactions between ocean currents, wind patterns, and microplastic (MP) transport in LMNP. (A) Map showing ocean current directions and the Atlantic Equatorial Air Mass (AEAm) flow (summer). (B) Spatial distribution of the Contamination Factor (CF) of MPs, overlaid with the North Brazil Current (NBC) routes and AEAm flow. (C) Wind rose showing coastal wind direction and average wind speed at 100m altitude in Maranhão. Details provided in Text S8 of Supporting Information.

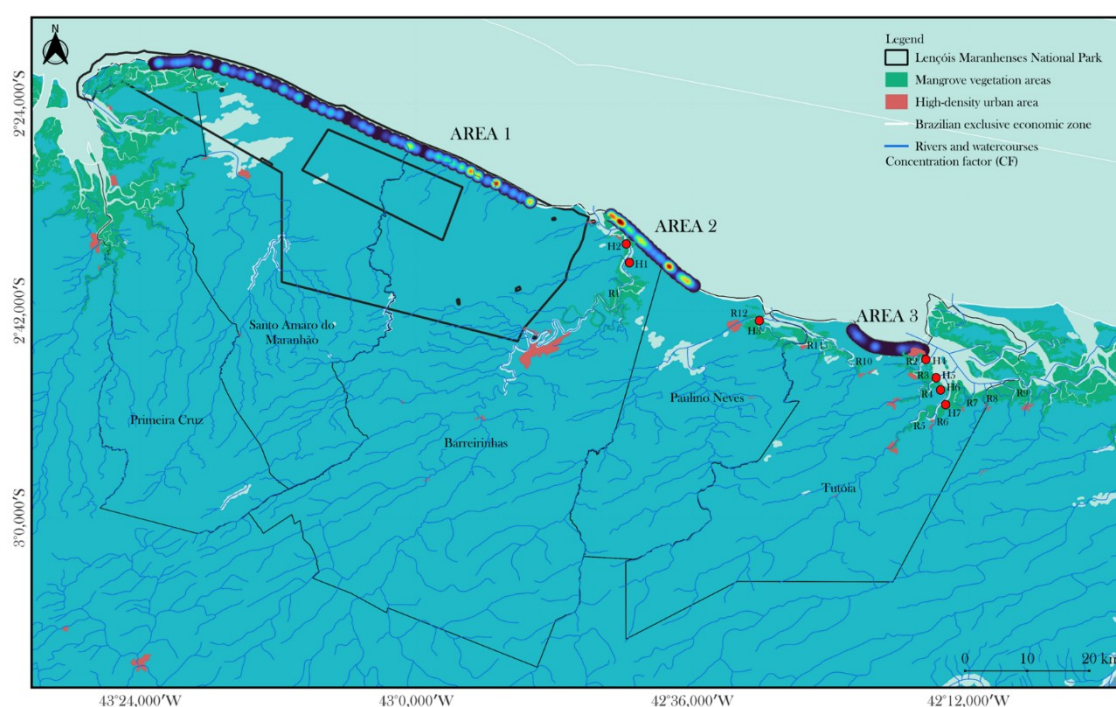


Figure 7. Map of contamination factors (CFs) in the investigated areas and associated geographic features. Area 1 encompassed the entire beach extension within the boundaries of the *Lençóis Maranhenses* National Park (LMNP); Area 2 included beach sections in the municipalities of Barreirinhas and Paulino Neves, located outside the LMNP boundaries; and Area 3 covered the entire coastal extent of the municipality of Tutóia (State of Maranhão, Northeastern Brazil). H1 to H7: Hotspots (plastic waste input points into the ocean) identified by Alencar et al. (2023). R1: Preguiça River; R2: Comum River; R3: Porto de Areia River; R4: Bom Gosto River; R5: Barro Duro River; R6: Tamboril River; R7: Cajazeiras River; R8: Flecheira Grande River; R9: Água Doce River; R10: Tutóia Velha River; R11: Cangatã River; and R12: Novo River [according to the National Water Agency (ANA, 2024)].

2.5. Discussion

In this study, we addressed the issue of MP pollution in the sand sediments of the LMNP, one of the most unique and vulnerable ecosystems on the planet, which has recently been recognized as a natural heritage of humanity by UNESCO (24). The lack of previous data on the distribution, classification, and potential sources of MPs in this region highlights the relevance of this investigation. In this context, we focused on identifying MP pollution patterns, correlating them with environmental and anthropogenic variables that influence their presence, and adopting an approach that integrated chemical analyses, such as Raman spectroscopy and dispersion modeling. Our findings provide a crucial scientific basis for developing public policies and conservation practices in the LMNP, serving as a reference for similar investigations in tropical and subtropical ecosystems worldwide. Specifically, in terms of characterizing the identified MPs, whose importance lies in understanding their potential sources and environmental impacts (54,55), we note that the diversity in terms of size, color, type, and chemical composition of MPs reflects both the complexity of local

pollution and the influence of external factors. The predominance of **PE** and **PP**, synthetic polymers frequently associated with disposable plastic products, such as plastic packaging and disposable plastic bottles (56), corroborates previous studies in tropical coastal ecosystems, such as those by Acosta-Coley & Olivero-Verbel (57) (urban beach in Colombia), Delvalle-de-Borrero et al. (58) (on Pacific and Caribbean beaches in Panama), Mohan et al. (59) (in beach sediments from the tropical ecosystem of an Indian island), as well as by Pegado et al. (60) (on Brazilian beaches). Furthermore, the wide color diversity observed, including blue, white, green, yellow, red, orange, purple, gray, and brown fragments in areas 1 (**LMNP**) and 2, reflects a variety of origins, possibly associated with domestic, industrial, and marine waste, as reported in previous studies on coastal pollution (61-63).

The greater chromatic diversity in areas 1 and 2, compared to area 3 (Figures 3C-H), may indicate a greater complexity in **MP** inputs, with local sources (such as tourism and urban activities) and external sources (transport by ocean currents and winds) interacting to influence deposition patterns. Additionally, fragments of less common colors, such as violet, gray, and brown, may be associated with specific plastic products or differentiated degradation processes, reinforcing the hypothesis that these areas are subject to various anthropogenic and environmental impacts. On the other hand, the similarity of this diverse color pattern between these areas (Figures 3C-F) reinforces the suspicion that area 2, immediately adjacent to the park, acts as an active source of **MPs** for the **LMNP**. This continuous contribution can be explained, as demonstrated in Figure 6, by the flow of plastic materials transported by coastal currents, winds, and even by the recreational and tourist use of the beaches in Area 2, which increases the pollution load in the protected region. This hypothesis is strengthened by the high spectral similarity observed between the **MPs** of areas 1 and 2 (Figures 5, S3 and S4), indicating that a significant fraction of the **MPs** in the **LMNP** may share the same origin as the waste found in the adjacent area. Furthermore, the geographic proximity and shared environmental characteristics between the two areas suggest that **MP** transport, potentially mediated by hydrodynamic and atmospheric processes, plays a crucial role in the dynamics of **MP** deposition in the **LMNP**, highlighting the vulnerability of this ecosystem to external sources of pollution.

On the other hand, the identification of exclusive particles in the **LMNP**, such as **PEEK**, reveals a unique contamination pattern, indicating contributions from specific sources and environmental dynamics that favor the deposition and retention of high-density polymers of atypical origin, positioning the park as a hotspot for **MPs** with these characteristics. **PEEK**, widely used in high-performance industrial applications, such as the manufacture of aerospace (64), automotive (65), and medical components (66), is rarely associated with common urban waste, suggesting a differentiated origin, possibly related to long-range transport. In this case, the vast extension of coastline and width of beaches in the **LMNP** creates an environment conducive to the interception of **MPs** of transoceanic origin, a phenomenon already documented in remote coastal ecosystems by studies such as those by Moreira et al. (67). Furthermore, the higher maximum wave height and more extended period of primary swelling waves observed in the park favor the transport of dense **MPs**, functioning as dynamic mechanisms that directly influence their deposition. Higher waves with

extended periods increase the transport energy in the coastal environment (68); however, when they reach lower energy zones, such as beaches, they promote the sedimentation of dense particles, such as PEEK. The presence of marine peatlands in several areas of the LMNP (Figures 4C-E) may also be a key factor for the accumulation of dense MPs, acting as “natural filters” that combine geomorphological, hydrodynamic, and chemical characteristics, as also reported in Liebezeit & Dubaish (69) and Cyvin et al. (70). These organic deposits create low energy microzones, which are ideal for temporarily retaining dense particles, thereby favoring their persistence in the environment even under dynamic conditions, such as remobilization associated with tidal or wave events. Additionally, the unique morphology of the LMNP beaches, characterized by gradual transitions from dunes to lagoons, further increases the probability of retaining these particles. Therefore, these geomorphological characteristics, combined with the specific hydrodynamic conditions of the region, form a highly efficient system for the interception and retention of dense MPs of differentiated origin, which reinforces the importance of monitoring less obvious sources of contamination, including long-distance industrial inputs, which can contribute to complex and highly differentiated pollution patterns in protected ecosystems such as the LMNP.

Another relevant aspect to be highlighted is that the most polluted samples collected in the LMNP were positively associated with areas of higher population density and intense tourist activity, located within the territorial limits of the municipality of Barreirinhas, which offers the most immediate access to the collection sites (Figure 7). This relationship suggests that plastic consumption and the low coverage of solid waste management services in this region may contribute to a more pronounced environmental impact in the park. According to Alencar et al. (71), Barreirinhas presents the highest consumption of plastics among adjacent municipalities and the highest risk classification for plastic waste leakage, evidencing a critical scenario for the mobilization of this waste. The proximity of the most polluted collection points in the park to the mouth of the Preguiça River (R1 – Figure 7) supports the hypothesis that this watercourse plays a significant role in transporting plastic waste from urban and tourist activities to the marine environment. As illustrated in Figure 7, the Preguiça River is directly connected to the urban area of Barreirinhas, marked by recurring urban waste and intense tourist and boat traffic. This dynamic, therefore, creates a direct connection between the urban region, the local population and visitors, and the park's beaches, increasing the contribution of waste. Additionally, the Preguiça River contains two hotspots identified as critical points of plastic waste input to the ocean (H1 and H2, Figure 7), which, according to estimates by Alencar et al. (71), contribute approximately 901 tons/year of plastic waste, a volume much higher than that of the other hotspots identified in the different areas investigated (Figure 7). In addition, the river's discharge into the sea, aligned with the predominance of the NBC flow (Figure 6), appears to act as a mechanism that facilitates the transport of plastic waste to the LMNP beaches. Therefore, this interaction between river dynamics and ocean currents can create a continuous deposition pattern, reinforcing the municipality of Barreirinhas' role as a source of pollution in the park.

On the other hand, the pollution load in area 2, which includes beaches in the municipalities of Barreirinhas and Paulino Neves, was positively associated with factors such as intense tourist activity, the proximity of the collection sites to urban roads and highways, and high plastic consumption by local populations (Figure S2B). These elements indicate significant anthropogenic pressure on the area, enhanced by contributions from the urban area of Paulino Neves, which is connected to the Rio Novo that flows east of the collection sites (R3 – Figure 7). This river, also identified by Alencar et al. (71) as a hotspot for the contribution of plastic waste with estimates of 232 tons/year (Figure 7), tends to play an essential role in the dynamics of transport of MPs from area 2 to adjacent regions, such as area 1 (LMNP). This hypothesis is corroborated by the spectral analyses performed (Figures 5, S3 and S4), which revealed high similarity between fragments of PE-MPs, PEC-MPs, and PP-MPs found in area 2 and on the beaches of the LMNP. This spectral similarity not only suggests a shared origin but also highlights an active transport and dispersion mechanism, likely mediated by the NBC flow, the action of coastal winds, and the seasonal effects of the AEA (Figure 6), particularly during the summer when these hydrodynamic factors intensify. Therefore, the geographic proximity, combined with the hydrodynamic and atmospheric characteristics, creates an interconnected system that facilitates the continuous transport of MPs from Area 2 to the LMNP, reinforcing that pollution on the park's beaches cannot be dissociated from intense human activities and waste sources located in neighboring areas, whose interconnection highlights the multifactorial and dynamic nature of MP pollution, in which multiple environmental and human vectors contribute to the redistribution of plastic waste along the coast.

Therefore, these findings highlight the urgent need for local interventions to mitigate plastic pollution, but above all, they underscore the importance of an integrated approach between municipalities. As discussed by Akenji et al. (72), most local governments face difficulties in fully meeting their waste management responsibilities, with collection often carried out by local communities or grassroots initiatives, such as waste banks, supported by municipal administrations. However, a significant gap remains in the coverage of collection services and inter-municipal cooperation. Thus, local governments must develop an integrated system, from collection to recycling and final disposal, and invest in the technical development of their teams to deal more efficiently with this environmental problem. Waste management, especially in areas of high tourist pressure, should be reinforced with regional policies that consider ecological and hydrodynamic connectivity between municipalities, which is essential to reduce the contribution of adjacent areas to park pollution, promoting not only the protection of the LMNP but also the conservation of coastal ecosystems on a broader scale.

Interestingly, area 3 presented the lowest pollution load (Figures 2A-B), with an inverse correlation with the higher population density and proximity to larger urban areas (Figure S2B), which could potentially be associated with a high pollution load, as previously reported by Zhou et al. (73) and Kunz et al. (74). However, our data point to factors that explain this attenuated pollution and suggest important directions for further investigation. The lower CF values and the lower

percentage of contaminated samples can be attributed primarily to the more excellent coverage of services related to waste management and in the municipality of Tutóia, the highest service for home garbage collection, home cleaning services, and the high percentage of garbage disposal in dumpsters stood out. As discussed by Hettiarachchi & Meegoda (75), efficient municipal waste management is a crucial factor in mitigating pollution on beaches. Additionally, area 3 is located near mangroves (to the east, Figure 7), and although our study did not directly compare sites with and without mangroves, multivariate analyses (e.g., PCA) indicated that proximity to mangrove vegetation may be associated with lower MP concentrations. This observation aligns with previous findings suggesting that mangroves can act as natural interceptors, retaining debris and potentially reducing the entry of MPs into adjacent beaches (76-80). While not conclusive, this hypothesis warrants further investigation through targeted studies. Another relevant aspect was the higher sea surface wave from direction recorded in this area (47°), compared to areas 1 (26°) and 2 (37°), indicating that the waves arrive at a more oblique angle to the coast, which promotes lateral transport of particles along the coastline and hinders their direct deposition in coastal sediments. This longitudinal transport also favors the redistribution of particles to adjacent areas, reducing local accumulation. At the same time, the unique geography of Area 3, marked by a prominent continental bulge (Figure 7), acts as a natural barrier that can divert debris transported by winds, NBC, and other marine sources, directing it to more exposed regions, such as areas 1 and 2, or retaining it in areas upstream of the barrier. This interaction between the oblique waves and the geographic barrier amplifies the mitigating effect by limiting both the arrival of MPs and their retention in Area 3.

2.6. Conclusions, Possible paths and Future Perspectives

In conclusion, our study revealed, for the first time, the presence of MPs in the most recent natural heritage site of humanity, LMNP, as well as the complexity of pollution in the park and its adjacent areas, highlighting the environmental and anthropogenic factors that influence their distribution. The analysis demonstrated that the proximity of urban waste sources and transport, mediated by currents and winds, could significantly contribute to the pollution of the park. In contrast, area 3, protected by natural geographic barriers and greater coverage of waste management services, presented the lowest levels of pollution. These results reaffirm the importance of understanding the interaction between natural dynamics and human activities in mitigating the impacts of marine pollution in sensitive coastal areas. In addition, the integration of analytical methods, such as spectroscopy and dispersion modeling, supported hypotheses of active MP transport between areas, revealing specific patterns in the chemical composition and likely origin of the waste. The statistical association between lower MP concentrations and proximity to mangrove areas also suggests that these ecosystems may function as natural barriers to contamination. Although not directly tested in this study, this potential filtering role highlights the ecological importance of mangroves for the protection of the LMNP and warrants further investigation.

Therefore, the study's findings contribute to an integrated vision of waste management and environmental protection while also providing support for inter-municipal policies aimed at mitigating plastic pollution. Thus, although MP pollution is multifaceted and complex – driven by interconnected natural and anthropogenic dynamics – the suggestions presented in Text S10 of the Supporting Information may be useful for park management and regional municipal authorities. These recommendations may contribute to the preservation and sustainable use of the LMNP and its surrounding areas, particularly in the context of tourism.

On the other hand, it is equally important that future studies advance the understanding of the transport and deposition mechanisms of MPs in areas beyond the coastal zone of the LMNP, exploring gaps that were not addressed within the scope of this study. A key focus would be to evaluate the impact of MPs carried by the winds into the interior of the park, particularly in its temporary and permanent lagoons, as these bodies of water can serve as areas of accumulation for plastic particles. Additionally, it is essential to investigate how these particles interact with the local fauna, including aquatic and terrestrial organisms that rely on the lagoons as habitats or water sources, and to evaluate potential toxic effects and bioaccumulation in the food chain. Another aspect to be explored involves the detailed identification of the aerial and terrestrial routes of MPs, considering the role of mobile dunes and seasonal wind flows in redistributing particles throughout the park. Studies on the dynamics of MPs in lagoons, including their chemical composition, persistence, and influence on the physicochemical properties of the water, are also crucial for understanding the impacts on fragile and highly interconnected ecosystems. These investigations would expand knowledge of the multiple transport routes of MPs in the LMNP and provide valuable support for conservation strategies that incorporate the integrated management of coastal and inland areas, thereby promoting the protection of both biodiversity and the essential ecosystem services provided by the park.

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2.8. Considerações Gerais

A presente tese reuniu e discutiu, sob uma perspectiva integrada, os avanços científicos obtidos a partir de duas frentes complementares de investigação sobre a poluição por microplásticos (MPs) em Patrimônios Naturais da Humanidade reconhecidos pela UNESCO, com ênfase no Parque Nacional dos Lençóis Maranhenses (PNLM). Ao abordar, inicialmente, um panorama global por meio de uma revisão sistemática da literatura e, em seguida, apresentar uma análise empírica inédita em território brasileiro, esta tese buscou preencher lacunas críticas no conhecimento sobre a presença, distribuição e implicações ecológicas dos MPs em áreas oficialmente protegidas e com reconhecimento internacional por seu valor ecológico e paisagístico.

O primeiro artigo demonstrou que a poluição por MPs está presente em pelo menos 35 sítios naturais reconhecidos pela UNESCO, localizados em 24 países e distribuídos por todos os continentes. As matrizes mais estudadas nesses locais são sedimentos e organismos marinhos, com predominância de fragmentos plásticos e fibras sintéticas. A maior parte das fontes apontadas para essa contaminação decorre do manejo inadequado de resíduos sólidos urbanos, da atividade turística e da proximidade com centros urbanos e industriais. Esse levantamento global evidenciou não apenas a extensão geográfica do problema, mas também o fato de que nem mesmo os locais considerados como ícones de conservação ambiental estão imunes às pressões sistêmicas impostas pela sociedade contemporânea. Além disso, a análise das estratégias de mitigação identificou iniciativas ainda incipientes, fragmentadas e, muitas vezes, dependentes de contextos políticos e institucionais frágeis. O estudo ressaltou, portanto, a urgência de articulações intergovernamentais mais robustas, capazes de tratar a poluição por plásticos e microplásticos como um desafio transfronteiriço e multidimensional.

O segundo artigo representou um marco no estudo da poluição por MPs em áreas protegidas brasileiras ao documentar, pela primeira vez, a ocorrência desse tipo de contaminante no

PNLM. Foram identificados 203 MPs em 60 amostras coletadas, com destaque para as áreas mais próximas a centros urbanos, rotas fluviais e áreas de uso turístico. As análises espectroscópicas indicaram a predominância de polímeros como polietileno, polipropileno e poliestireno – compostos comumente associados a embalagens descartáveis e produtos de uso doméstico. A modelagem hidrodinâmica e a caracterização ambiental das zonas amostradas revelaram ainda que os MPs não se distribuem aleatoriamente, mas respondem a vetores ambientais como correntes marinhas, marés e ventos alísios. Com isso, mesmo regiões afastadas de áreas antrópicas e aparentemente isoladas mostraram-se vulneráveis ao transporte e deposição desses poluentes. A partir dessa abordagem multiescalar, foi possível delinear rotas de entrada de MPs e indicar áreas prioritárias para ações de monitoramento e mitigação.

Ambos os artigos revelam, em conjunto, a natureza difusa, persistente e transfronteiriça da poluição por microplásticos, mesmo em áreas sob regimes de proteção legal. A tese, nesse sentido, avança na consolidação do entendimento de que a designação de “Patrimônio Natural da Humanidade” não é, por si só, garantia de proteção efetiva contra pressões ambientais globais. Os dados apresentados também reforçam o papel fundamental das ferramentas científicas – como a espectroscopia de infravermelho, o geoprocessamento e a modelagem ambiental – na produção de evidências capazes de subsidiar a tomada de decisão por parte de gestores públicos.

A relevância dos achados transcende o campo acadêmico e tem implicações diretas para a gestão ambiental. As informações geradas constituem um importante subsídio para o Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio) e outros órgãos gestores envolvidos na conservação do PNLM e de outras unidades de conservação no Brasil. Esses resultados podem ser incorporados aos planos de manejo, aos protocolos de monitoramento ambiental e às políticas de educação e comunicação ambiental voltadas às populações do entorno, turistas e demais atores sociais interessados.

Além disso, os achados apresentados nesta tese reforçam a necessidade urgente de ampliação de estudos sobre poluição por microplásticos em unidades de conservação brasileiras e, especialmente, em sítios reconhecidos pela UNESCO. Ao tornar visível a presença de contaminantes invisíveis em paisagens frequentemente associadas à pureza ambiental, o presente trabalho convida à reflexão crítica sobre a efetividade das ações de conservação e sobre o papel da ciência na denúncia, compreensão e enfrentamento das múltiplas formas de degradação ambiental que atingem até mesmo os ambientes mais emblemáticos do planeta.

Por fim, esta tese não apenas cumpre o papel de documentar cientificamente uma realidade negligenciada, como também instiga reflexões urgentes sobre o papel da ciência na proteção dos bens naturais, a responsabilidade intersetorial na mitigação dos impactos ambientais e a urgência de reavaliar os paradigmas de consumo e descarte que têm guiado as sociedades modernas. A perpetuação do status de Patrimônio Natural da Humanidade atribuído aos Lençóis Maranhenses

dependerá, em grande medida, da capacidade coletiva de enfrentar a poluição plástica como uma ameaça real e presente — ainda que microscópica.

2.9. Perspectivas para Pesquisas Futuras

Com base nos avanços obtidos nesta tese, algumas frentes de investigação se mostram promissoras e necessárias para o aprofundamento do conhecimento sobre os efeitos da poluição por microplásticos em áreas protegidas:

1. Monitoramento de longo prazo da presença de MPs no PNLM, com inclusão de diferentes matrizes ambientais (água, solo, organismos) e variabilidade sazonal.
2. Estudos ecotoxicológicos locais, que avaliem os efeitos dos MPs sobre espécies-chave da biodiversidade marinha e costeira da região.
3. Investigações sobre nanoplásticos, sua ocorrência e seus efeitos potenciais, ampliando o espectro dos contaminantes analisados.
4. Modelagens preditivas que considerem cenários futuros de pressão turística, mudanças climáticas e urbanização no entorno do parque.
5. Análises sociopolíticas voltadas à compreensão dos entraves e oportunidades para implementação de políticas públicas integradas de combate à poluição plástica.

A continuidade das pesquisas nesse campo é imprescindível para assegurar que o conhecimento científico seja capaz de dialogar com a gestão ambiental e contribuir efetivamente para a proteção dos ecossistemas naturais mais emblemáticos e vulneráveis do planeta.

**TRACKING MICROPLASTICS IN PARADISE: FIRST EVIDENCE OF POLLUTION
IN LENÇÓIS MARANHENSES NATIONAL PARK (MARANHÃO, BRAZIL), A
UNESCO WORLD HERITAGE SITE**

Élida Priscila Bogéa Carvalho^{a,b}, Wesley Rodrigues Soares^{b,c}, Rafaela Ribeiro de Brito^{b,c}, Bárbara Beatriz da Silva Nunes^{a,b}, Aline Sueli de Lima Rodrigues^{b,c}, Ariane Guimarães^b, Giuliano Buzá Jacobucci^a, Letícia Paiva de Matos^b, Abraão Tiago Batista Guimarães^b, Alex Rodrigues Gomes^b, Neuciane Dias Barbosa^d, Estefan Monteiro Fonseca^e, Thiarlen Marinho da Luz^{a,b,f}, Guilherme Malafaia^{b,c,f,*}

^aPost-Graduation Program in Ecology, Conservation, and Biodiversity, Federal University of Uberlândia, Uberlândia 38408144, MG, Brazil.

^bLaboratory of Toxicology Applied to the Environment, Goiano Federal Institute - Urutaí Campus, Rodovia Geraldo Silva Nascimento, 2,5 km, Zona Rural, Urutaí 75790-000, GO, Brazil

^cPost-Graduation Program in Conservation of Cerrado Natural Resources, Goiano Federal Institute, Urutaí 75790-000, GO, Brazil.

^dState University of Amapá, Macapá, AP, Brazil

^eAEQUOR-Laboratory of Environmental Intelligence, 24901-040 Maricá, RJ, Brazil. Department of Geology and Geophysics, Institute of Geosciences, Federal Fluminense University, 4210-340 Niterói, RJ, Brazil

^fPost-Graduation Program in Biotechnology and Biodiversity, Goiano Federal Institute, GO, Brazil.

*Email: guilherme.malafaia@ifgoiano.edu.br

SUPPORTING INFORMATION

Text S1 - Sampling procedures

Specifically, the collection campaigns were carried out between November 25 and 27, 2023, during the dry season in the region. This period was strategically chosen, considering the lower influence of rainfall on the transport and redistribution of MPs, which allows a more accurate analysis of sediment pollution levels. Collections were directed to the surface sediment, using the upper high tide line as a reference, as established in protocols for sampling sandy beaches, due to its propensity to accumulate MP particles transported by the tide (1). Three areas were selected for sampling. Area 1 encompassed the entire stretch of beach within the LMNP limits, measuring 65 km in length and including parts of the municipalities of Primeira Cruz, Santo Amaro do Maranhão, and Barreirinhas, with 50 samples collected (Figure 1). Area 2 encompassed stretches of beaches in the municipalities of Barreirinhas and Paulino Neves, located outside the LMNP limits, spanning 17.5 km and yielding 20 samples. Finally, Area 3 covered the entire coastal area of the municipality of Tutóia, with 12.8 km of beaches, from which 22 samples were collected. These three areas present distinct environmental, geographic, and anthropogenic characteristics that may influence the observed disparities in MP pollution. Area 1, located within the LMNP, is characterized by its remoteness from urban centers, reduced direct anthropogenic pressure, and the presence of unique geomorphological features such as extensive dune fields and marine peat. In contrast, Area 2 includes stretches of coastline near densely inhabited and highly touristic municipalities, with greater proximity to plastic waste hotspots and rivers known to transport urban debris. Area 3, while also outside the park, differs by encompassing regions with better waste management services and natural protective features such as mangroves and geographic barriers, which may contribute to reduced MP accumulation. Thus, the sampling extended 95.3 km, with 92 samples collected (Figure 1). The inclusion of sampling areas outside the park boundaries aimed to evaluate the influence of these regions on the LMNP since, according to the Brazilian Institute of Geography and Statistics (IBGE), these areas make up the direct zone of influence of the park, which is essential to understand the dynamics of pollution by MPs involving the region adjacent to the park.

Text S2 – Sample processing and microplastic extraction

Initially, the samples were divided into two aliquots of similar weight and transferred to additional conical tubes. During this division, visible MPs were separated and stored for later analysis. Then, each subsample was subjected to the flotation process, which consisted of

immersing the samples in a 30 mL saturated zinc chloride (ZnCl_2) solution (1.7 g/cm^3), followed by manual stirring for 2 minutes and then resting for 30 minutes. This solution was chosen to allow the separation of a wide range of polymers present in the sand samples, considering their different densities and the need for efficient separation, similar to Crutchett & Bornt (2) and Gopakumar et al. (3). After the flotation step, the samples were centrifuged at 2500 rpm for 5 min at room temperature ($25\text{-}28^\circ\text{C}$) to facilitate the sedimentation of non-polymeric particles. The supernatant containing potential MPs was filtered through a stainless steel membrane (AISI 304) (400 mesh, $28 \mu\text{m}$ wire diameter, and $36 \mu\text{m}$ aperture) using a vacuum pump. After filtration, the membranes were placed in previously sterilized Petri dishes and dried in an oven with forced air circulation at 50°C for 8 h to eliminate residual moisture. The resulting dry filters were inspected using a stereomicroscope, allowing for visual separation. All MPs (with diameters ranging from $300 \mu\text{m}$ to 5 mm) were collected using stainless steel tweezers and stored in previously sanitized and sterilized conical-bottom microtubes. The MPs targeted in this study are classified as large MPs according to the guidelines of ISO/TR 21960:2020 (4) and the study by Pegado et al. (5). This size range was selected based on technical criteria, aiming to minimize potential influences of external plastic contamination and maximize the accuracy of polymer identification and characterization. Although rigorous anti-contamination procedures were applied (see item “2.4”), particles with diameters smaller than $300 \mu\text{m}$ tend to be more susceptible to inadvertent environmental contamination, even under controlled conditions. Additionally, suspicious particles were previously evaluated using the hot needle test method, as described in Beckingham et al. (6). Only particles with specific visual characteristics of shape, color, and texture, indicative of polymeric materials, were collected, and those that demonstrated melting or deformation characteristics typical of thermoplastic polymers were extracted for subsequent analysis. After extraction, the MPs were subjected to alkaline digestion in conical-bottom microtubes using a 30% hydrogen peroxide solution (1 mL, 2 h, room temperature, $25\text{-}28^\circ\text{C}$), similar to the method described by Prata et al. (7). This process was carried out to remove organic microresidues that were eventually not identified in the initial visual inspection and could act as artifacts in the subsequent chemical characterization (see item “2.5”). After digestion, the MPs were washed twice with purified water, transferred to sterilized Petri dishes, and dried in an oven at 50°C for 5 h. In parallel with these procedures, the sand content remaining after flotation and centrifugation was washed with running water to remove the ZnCl_2 solution. The aliquots were then dried in an oven at 50°C for 48 h and subsequently weighed on an analytical balance, allowing the quantification of MPs per unit mass of sand on a dry basis. The resulting sand, as well as the ZnCl_2 solutions, were sent for safe disposal by a company specialized in treating laboratory waste,

ensuring compliance with environmental standards and a responsible and controlled disposal process.

Text S3 – Anti-contamination procedures

During the collection, processing, and analysis of samples, we employed various strategies to minimize potential external contamination. All equipment and materials, such as glassware, collection tubes, and metal instruments, were thoroughly rinsed with purified water and 70% ethyl alcohol inside a previously sanitized laminar flow hood. Subsequently, the materials were heated to ensure that any potential MPs adhered to their surfaces and then immediately covered with aluminum foil, which had also been heated beforehand. The collection tubes were kept closed until the exact moment of collection, including the “environmental blanks,” which consisted of tubes opened simultaneously with active sampling along the length of the beaches, exposed to the environment during the collection period, and closed immediately afterward. After collection, all tubes were closed and opened exclusively in the laboratory, inside a laminar flow hood, under controlled conditions. The water and ethyl alcohol used were previously filtered through a 0.45 μm nitrocellulose membrane. In addition, the researchers used personal protective equipment, including 100% cotton lab coats and gloves. Their gloved hands were sanitized with purified water and 70% ethanol before each step. The work areas were kept continuously sanitized, while the benches in the procedure room and the internal area of the laminar flow hood were regularly cleaned with 70% ethyl alcohol. During the experimental procedures, the air circulation in the work areas was turned off, and access was restricted to the researchers involved in the study. The “procedural blanks” consisted of membranes placed in glass Petri dishes positioned at different points in the laboratory environment to monitor possible environmental contamination. In parallel with the sample analyses, these “blanks” were inspected under a stereomicroscope, and no plastic particles were identified in the size range established in our study ($300\text{ }\mu\text{m} < x < 5\text{ mm}$).

Text S4. Characterization of microplastics

Considering that the characteristics of MPs determine their distribution and impact on the environment, in addition to helping predict their potential sources, all extracted particles were analyzed and classified according to color patterns (red, orange, yellow, green, blue, violet, black, white, transparent, gray, or brown) and types (fragments, fiber/filaments, foam, film, bead or others), based on Hidalgo-Ruz et al. (8) and Martí et al. (9). In addition, all MPs were photographed and subsequently analyzed using ImageJ software (10) to determine their size (diameter, area, and perimeter) and complementary shape characteristics based on the circularity and solidity parameters, similar to those used by Su et al. (11). To determine the polymeric

chemical nature of the extracted MPs, all identified particles ($n = 317$) were analyzed using Raman spectroscopy (Cora 5001 spectrometer, software version 1.4.1), like Luz et al. (12). The laser source operated at a wavelength of 785 nm, with a power of 45 mW, and the automatic exposure feature was activated, with an exposure time of 10,000 milliseconds per sample. The orientation of the focus rotor was vertical, and the position of the focus stage was at -9.80. The dark background setting was activated to minimize background noise. Subsequently, the obtained spectra were processed using the Spectragryphy v1.2.16.1 software, following a specific sequence to ensure data quality and consistency. First, we applied the advanced baseline correction to remove any trend or baseline shift that could interfere with the analysis of the characteristic peaks of the spectra. We then used advanced smoothing to reduce noise in the spectra, and the next step involved removing cosmic spikes and eliminating interference caused by cosmic radiation or other noise sources that could introduce artifacts into the spectra. Finally, we applied peak normalization to standardize the signal intensities. We compared the spectra with those available in the custom spectral library of the Laboratory of Applied Toxicology for the Environment (Instituto Federal Goiano, Campus Urutaí, Brazil). This library comprises 23 polymer types derived from the analysis of 350 plastic products of varying colors, sizes, and applications, encompassing both pristine and weathered plastic polymers. An average similarity index of 87.5% was achieved for the identification of polymers in our library when compared with the Japan Standard library, the standard library of the equipment, open-access libraries (such as the Spectral Database for Organic Compounds, KnowItAll, and PubSpectra), and scientific articles. Spectra with a quality index of ≥ 0.7 were accepted for polymeric identification of the MPs in the analyzed samples, while those with a quality index of < 0.6 were rejected. Spectra with a quality index between 0.6 and 0.7 were individually inspected and interpreted based on the proximity of the absorption frequencies about the known chemical bonds of the polymers, similar to Woodall et al. (13), considering that degradation processes, such as oxidation reactions, can alter the chemical composition of the polymers, resulting in discrepancies between the reference spectra and those from environmental samples.

Text S5. Distribution maps, polymer hazard index, and pollution load index

After processing and analyzing the samples, the concentrations (MPs/kg) were corrected for sampling density, taking into account the length (km) of the sampled beach sections and the number of samples collected in each area. To this end, a specific correction factor was calculated for each area, obtained by dividing the number of samples collected by the length of the corresponding area. The highest value among these factors was used as a reference and divided

by the correction factor for each area. Then, each MP concentration was adjusted by multiplying this factor, resulting in data expressed as “(number of MPs/kg)/km.” These data were then combined with data on the chemical composition of the MPs and used in the risk analysis by determining the contamination factor (CF) and the polymer hazard index (PHI), as described by Das et al. (14). The CF was calculated following Equation 1, where “Ci” represents the concentration of MPs [(item/kg)/km] at the site “i,” while “C0” denotes the reference or background concentration of MPs. Due to the lack of previous data in the studied areas, we adopted the lowest observed concentration of MPs as the background concentration, as described by Ranjani et al. (15) and Gupta et al. (16). The PHI was calculated according to Lithner et al. (17), associating the environmental risk with the specific polymers of the MPs. For this, we used the formula expressed in Equation 2, where “Pp” represents the polymeric percentage of the MPs in each area, and “Hs” denotes the hazard score of each polymer, as defined by Lithner et al. (17).

$$CF_i = \frac{C_i}{C_0} \quad \text{Eq. 1}$$

$$PHI = \sum P_p \times H_s \quad \text{Eq. 2}$$

Spatial distribution maps were created using QGIS software (desktop version 3.38.3), with a heatmap rendering applied in false color using a single band configuration. The visualization mode was set to continuous, with 255 classes representing different combinations of CF and PHI gradients.

Text S6 - Dispersion simulation

To investigate the potential influence of ocean currents and winds on the dispersion of MPs between areas 1 and 2, we conducted a literature review that included data on the types and flows of prevailing ocean currents in the region [as described in Pickard & Emery (18), Neumann & Pierson (19) and Harari (20)], local wind patterns and direction [obtained from the Global Wind Atlas (21)], as well as information on air masses with seasonal effect in the studied area, according to Nimer (22), Borsato (23) and Borsato & Massoquim (24). In addition, we used Plastic Tracker, a tool based on the Pol3DD Lagrangian dispersion model, which simulates large-scale dispersion patterns (25), to generate simulations of potential dispersion routes considering interactions with currents and winds based on predefined internal algorithms and parameters, according to Luz et al. (12). It is important to note that Plastic Tracker is an open-access platform

with limited configurability: users cannot define or adjust physical assumptions such as floating depth, vertical mixing, or degradation rates. Moreover, while it incorporates oceanographic (HYCOM/GLORYS) and atmospheric (ECMWF) reanalysis datasets, the model does not allow direct selection or visualization of seasonal differences. Therefore, the outputs should be interpreted as general, indicative trajectories rather than precise forecasts. The analysis of the resulting routes focused on the directions and senses of the dispersion trajectories to verify the consistency of the simulated patterns with previously collected oceanographic and atmospheric information, allowing us to infer the plausibility of the transport of MPs between the sample regions (from area 2 to area 1).

Text S7 - Statistical analyses

In our study, we applied a customized statistical approach to meet the specific objectives of each analysis. For comparisons between parameters associated with pollution load and MP characteristics in the different areas, we used the one-way ANOVA test with Tukey's post-test or the Kruskal-Wallis test, with Dunn's post-test, defined based on the verification of the assumptions of normality and homogeneity of data variance (Shapiro-Wilk and Levene test, respectively). To identify which environmental, geographic, and land use variables significantly influenced MP pollution levels in the investigated areas, we performed a Principal Component Analysis (PCA) using the data from the variables presented in Table S1 and the CF values. Initially, variables with zero standard deviation between areas were excluded from the analysis. To ensure numerical compatibility for subsequent analyses, we added 2.5 to all values of the remaining variables, including those originally null, thereby minimizing distortions in variance and correlation calculations. Then, the mean values of each variable per area, combined with the CF data, were submitted to PCA. To interpret the PCA, we considered criteria that included eigenvalues greater than 1 for selecting significant principal components (PCs), construction of biplots to visualize the relationships between variables and areas, analysis of loadings to identify the contribution of each variable in the PCs, and PC scores to evaluate the distribution of the areas in the component space. The analysis was conducted based on the correlation matrix, which inherently centers and scales each variable (i.e., performs a Z-transformation), thereby standardizing the data and eliminating scale discrepancies. This procedure allowed for the exploration of interrelationships between variables, both within and between areas. A similar analysis was performed using data from the characterization of the MPs and the CF observed in the areas. Specifically, for the samples collected at LMNP (Area 1), the CF values were grouped into three subgroups based on the observed contamination levels: low, medium, and high CF.

These subgroups were then combined with the variables in Table S1 (exclusive to area 1) in a PCA, aiming to identify environmental and anthropogenic factors most correlated with the highest pollution levels by MPs in this area, adopting the criteria described above.

For the spectral comparison between the MPs identified in areas 1 and 2, we used spectral data that included the Raman shift (cm^{-1}) in the range of 800 to 1800 cm^{-1} - selected because it encompasses bands characteristic of the specific functional groups of the polymers of interest - and the amplitude of the Raman peaks, representing the relative intensity of each signal. Initially, these data were subjected to a correlation analysis (Pearson or Spearman, depending on the assumptions of normality and linearity of the data) to assess the spectral similarity between the MPs of the different areas, using correlation coefficients and p-values as criteria for statistical significance. Subsequently, the data were processed in a PCA to identify patterns of variability and spectral grouping trends (adopting the requirements described above), complemented by a hierarchical cluster analysis using the Ward method, with Euclidean distance as a measure of proximity, aiming to identify and group the MPs with similar spectral profiles between the areas. For all analyses, we adopted a significance level of 95%, using the software GraphPad Prism v.10.4.0 and PAleontological STatistics (PAST).

Text S8 – Supplementary Information for the title and legend of Figure 6

Interactions between ocean currents, wind patterns, and microplastic (MP) transport in the Lençóis Maranhenses National Park (LMNP). (A) Illustrative map showing the directions of ocean currents along the Brazilian coast and the Atlantic Equatorial Air Mass (AEAm) flow (summer). (B) Spatial distribution of the Contamination Factor (CF) of MPs in the investigated areas overlaid with the North Brazil Current (NBC) routes and the seasonal AEAm flow. (C) The wind rose indicates the predominance of coastal winds aligned with MP transport and the average wind speed at 100 meters altitude in the State of Maranhão, Northeastern Brazil. Legend: NECC: North Equatorial Countercurrent; SEUC: Southern Equatorial Undercurrent; cSEC: Central branch of the South Equatorial Current; EUC: Equatorial Undercurrent; SICC: South Intermediate Countercurrent; NICC: North Intermediate Countercurrent; NBUC: North Brazil Undercurrent; GD: Guinea Domes; NEC: North Equatorial Current; NEUC: Northern Equatorial Undercurrent; BC: Brazil Current; MC: Malvinas Current; SD: Subantarctic Front; SAC: South Atlantic Current. Dashed arrows indicate the predominant wind direction. Area 1 encompassed the entire beach extension within the boundaries of the Lençóis Maranhenses National Park (LMNP), Area 2 included beach sections in the municipalities of Barreirinhas and

Paulino Neves, located outside the LMNP boundaries, and Area 3 covered the entire coastal extent of the municipality of Tutoia (State of Maranhão, Northeastern Brazil).

Text S9. Principal Component Analysis (PCA) of Environmental, Geographic, and Anthropogenic Variables Associated with Microplastic Contamination

To understand which variables in terms of environmental, geographic, and land use characteristics exert the most significant influence on the levels of MP pollution in the investigated areas, we performed a PCA with the collected data. As shown in Figure S2B, the PCA revealed that PC1 and PC2 together explained 100% of the total variance and highlighted a clear separation between the areas based on the factors that contributed most to the presence of MPs. Area 1 (LMNP), located in the lower left quadrant (PC1score: -6.73 and PC2score: -1.56) (Figure S2B), was strongly influenced by variables with negative loadings in both components (Table S3). The greater distance from urban areas (PC1: -5.86 and PC2: -0.84), port complexes (PC1: -6.15 and PC2: -0.13), oil refineries (PC1: -6.15 and PC2: 0.07), characterize this area as less impacted by direct urban and industrial activities. Furthermore, local physical characteristics such as greater length of coastline (PC1: -5.84 and PC2: -0.88), predominance of beaches, dunes and sandbanks (PC1: -5.99 and PC2: -0.84) and a higher granulometry of sand grains [perimeter (PC1: -5.67 and PC2: -1.07), diameter (PC1: -5.68 and PC2: -1.06) and area (PC1: -5.69 and PC2: -0.106)] seem to influence the presence and dispersion of MPs. The oceanographic dynamics, with a higher maximum wave height (PC1: -6.08 and PC2: 0.55) and a longer period of primary swelling waves (PC1: -5.32 and PC2: -1.38), also suggest an influential role in the movement of MPs.

Area 2, with a PC1score of 0.86 and a PC2score of 4.03, was associated with variables with positive loadings in PC2, reflecting a greater influence of anthropogenic factors (Figure S2B and Table S3). The intense tourist activity (PC1 = 0.02; PC2 = 3.62), the large territorial area of the municipalities (PC1 = -3.87; PC2 = 2.82), proximity to urban roads or highways (PC1 = -4.53; PC2 = 2.45) and the high consumption of plastic by local populations (PC1 = 3.87; PC2 = 2.51) indicate significant pressure on this area. The relationship between these variables and high contamination (100% of the samples) suggests that the contribution of MPs is directly linked to these human factors, evidenced by a higher CF (Figure 2A). Area 3, with PC1score of 5.97 and PC2score of -2.42 (Figure S2B and Table S3), presented the lowest levels of pollution by MPs, reflected in the lowest percentage of contaminated samples (54.5%) and a reduced CF (Figure 2A). This positioning in the PCA was determined by variables with positive loadings in PC1, such as the greater direction of the sea surface wave from direction (PC1: 5.35 and PC2: -0.22) and the greater percentage of people served by household garbage collection (PC1: 5.33 and PC2: -

0.35), household cleaning services (PC1: 5.26 and PC2: -0.57) and garbage disposal in dumpsters (PC1: 5.13 and PC2: 1.06), in addition to the greater extension of forest formation areas (PC1: 4.56 and PC2: -1.45) and mangroves (PC1: 4.68 and PC2: -1.35) in the municipality. Additionally, higher population density (PC1: 5.11; PC2: -0.84) and proximity to larger urban areas (PC1: 3.75; PC2: -1.98) showed an inverse association with CF (PC1: -3.61; PC2: 2.93) (Figure S2B and Table S3).

After jointly analyzing the three investigated areas, we opted for a more detailed approach focused exclusively on the LMNP area, seeking to identify contamination patterns and specific environmental and anthropogenic factors that could be associated with different concentrations of MPs along the park's edge. For this, the MP CF data from the samples collected at the LMNP were organized into three distinct subgroups based on the observed contamination levels (median $\pm$ SEM): subgroup A (AS, low): 2.14 ± 0.31 ; subgroup B (SB, medium): 4.90 ± 0.13 ; and subgroup C (SC, high): 9.90 ± 1.02 [(MPs/kg)/km]. We then performed a PCA associating the identified subgroups with the collected environmental and anthropogenic variables to identify the factors potentially most correlated with the highest level of MP pollution in this area (Figures 4A-B). Our analysis revealed that the first two principal components (PC1 and PC2) explained 100% of the total variance, with PC1 accounting for 86.9% and PC2 for 13.1%. As shown in Figure 4B, the variables that showed a positive correlation with the samples with the highest contamination (SC) included the area of the territorial unit, the total population and population density of the municipalities where the LMNP is located, as well as the number of tourists (PC1: 4.276 and PC2: -0.428), the total emerged beach width (PC1: 4.361 and PC2: -0.017) and the waste spill risk classification (PC1: 4.149 and PC2: -0.667) (Table S4 – see “Supplementary Material”). In addition, field observations revealed the existence of marine peat in several stretches of the LMNP (Figures 4C-E), which coincided with locations with the highest concentration of MPs. In contrast, we observed a negative association between the SC CF and the diameter of the sand grains (PC1: -5.434 and PC2: 0.461) (Table S3), indicating that locations with finer sand grains are more associated with higher concentrations of MPs in the park

Text S10. Management Recommendations for Mitigating Microplastic Pollution in LMNP and Surrounding Coastal Areas

1. It is essential that all municipalities in the region have full collection service coverage, as well as be supported by initiatives that encourage the separation, collection, and recycling of plastics, with the involvement of municipal governments. This is particularly important,

considering that a significant portion of the MPs found in the LMNP originate from land, underscoring the need to prevent improper waste disposal at the source.

2. Ensure the application and enforcement of Brazilian legislation to monitor and prevent activities that degrade mangroves, such as irregular occupations and waste dumping, as these areas play a crucial role as natural barriers against the entry of MPs into the park's ecosystems.
3. Implement ongoing programs to monitor pollution by MPs in the LMNP, with regular data collection covering the primary sources, distribution patterns, and chemical composition of plastics. These programs should include monitoring human activities that may contribute to the release of MPs, systematic monitoring of the coastline and areas of influence, and the integration of technologies such as remote sensing and spectral analysis to identify contamination hotspots. Additionally, community participation and the formation of partnerships with research institutions can enhance the efficiency of monitoring and facilitate mitigation actions based on scientific data.
4. Encourage the integration of studies that are commonly developed in the LMNP with strategies to mitigate pollution by MPs. Research on plant biodiversity, such as studies on mangroves and other native plants, can be directed to investigate their capacity to act as natural barriers, retaining MPs before they reach sensitive areas. Studies on fauna and animal ecology, such as monitoring of sea turtles and fish, can incorporate analyses of the impacts of MPs on these organisms, helping to identify critical areas of contamination. The exploration of socio-environmental aspects, such as local conflicts and the use of natural resources, can be linked to raising awareness among communities about proper waste disposal practices and reducing the use of single-use plastics. Environmental education programs based on traditional knowledge could incorporate participatory monitoring activities of MPs, while analyses of tourist carrying capacity could inform the implementation of sustainable waste management practices. By supporting research focused on these connections, the LMNP would not only increase knowledge about the impacts of MPs but also strengthen integrated conservation and sustainability strategies, promoting an innovative model of environmental management.
5. Intensify sustainable tourism strategies to mitigate pollution by MPs and conserve the ecosystem. This would include educational programs to raise awareness of the impact of MPs and encourage practices such as "zero waste," as well as sustainable infrastructure, with selective collection stations and hydration points to reduce the use of single-use plastics.

6. Expand or improve practices to regulate visitor flows and control tourism activities, including dynamic monitoring, e.g., through the use of technologies such as drones and sensors to assess impacts in real time and adjust visitor limits as necessary. Expand training for guides on sustainable tourism practices and the importance of mitigating pollution from PMs, and offer benefits to tour operators who adopt more sustainable measures.
7. Environmental taxes could be introduced to finance conservation actions. At the same time, partnerships with ecotourism companies and NGOs would strengthen monitoring and the adoption of responsible practices, consolidating the LMNP as a reference in sustainable tourism.
8. Expand and strengthen the establishment of regional consortia for solid waste management, promoting the sharing of resources, infrastructure, and technology, as well as developing and implementing integrated action plans to mitigate plastic pollution, considering the joint impact of cities in the region.
9. 9. Promote the technical training of municipal managers in modern solid waste management practices by offering courses and training focused on recycling, composting, and sustainable waste management. Additionally, establish partnerships with research institutions to develop local recycling technologies.
10. Create tax and economic incentives for local companies that invest in alternatives to disposable plastic, promoting the use of biodegradable and reusable materials in municipalities under the park's influence, particularly in tourist areas and businesses that rely on visitor traffic to the LMNP.

Table S1. Environmental, geographical, and land use variables surveyed for the investigated areas.

Variables related to municipalities	Data source
Demographic and municipal development indicators: Total population, population density (inhabitants/km²), Municipal Human Development Index (HDI), and territorial unit area (km²), obtained from the Brazilian Institute of Geography and Statistics (IBGE).	IBGE (26)
Household waste disposal: Percentage of individuals disposing of waste in public service containers, burning or burying waste on their property, dumping waste in vacant lots, slopes, or public areas, and those served by household waste collection services, including public cleaning services.	IBGE (27)
Municipal land use and coverage: Percentage of the municipality's total area occupied by vegetation formations (forests, savannas, mangroves, and non-forest formations), pastures, agricultural areas, urban zones, beaches, dunes, sandy areas, and water bodies (rivers, lakes, and oceans).	MapBiomias (28)
Plastic pollution risk indicators: This includes plastic consumption, the classification of potential stock of plastic waste prone to leakage (EPRPE), which indicates the quantity of plastic waste available for dispersion in the environment, and the classification of plastic waste leakage risk.	Alencar et al. (29) and Pacto Global da ONU – Rede Brasil (30)
Number of tourists in the year before data collection: Total number of tourists (international and national) who visited the municipality in the year preceding data collection, based on information provided by the Brazilian Ministry of Tourism.	Ministério do Turismo (31)
Meteorological and oceanographic variables	

Climatic and meteorological indicators: Includes daily (on the collection day) and monthly (30 days before collection) averages from the nearest meteorological station to the evaluated stretch or beach. Variables include air temperature (°C), wind speed (m/s), wind direction (°), gust speed (m/s), solar radiation (Kj/m²), and total precipitation (mm).

Obtained from the National Institute of Meteorology database, Ministry of Agriculture and Livestock, Brazil (32).

Tidal range (1st, 2nd, and 3rd tide) and tidal coefficient: Recorded in the municipality on the day of data collection.

Provided by the Hydrography Center of the Brazilian Navy (33).

Local oceanographic Indicators: These variables are recorded at the evaluated stretch or beach on the collection day. These comprise seawater salinity (PSU), seawater velocity (m/s), seawater potential temperature (°C), sea surface wave direction (°), sea surface wave significant height (m), sea surface wind wave direction (°), sea surface wind wave mean period (s), sea surface wind wave significant height (m), mole concentration of dissolved molecular oxygen in seawater (mmol/m³), seawater alkalinity expressed as mole equivalent (mol/m³), seawater pH reported on the total scale, mass concentration of chlorophyll an in seawater (mg/m³), and mole concentration of phytoplankton expressed as carbon in seawater (mmol/m³).

Derived from data assimilation models supplied by the Copernicus Marine Environment Monitoring Service (34-36).

Variables related to the sampling point or beach segment

Total emerged beach width (TEBW): Measured in meters (m), including the area periodically covered and uncovered by water, as well as the detrital material strip (sand, gravel, pebbles) up to the edge of natural vegetation or another ecosystem. Measurements were conducted using satellite images and Google Earth Pro tools, calculating the Euclidean distance between the lowest high-tide line and the base of the frontal dune.

This variable was measured according to the criteria defined by the Brazilian Ministry of Economy (37) and McSweeney et al. (38).

Proximity to Urban Areas: The distance (km) from each sampling point to the nearest urban area was assessed using shapefiles obtained from IBGE and measurement tools from QGIS

IBGE (39) e QGIS Development Team (40)

software (desktop version 3.38.3). The area (km²) of the closest urban zone was extracted from shapefile data, along with the categorization of each zone based on the degree of urbanization (“sparsely populated,” “moderately populated,” or “densely built”).

Shoreline classification: The shoreline where the sampling occurred was classified based on the relationship between form and incident hydrodynamic energy, according to Fellowes et al. (2019) and Gallop et al. (2020), with some modifications. The classification uses the embayment morphometric parameter (γ_e), calculated as $\gamma_e = a/\sqrt{A_e}$, where “a” is the embayment depth and “ A_e ” is the embayment area. Classes were defined by γ_e values, ranging from “exposed” ($\gamma_e < 0.36$) to Class V ($\gamma_e > 2.3$ or beaches within a bay). Measurements were performed using Google Earth tools.

Distance from the nearest river mouth: Euclidean distance (km) from each sampling point to the main river mouth of the closest sub-basin, considering the bank (right or left) as a reference, following similar procedures adopted in previous studies. This variable was calculated based on plotting sampling points on a map using the shapefile from the Ottocoded Hydrographic Base of the Brazilian National Water Agency (ANA). Measurements were taken using QGIS software (desktop version 3.38.3) tools.

Proximity to the nearest urban road or highway: Euclidean distance from each sampling point to the nearest urban road (expressways, arterial, collector, or local roads) or highway (state or federal - radial, longitudinal, transversal, diagonal, or connecting roads). Rural unpaved roads were excluded from the evaluation. This variable was calculated based on plotting sampling points on a map using shapefiles of the federal and state road networks obtained from the

National Department of Transport Infrastructure (DNIT) of Brazil and QGIS measurement tools (desktop version 3.38.3).

Proximity to petroleum storage and distribution terminals: Euclidean distance from each point to the nearest petroleum storage and distribution terminal. This variable was calculated using shapefiles of terminals obtained from the Geographic Information System of the Brazilian Energy Sector, accessed via the MapBiomias Brazil platform and measurement tools from QGIS (desktop version 3.38.3). MapBiomias Brasil (50)

Proximity to petroleum refineries or processing facilities: Euclidean distance from each point to the nearest petroleum refinery or other processing facilities, similar to previous studies. This variable was calculated using shapefiles of terminals obtained from the Geographic Information System of the Brazilian Energy Sector, accessed via the MapBiomias Brazil platform and QGIS measurement tools (desktop version 3.38.3). MapBiomias Brasil (50) and Pegado et al. (5)

Proximity to port complexes: Euclidean distance from each sampling point to the nearest port complex. This variable was calculated based on plotting sampling points on a map using shapefiles of terminals obtained from the National Water Agency (ANA) and QGIS measurement tools (desktop version 3.38.3). ANA (51)

Proximity to infrastructures: Evaluated whether the sampling point was located within 500 m of coastal structures (e.g., groins), parking lots, urban watercourses or sewage discharge channels, sports facilities, and condominiums/resorts, adapted from previous studies. The evaluation was conducted in the field and supplemented with satellite image analysis and Google Earth Pro measurement tools. Results were categorized as "yes" (within distance) or "no" (outside distance). Lozoya et al. (47), Bissen & Chawchai (52), Bridson et al. (53), Thepwilai et al. (49), Google (54)

Classification of structures for bathers/visitors: This variable assessed the number of structures for bathers and visitors (e.g., tents, kiosks, umbrellas, chairs) within a maximum radius of 500 m from the sampling point. The presence of these structures was categorized as "absent," indicating no visible facilities; "few," representing a limited number of structures, such as a few chairs or tents; and "many," characterizing a significant number of facilities, with numerous chairs, umbrellas, and beach services available. The evaluation was conducted in the field and complemented by satellite image analysis using Google Earth Pro, ensuring an objective and rigorous approach to categorization.

Google (54)

Table S2. Loading and PC score values of Principal Component Analysis (PCA) for the two main components (PC1 and PC2) for different variables analyzed (concentration factor and microplastic characteristics).

ID variables	Variable IDs meaning	Principal components (loadings)	
		PC1	PC2
Microplastics	Concentration factor (CF)	-3.41	0.04
2	Diameter mean (mm) of microplastics	-2.02	-2.50
3	Circularity mean of microplastics	1.33	2.20
4	Solidity mean of microplastics	1.00	-3.03
5	Particle type (Fragments) (%)	-3.24	0.73
6	Particle type (Fiber/filaments) (%)	2.77	-2.46
7	Particle type (Foam) (%)	4.36	0.65
8	Particle type (Bead) (%)	-3.14	0.91
9	Polyethylene (PE) microplastics	3.46	1.49
10	Polypropylene (PP) microplastics	-3.40	-0.29
11	Polystyrene (PS) microplastics	-3.34	-0.63
12	Polyvinyl chloride (PVC) microplastics	-2.95	-1.57
13	Polyethylene terephthalate (PET) microplastics	4.20	0.89
14	Expanded polystyrene (EPS) microplastics	3.80	1.27
15	Polyether ether ketone (PEEK) microplastics	-0.80	-3.02
16	Random propylene-ethylene copolymers (PEC) microplastics	0.17	-3.10
17	Ethylene-methyl acrylate copolymers (EMA) microplastics	-3.38	0.33
18	Poly(ethylene-vinyl acetate) (PEVA) microplastics	3.87	-1.63
19	Thermoplastic polyurethane (PTMG-MDI-BD) microplastics	4.36	0.65
21	Red-colored microplastics (%)	-3.22	-1.03
22	Orange-colored microplastics (%)	-0.80	-3.02
23	Yellow-colored microplastics (%)	4.09	-1.35
24	Gren-colored microplastics (%)	-2.55	1.53
25	Blue-colored microplastics (%)	-3.27	0.67
26	Purple-colored microplastics (%)	-3.40	-0.28
27	Black-colored microplastics (%)	-2.47	1.59
28	White-colored microplastics (%)	4.48	-0.53
29	Transparent microplastics (%)	4.52	-0.34
30	Grey colored microplastics (%)	-3.17	0.86
31	Brown colored microplastics (%)	-3.40	-0.28
Areas ⁽¹⁾		PC scores	
		PC1	PC2
Area 1		-1.23	-3.45
Area 2		-3.79	2.44
Area 3		5.02	1.00

⁽¹⁾**Area 1** encompassed the entire stretch of beach within the boundaries of the Lençóis Maranhenses National Park (LMNP); **Area 2** included beach segments in the municipalities of Barreirinhas and Paulino Neves, located outside the LMNP boundaries; and **Area 3** covered the entire coastal stretch of the municipality of Tutóia (Maranhão State, Northeast Brazil).

Table S3. Loading and PC score values of Principal Component Analysis (PCA) for the two main components (PC1 and PC2) for different variables analyzed (concentration factor and environmental, geographical, and land use variables).

ID variables	Variable IDs meaning	Principal components (loadings)	
		PC1	PC2
Microplastics)	Concentration fator (CF)	-3.62	2.94
2	Number of tourists	0.03	3.63
3	Length of beaches/stretchers (km)	-5.84	-0.88
4	Total population (number of inhabitants)	5.35	0.34
5	Population density (number of inhabitants/km ²)	5.12	-0.85
6	Area of the territorial unit (km ²)	-3.87	2.82
7	Municipal Human Development Index	4.54	1.95
8	Percentage of people served by garbage collection at home	5.33	-0.36
9	Percentage of people served by garbage collection at home by cleaning service	5.26	-0.57
10	Percentage of people who deposit garbage in a cleaning service dumpster	5.14	1.07
11	Percentage of people who burn garbage on their property	-6.07	0.63
12	Percentage of people who bury garbage on their property	4.97	-1.06
13	Percentage of people who throw garbage on vacant land, hillside, or public area	4.76	-1.29
14	1st tide (m) - collection day	-6.15	0.23
15	2nd tide (m) - collection day	-5.96	-0.70
16	3rd tide (m) - collection day	-6.15	0.25
17	Tidal coefficient (m) - collection day	3.75	2.60
18	Forest formation (%)	4.57	-1.46
19	Savanna formation (%)	4.12	2.34
20	Mangrove (%)	4.69	-1.36
21	Non-forest natural formation (%)	0.60	3.61
22	Pasture (%)	-5.78	1.25
23	Beaches. dunes and sandbanks (%)	-5.99	0.84
24	Urbanized area (%)	5.38	0.03
25	River, lake, and ocean (%)	3.31	-2.18
26	Plastic consumption	3.87	2.52
27	Leakage risk classification	5.25	-0.60
28	Temperature (average recorded on the day of collection) (°C)	4.94	1.44
29	Wind speed (average recorded on the day of collection) (m/s)	4.94	1.44
30	Wind direction (average recorded on the day of collection) (o)	-5.66	-1.10
31	Wind gust (average recorded on the day of collection) (m/s)	4.94	1.44
32	Solar radiation (average recorded on the day of collection) (kj/m ²)	4.94	1.44
33	Total emerged beach width (TEBW) (m)	4.74	1.72
34	Distance from the sampling point to the nearest urban area (km)	-5.87	-0.84
35	Classification of the urban area (not very dense, dense or densely built)	4.94	1.44

36	Area (km ²) of the urban area closest to the sampling point	3.76	-1.98
37	Distance from the mouth of the nearest river (km)	-6.10	0.51
38	Proximity to the nearest urban road or highway (km)	-4.54	2.46
39	Proximity to an oil and derivatives storage and distribution terminal (km)	5.37	-0.10
40	Proximity to an oil refinery or other processing facilities (km)	-6.16	0.08
41	Proximity to a port complex (km)	-6.15	-0.13
42	Proximity to an area of mangrove vegetation (km)	-5.77	-0.97
43	Proximity to urban watercourses or sewage discharge channels	4.31	-1.65
44	Sea water velocity (ms)	3.71	-2.00
45	Sea water salinity ($\times 10^{-3}$)	-5.70	1.37
46	Sea water potential temperature (°C)	-3.34	3.05
47	Sea surface wave from direction (°)	5.36	-0.23
48	Sea surface wave maximum height (m)	-6.09	0.55
49	Sea surface primary swell wave mean period (s)	-5.33	-1.39
50	Mole concentration of dissolved molecular oxygen in seawater (mmol/m ³)	4.33	2.15
51	Sea surface primary swell wave from direction (°)	-5.96	0.92
52	Area mean (μm^2) of sand grains	-5.69	-1.06
53	Perimeter mean (μm) of sand grains	-5.68	-1.07
54	Diameter mean (μm) of sand grains	-5.69	-1.07
Areas ⁽¹⁾		PC scores	
		PC1	PC2
Area 1		-6.84	-1.61
Area 2		0.87	4.03
Area 3		5.97	-2.43

⁽¹⁾**Area 1** encompassed the entire stretch of beach within the boundaries of the Lençóis Maranhenses National Park (LMNP); **Area 2** included beach segments in the municipalities of Barreirinhas and Paulino Neves, located outside the LMNP boundaries; and **Area 3** covered the entire coastal stretch of the municipality of Tutóia (Maranhão State, Northeast Brazil).

Table S4. Loading and PC score values of Principal Component Analysis (PCA) for the two main components (PC1 and PC2) for different variables analyzed (concentration factor and environmental, geographical, and land use variables).

ID variables	Variable IDs meaning	Principal components (loadings)	
		PC1	PC2
1	Number of tourists	4.28	-0.43
2	Total population (number of inhabitants)	4.28	-0.43
3	Population density (number of inhabitants/km ²)	4.28	-0.43
4	Area of the territorial unit (km ²)	4.28	-0.43
5	Percentage of people served by garbage collection at home	4.28	-0.43
6	Percentage of people served by garbage collection at home by cleaning service	4.19	-0.60
7	Percentage of people who deposit trash in a cleaning service dumpster (%)	4.19	-0.60
8	Percentage of people who burn trash on their property (%)	-5.43	0.46
9	Percentage of people who bury trash on their property (%)	-5.25	-0.69
10	2nd tide (m) - collection day	-5.13	0.89
11	3rd tide (m) - collection day	-4.16	1.55
12	Tidal coefficient (m) - collection day	-5.43	0.46
13	Forest formation (%)	4.17	-0.64
14	Savanna formation (%)	4.30	-0.35
15	Mangrove (%)	4.04	-0.82
16	Non-forest natural formation (%)	4.13	0.75
17	Pasture (%)	4.04	-0.82
18	Beaches, dunes, and sandbanks (%)	4.13	0.75
19	Urbanized area (%)	-5.39	0.55
20	River, lake, and ocean (%)	4.13	0.75
21	Plastic consumption	-5.51	0.27
22	Leakage risk classification	4.15	-0.67
23	Total emerged beach width (TEBW) (m)	4.36	-0.02
24	Distance from the sampling point to the nearest urban area (km)	4.31	0.35
25	Classification of the urban area (not very dense, dense, or densely built-up)	3.87	1.08
26	Area (km ²) of the urban area closest to the sampling point	3.97	0.97
27	Distance from the mouth of the nearest river (km)	4.08	0.83
28	Proximity to nearest urban road or highway (km)	-4.01	-1.49
29	Proximity to oil and oil products storage and distribution terminal (km)	3.76	1.19
30	Proximity to oil refinery or other processing facilities (km)	4.09	0.81
31	Proximity to port complex (km)	-5.18	-0.77
32	Proximity to mangrove vegetation area (km)	1.42	2.22
33	Sea water potential temperature (°C)	3.66	1.27
34	Mole concentration of dissolved molecular oxygen in seawater (mmol/m ³)	4.33	-0.25
35	Perimeter mean (μm) of sand grains	4.36	-0.02

36	Diameter mean (µm) of sand grains	-5.43	0.46
	Subgroups ⁽¹⁾	PC scores	
		PC1	PC2
	Subgroup A (SA)	1.27	2.46
	Subgroup B (SB)	-6.12	-0.80
	Subgroup C (SC)	4.85	-1.66

⁽¹⁾The CF data of MPs from samples collected in the LMNP were organized into three distinct subgroups based on the observed contamination levels (median ± SEM): subgroup A (AS, low): 2.14 ± 0.31 ; subgroup B (SB, medium): 4.90 ± 0.13 ; and subgroup C (SC, high): 9.90 ± 1.02 [(MPs/kg)/km].

Table S5. The polymeric composition of microplastic fragments was identified in Area 1 [Lençóis Maranhenses National Park (LMNP)] and Area 2, which included beach segments in the municipalities of Barreirinhas and Paulino Neves, located outside the LMNP boundaries.

Color	Area (A)	ID Sample									
		MP1	MP2	MP3	MP4	MP5	MP6	MP7	MP8	MP9	MP10
Light blue	A1	PE	PEEK	PE	PEVA	PEVA	PEVA	PEVA	PE	PP	PE
	A2	PP	PP	PE	PE	PP	PP	PP	PP	PP	PE
Dark blue	A1	ABS	PE	PE	PEVA	PEVA	PE	-	-	-	-
	A2	PE	PE	EMA	-	-	-	-	-	-	-
Orange	A1	PEC	PEC	PE	PE	PEC	-	-	-	-	-
	A2	PP	PP	PEC	-	-	-	-	-	-	-
Red	A1	PP	PP	PEVA	PEVA	PP	-	-	-	-	-
	A2	PEC	PP	PEVA	-	-	-	-	-	-	-
White	A1	PEC	PEC	PE	PE	PEC	PEVA	PEC	PEVA	PEC	PE
	A2	PEC	PE	PP	PEC	PE	PEC	PP	PP	PEC	PE
Clear	A1	PP	PE	PP	PP	PP	PEC	PE	PP	PEVA	PEVA
	A2	PE	PE	PP	PE	PEVA	PE	PEVA	PEC	PEVA	PE
Purple	A1	PEC	PEC	PEC	-	-	-	-	-	-	-
	A2	PEC	PEC	PEC	-	-	-	-	-	-	-

Note - A1 and A2: Areas 1 and 2, respectively; **MP1 to MP10:** Identifications of the analyzed fragments; **PEC:** Random propylene-ethylene copolymer; **PEVA:** Ethylene-vinyl acetate copolymer; **PP:** Polypropylene; **PE:** Polyethylene; **PEEK:** Polyether ether ketone; **ABS:** Acrylonitrile butadiene styrene; **EMA:** Ethylene-methyl acrylate copolymer.

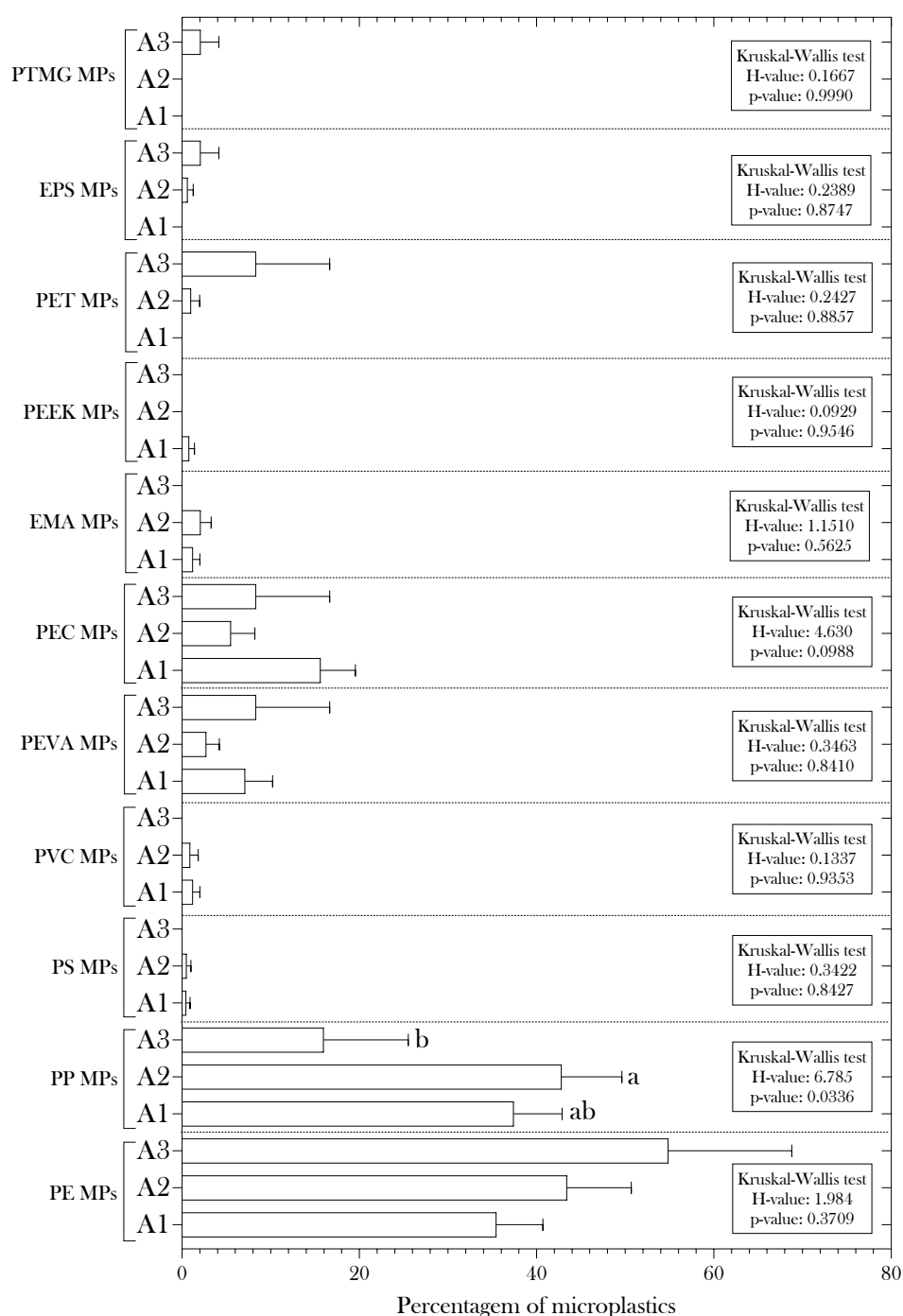


Figure S1. Percentage distribution of polymers identified in the microplastics (MPs) from the investigated areas. Bars represent the median and interquartile range, with a summary of the statistical analysis at the top of the graph. Distinct lowercase letters indicate significant differences between areas. Area 1 encompassed the entire beach extension within the boundaries of the Lençóis Maranhenses National Park (LMNP); Area 2 included beach sections in the municipalities of Barreirinhas and Paulino Neves, located outside the LMNP boundaries; and Area 3 covered the entire coastal extent of the municipality of Tutóia (State of Maranhão, Northeastern Brazil). The polymers include PTMG (polytetramethylene glycol), EPS (Expanded polystyrene), PET (Polyethylene terephthalate), PEEK (Polyether ether ketone), EMA (Ethylene-methyl acrylate copolymer), PEC (Random propylene-ethylene

copolymer), PEVA (Ethylene-vinyl acetate copolymer), PVC (Polyvinyl chloride), PS (Polystyrene), PP (Polypropylene), and PE (Polyethylene).

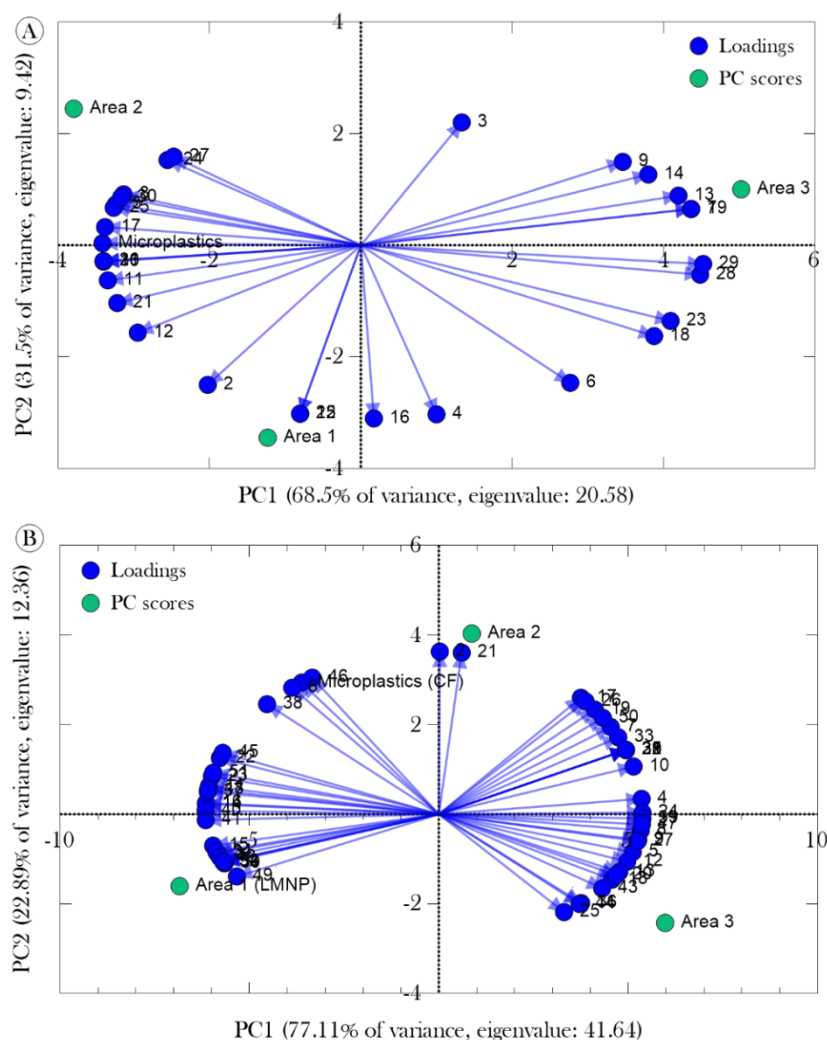


Figure S2. Principal Component Analysis (PCA) biplots highlight the microplastic (MP) pollution variance across the study areas. (A) PCA incorporating contamination factors (CFs) and MP characteristics. (B) PCA incorporating CFs and variables related to environmental, geographical, and land use characteristics. Blue vectors represent the variable loadings contributing to the principal components (PC1 and PC2), and green circles indicate the PC scores for each study area (Area 1, Area 2, and Area 3), showing their positioning based on the principal components. The meanings of the numbers associated with the vectors in “A” and “B” are presented in Tables S2 and S3, respectively (see “Supporting Information”). Area 1 encompassed the entire beach extension within the boundaries of the Lençóis Maranhenses National Park (LMNP); Area 2 included beach sections in the municipalities of Barreirinhas and Paulino Neves, located outside the LMNP boundaries; and Area 3 covered the entire coastal extent of the municipality of Tutóia (State of Maranhão, Northeastern Brazil).

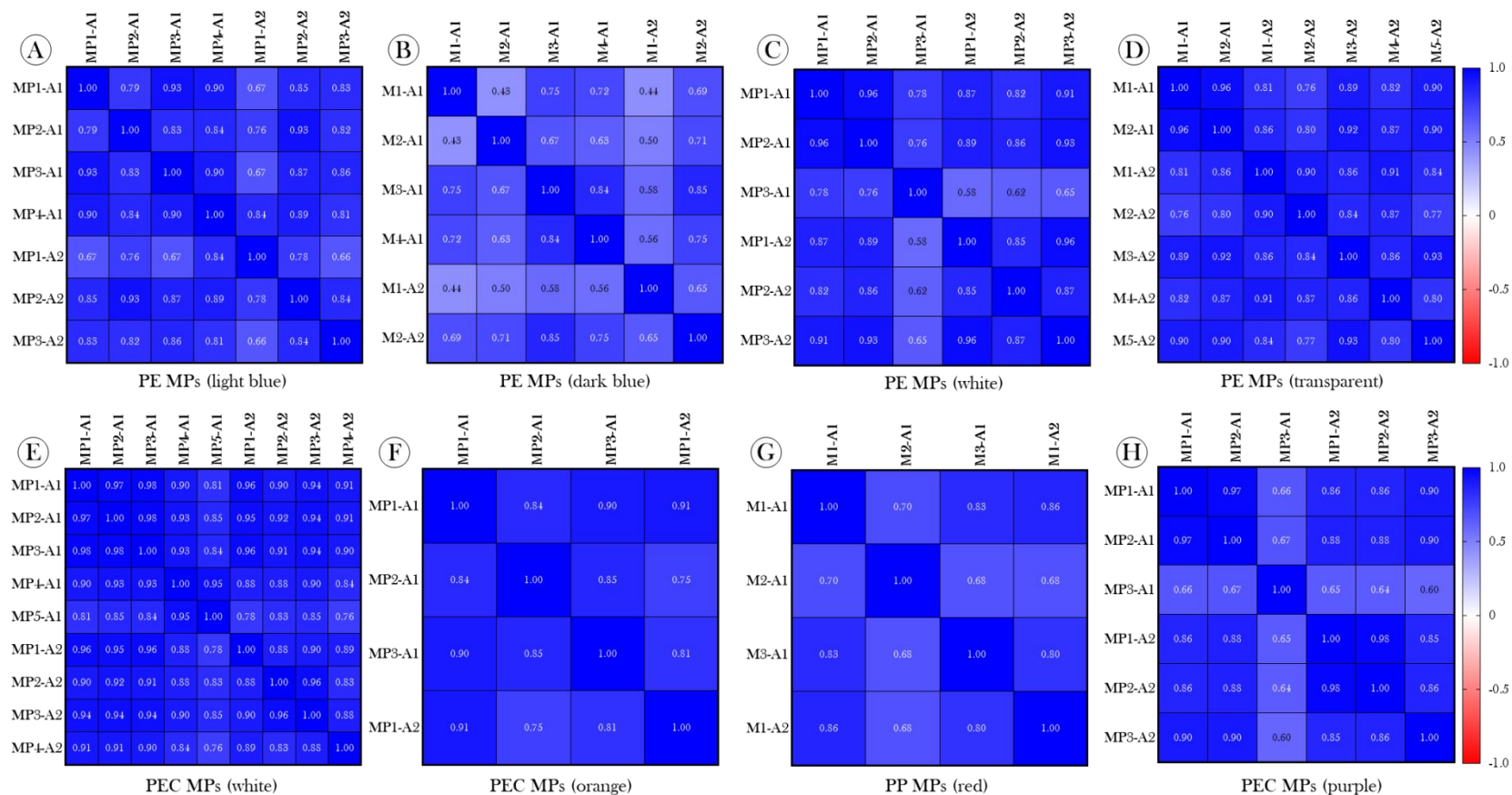


Figure S3. Correlation matrix of Raman spectra for microplastics (MPs) grouped by color and polymer type, highlighting structural similarities between MPs from the Lençóis Maranhenses National Park (LMNP) (Area 1) and Area 2 (which included beach sections in the municipalities of Barreirinhas and Paulino Neves, located outside the LMNP boundaries). (A-B) Light blue and dark blue polyethylene (PE) MPs, respectively; (C-D) White and transparent PE MPs; (E-F) White and orange random propylene-ethylene copolymer (PEC) MPs; (G-H) Red polypropylene (PP) MPs and purple PEC MPs. Values within the matrices represent the correlation coefficients. All correlations presented in the matrices were statistically significant ($p < 0.05$), based on Pearson or Spearman coefficients, depending on whether the normality and linearity assumptions were met.

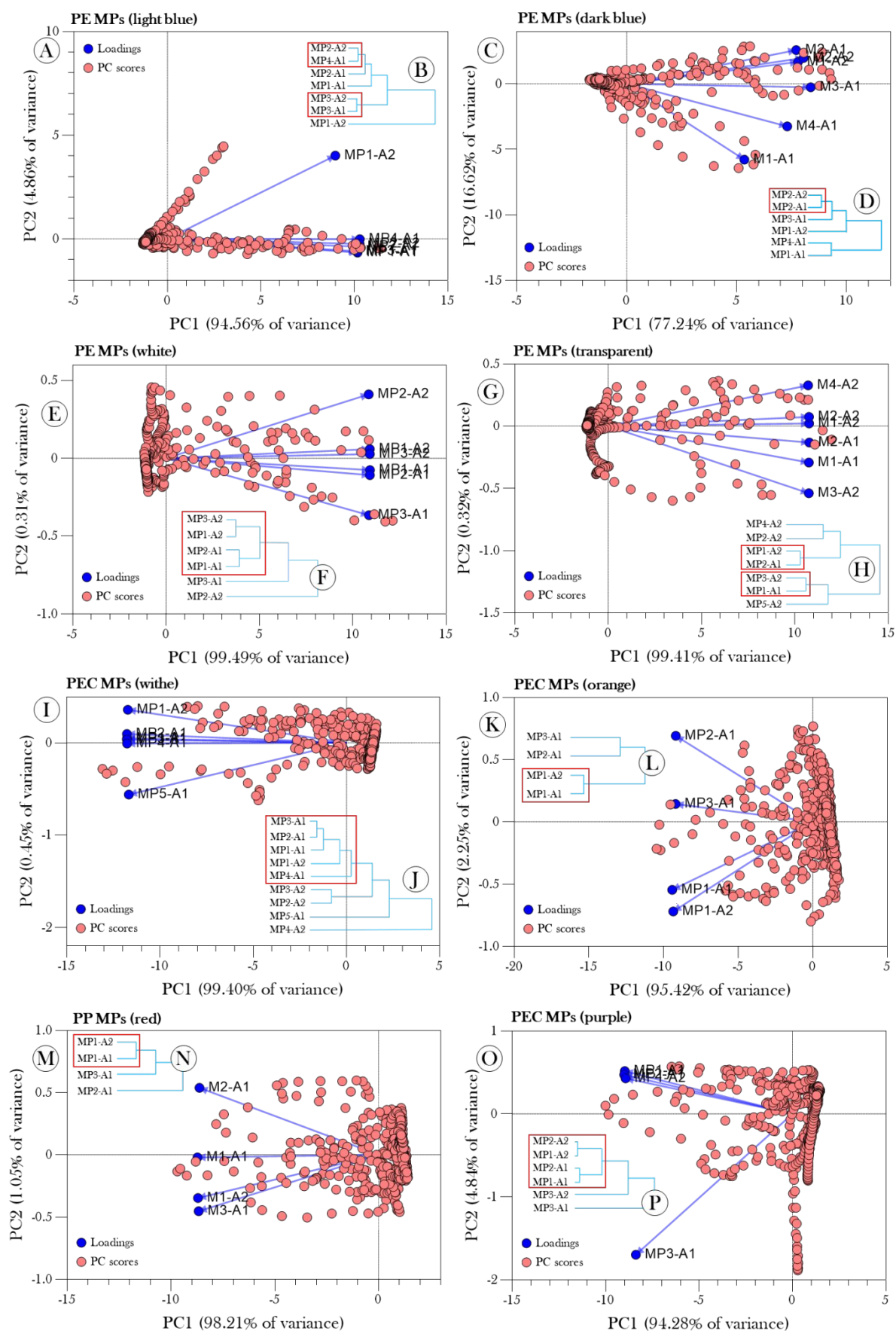


Figure S4. Results of Principal Component Analysis (PCA) and cluster analysis applied to the spectral readings of microplastics (MPs) grouped by color and polymer type between the

Lençóis Maranhenses National Park (LMNP) (Area 1) and Area 2 (which included beach sections in the municipalities of Barreirinhas and Paulino Neves, located outside the LMNP boundaries). (A, C, E, G, I, K, M, O) PCA biplots display the variance explained by the principal components (PC1 and PC2), with PC scores (represented by pink circles) and loadings (represented by blue circles). The percentages of variance explained by each principal component are indicated on the axes. (B, D, F, H, J, L, N, P) Cluster analysis for the same samples, highlighting groupings based on the structural and compositional similarity of the MPs.

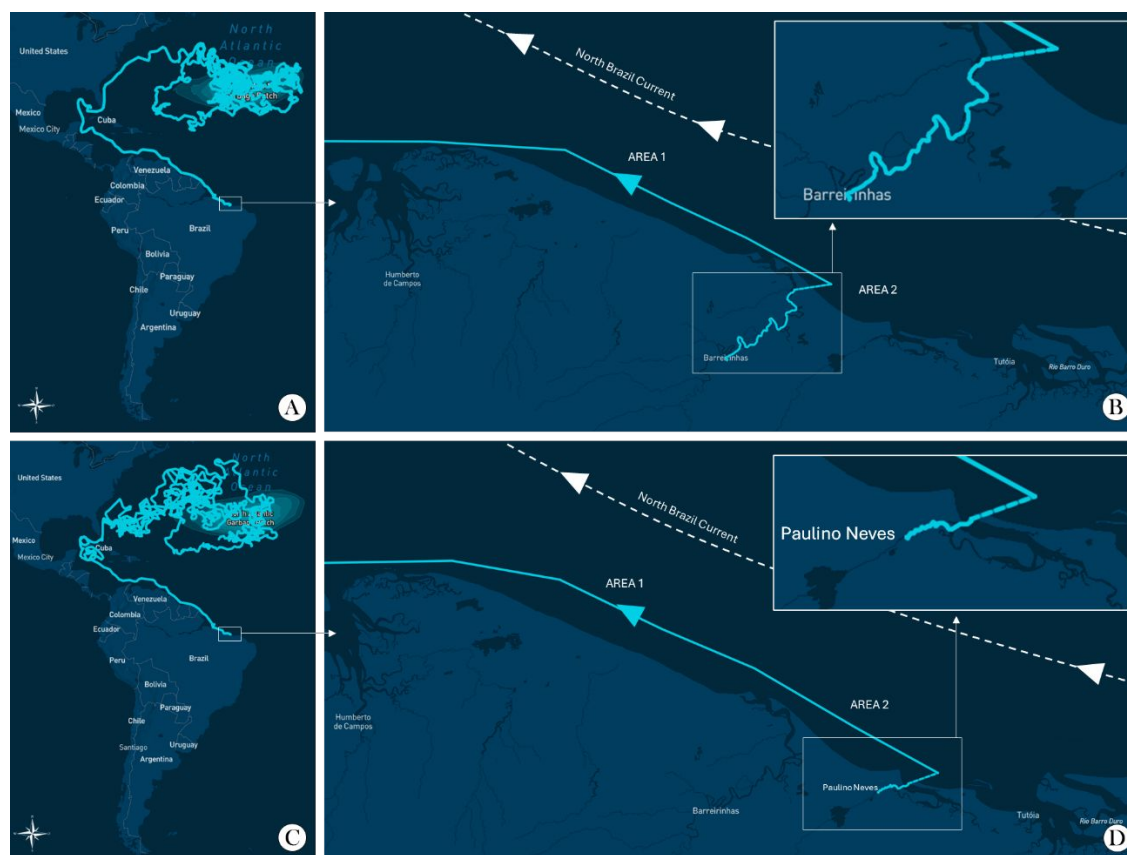


Figure S5. Simulation of microplastic (MP) particle dispersion using PlasticTracker. (A-B) Trajectories of particles originating from Area 2, following the predominant North Brazil Current (NBC) flow. Area 1 encompassed the entire beach extension within the Lençóis Maranhenses National Park (LMNP) boundaries, while Area 2 included beach sections in the municipalities of Barreirinhas and Paulino Neves, located outside the LMNP boundaries.

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