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DISTRIBUIÇÃO ESPACIAL E CARACTERIZAÇÃO DE MICROPLÁSTICOS EM AMBIENTES AQUÁTICOS DO ARQUIPÉLAGO DAS ILHAS CANÁRIAS

São Luís – MA

2026

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Dissertação apresentado em cumprimento às exigências do Programa de Pós-Graduação em Ecologia e Conservação da Biodiversidade da Universidade Estadual do Maranhão.

Orientadora: Profa. Dra. Marina Bezerra Figueiredo

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"Nós esquecemos que o ciclo da vida e da morte da natureza também é o nosso-
David Attenborough"

RESUMO

A poluição por microplásticos constitui um problema ambiental de escala global, especialmente relevante em ambientes marinhos e sistemas insulares. Esta dissertação teve como objetivo investigar a distribuição espaço-temporal e a caracterização de microplásticos em ambientes aquáticos do arquipélago das Ilhas Canárias, considerando a abundância, o tamanho das partículas, a morfologia e a composição polimérica. As amostragens foram realizadas em três campanhas oceanográficas, nas quais os microplásticos foram coletados na superfície e analisados por técnicas espectroscópicas. Foram registradas 780 partículas, com predominância de fragmentos (57,9%) e fibras (40,0%), sendo o politereftalato de etileno (PET) e o polietileno de baixa densidade (LDPE) os polímeros mais frequentes. O tamanho das partículas apresentou elevada variabilidade, evidenciando heterogeneidade estrutural da contaminação. A abundância diferiu significativamente entre as campanhas, com maior contribuição da campanha RAPROCAN25, responsável por mais de 80% dos registros, além da identificação de áreas de acúmulo com altas densidades de partículas. Diferenças significativas na composição morfológica e polimérica entre as campanhas indicaram variações nos padrões de aporte e nos processos de transporte e transformação ambiental, com associação marcante entre fibras e PET, e entre fragmentos e poliolefinas. Os resultados demonstram que a contaminação por microplásticos no arquipélago é espacialmente agregada, composicionalmente dinâmica e predominantemente derivada de fontes secundárias. A distribuição desses contaminantes é influenciada pela interação entre a Corrente das Canárias, a conectividade com o giro subtropical do Atlântico Norte, a pressão antrópica e as características geomorfológicas locais, que favorecem a retenção e a formação de áreas de acúmulo. Nesse contexto, o arquipélago atua como uma zona estratégica de interceptação e redistribuição de poluentes em escala oceânica, reforçando sua importância como área-chave para o monitoramento e a compreensão da poluição marinha por microplásticos.

Palavras-chave: Poluição marinha; Composição polimérica; Heterogeneidade espacial; Hotspots; Sistemas insulares.

ABSTRACT

Microplastic pollution has become a global environmental issue, particularly relevant in marine and insular systems. This dissertation aimed to investigate the spatiotemporal distribution and characterization of microplastics in aquatic environments of the Canary Islands archipelago, considering abundance, particle size, morphology, and polymer composition. Sampling was conducted during three oceanographic campaigns, in which surface microplastics were collected and analyzed using spectroscopic techniques. A total of 780 particles were recorded, with a predominance of fragments (57.9%) and fibers (40.0%). Polyethylene terephthalate (PET) and low-density polyethylene (LDPE) were the most frequent polymers. Particle size showed high variability, indicating structural heterogeneity of contamination. Microplastic abundance differed significantly among campaigns, with the RAPROCAN25 campaign accounting for more than 80% of the total records, as well as exhibiting the highest densities and the most intense local accumulation areas (hotspots). Significant differences in morphotype and polymer composition among campaigns suggest variations in input sources, transport pathways, and environmental processing, with a strong association between fibers and PET and between fragments and polyolefins. Overall, the results indicate that microplastic contamination in the Canary Islands is spatially aggregated, compositionally dynamic, and predominantly derived from secondary sources. The distribution patterns are strongly influenced by the interaction between the Canary Current, the connectivity with the North Atlantic subtropical gyre, anthropogenic pressure, and local geomorphological features, which favor retention and accumulation processes. In this context, the archipelago acts as a strategic zone for the interception and redistribution of marine pollutants at the oceanic scale, highlighting its importance as a key area for monitoring and understanding microplastic pollution.

Keywords: Marine pollution; Polymer composition; Spatial heterogeneity; Hotspots; Insular systems.

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1 INTRODUÇÃO

Os materiais plásticos, em razão de suas propriedades físico-químicas, como elevada durabilidade, resistência à degradação, impermeabilidade e baixo custo de produção, têm se consolidado como componentes fundamentais em diversas aplicações, tornando-se amplamente incorporados às atividades cotidianas (Evode *et al*., 2021). Em contrapartida, mesmo promovendo facilidade e benefícios ao ser humano, a ocorrência do plástico é prejudicial quando descartados de forma irregular no ambiente (Araújo; Silva-Cavalcanti, 2016).

Ao final do seu ciclo de vida, os produtos ou embalagens plásticas são reciclados, incinerados, enterrados em aterros, despejados em locais não regulamentados ou descartados no meio ambiente (Mihai *et al*., 2024).

Esse descarte de maneira irregular contribui para a ampla dispersão de resíduos plásticos, os quais causam incontáveis danos nos ecossistemas e aos organismos que neles habitam através de emaranhamento e ingestão (Paul *et al*., 2024). Tais impactos afetam desde a fauna marinha pelo acúmulo de resíduos plásticos possibilitando bloqueios gastrointestinais até a liberação de oxigênio pelos oceanos para a existência de vida na biosfera (Galgani *et al*., 2022).

A problemática da poluição plástica tem atingido proporções globais alarmantes. Relatórios internacionais indicam que os plásticos representam cerca de 85% dos resíduos que chegam aos oceanos, com projeções de que, até 2040, o volume anual de entrada possa atingir entre 23 e 37 milhões de toneladas (UNEP, 2021). Esse cenário evidencia que a poluição plástica não se limita a uma questão ambiental, mas também apresenta implicações climáticas relevantes.

Grande parte dos plásticos não são biodegradáveis, sofrendo processos de fotodegradação que resultam na fragmentação em partículas menores denominadas microplásticos (MPs) (Rocha-santos *et al*., 2022), e referem-se a itens com tamanho de 1-5000 μm (0,001 – 5 mm) de diâmetro (Frias; Nash, 2019).

Os microplásticos são classificados em primários, quando produzidos intencionalmente em dimensões reduzidas, e secundários, quando originados da fragmentação de materiais plásticos maiores (Lehtiniem *et al*., 2018). Os primários estão associados principalmente a emissões industriais e à liberação de partículas durante a fabricação e o uso de produtos plásticos, enquanto os secundários resultam da degradação de resíduos plásticos sob a ação de

processos de intemperismo, que promovem sua fragmentação progressiva em partículas menores (Laskar; Kumar, 2019).

Devido à ação de correntes oceânicas e ventos, os microplásticos podem ser transportados a longas distâncias, sendo encontrados inclusive em regiões remotas (Andrade *et al*., 2021). Essas partículas afetam organismos em diferentes níveis tróficos, desde microorgasnismos até grandes vertebrados, podendo causar desnutrição, asfixia e intoxicação (Hammer *et al*., 2012). A ingestão de microplásticos já foi registrada em diversos grupos marinhos, aumentando as preocupações acerca dos efeitos cumulativos ao longo da cadeia alimentar (Wang *et al*., 2019).

Além de sua persistência, os microplásticos apresentam elevada capacidade de adsorção de substâncias químicas tóxicas, atuando como vetores de contaminantes no ambiente e nos organismos (Zambrano-pinto *et al*., 2024). Evidências recentes indicam que sua exposição pode representar riscos potenciais à saúde humana, incluindo efeitos respiratórios, cardiovasculares e alterações endócrinas, além de possível associação com processos carcinogênicos (Yang e*t al*., 2023; Dzierżyński *et al*., 2024). A detecção dessas partículas em matrizes biológicas humanas sugere sua distribuição sistêmica e potenciais impactos a longo prazo (Enyoh *et al*., 2023; Ali *et al*., 2024).

Nesse contexto a intensificação da produção, consumo e descarte de materiais plásticos amplia os impactos sobre a integridade ecológica, as condições climáticas e a saúde pública (Singh *et al*., 2016). Adicionalmente aditivos químicos presentes nos polímeros como plastificantes, podem ser liberados no ambiente e acumulados em organismos, interferindo em processos fisiológicos essenciais (Mosca Angelucci; Tomei, 2022).

No que tange o arquipélago das Ilhas Canárias, destaca-se uma área particularmente vulnerável à poluição por microplásticos. A presença desses contaminantes é amplamente registrada em diferentes compartimentos ambientais, sendo influenciada tanto por fontes locais quanto pelo transporte de longa distância associado à dinâmica do Atlântico Norte (Schmid *et al*., 2018; Courtene-Jones *et al*., 2020). Estudos indicam que a região atua como uma zona de acumulação, com elevada ocorrência em praias, águas e sedimentos (Mart *et al*., 2023).

Além disso, fatores como pressão turística, dinâmica hidrodinâmica e características geomorfológicas das ilhas contribuem para a heterogeneidade na distribuição desses contaminantes, favorecendo a formação de áreas de acúmulo, especialmente em zonas de sotavento (Sharma *et al*., 2021; Tinel *et al*., 2025). Desta forma, as Ilhas Canárias configuram-se como um hotspot de poluição por microplásticos, reforçando a necessidade de

monitoramento contínuo e de estratégias integradas de mitigação (García-Regalado et al., 2024)

Diante deste cenário, este estudo investiga a distribuição espaço-temporal e a caracterização dos microplásticos em ambientes aquáticos das Ilhas Canárias, considerando abundância, tamanho e composição polimérica. Buscou-se compreender padrões de ocorrência, fontes de contaminação e processos de transporte e dispersão, avaliando a influência de fatores locais e remotos. Os resultados contribuem para o entendimento da dinâmica desses contaminantes e para o desenvolvimento de estratégias de monitoramento e mitigação da poluição marinha.

O Programa de Pós-Graduação em Ecologia e Conservação da Biodiversidade permite que a dissertação de mestrado seja estruturada e normatizada no formato de agregação de artigos científicos, conforme estabelecido em seu regimento (Capítulo XII, Seção I, Art. 60º). Dessa forma, o presente documento é organizado em um único capítulo, correspondente a um manuscrito científico destinado à publicação em periódico da área de Biodiversidade.

O estudo investiga a contaminação por microplásticos no arquipélago das Ilhas Canárias, com foco na análise dos padrões de distribuição e nas características das partículas, incluindo tamanho, morfologia e composição polimérica. Esse artigo foi submetido ao periódico Marine Pollution Bulletin, fator de impacto 4,9, classificado na área de Ecologia.

2 OBJETIVOS

2.1 Geral

- Avaliar a ocorrência, a distribuição e a composição polimérica de microplásticos nas regiões das Ilhas Canárias.

2.2 Específicos

- Analisar a abundância e a dispersão espacial de microplásticos nos pontos amostrais do arquipélago;
- Identificar a composição química dos microplásticos através de técnicas de espectroscopia infravermelha de alta resolução;
- Definir morfologicamente as partículas de materiais poliméricos presentes no ambiente estudado;
- Avaliar o papel do arquipélago como zona de retenção de resíduos plásticos.

3 FUNDAMENTAÇÃO TEÓRICA

3.1 Contexto oceanográfico e vulnerabilidade das Ilhas Canárias

O arquipélago das Ilhas Canárias está localizado a noroeste do continente africano e encontra-se sob forte influência da Corrente das Canárias, uma corrente de margem leste que flui em direção ao sul e integra o giro subtropical do Atlântico Norte (Hernández-Guerra *et al*., 2025). Essa corrente está associada à Corrente dos Açores, derivada da Corrente do Golfo, compondo um sistema de circulação oceânica de larga escala (Frazão *et al*., 2022).

Controlado principalmente pelos ventos alísios e pela interação com a margem continental africana, esse sistema desempenha papel fundamental no transporte de massas de água e materiais em suspensão (González-Pola *et al*., 2024; Pinho *et al*., 2025). Nesse contexto, a dinâmica dessas correntes favorece o transporte e a acumulação de resíduos plásticos no arquipélago, aumentando sua vulnerabilidade à poluição marinha (Schreiber *et al*., 2025).

3.2 Microplásticos no ambiente marinho: propriedades e dinâmica ambiental

Os plásticos apresentam uma ampla diversidade de propriedades físico-químicas que influenciam diretamente seu comportamento e destino no ambiente. Características como densidade, cristalinidade, composição polimérica e presença de aditivos determinam sua flutuabilidade, resistência à degradação e interação com o meio aquático (Casagrande *et al*., 2024).

Os microplásticos presentes no ambiente marinho são compostos predominantemente por polímeros de baixa densidade, como polietileno (PE) e polipropileno (PP), o que favorece sua flutuabilidade e permanência inicial na superfície oceânica (Rodríguez *et al*., 2026). Em função da ação de correntes superficiais, ventos e ondas, essas partículas podem ser transportadas a longas distâncias, contribuindo para sua ampla dispersão em ambientes marinhos.

A discrepância entre a quantidade de plástico produzida globalmente e aquela observada na superfície oceânica sugere a existência de importantes sumidouros ainda pouco compreendidos. Estima-se que apenas cerca de 0,2% do estoque de plástico oceânico esteja na superfície, indicando que a maior parte se encontra armazenada em compartimentos não superficiais (Ritchie *et al*., 2023).

Nesse contexto, os sedimentos marinhos são amplamente reconhecidos como importantes sumidouros de microplásticos, atuando como compartimentos finais de acumulação desses contaminantes (Yang *et al*., 2021).

Evidências indicam que a deposição ocorre de forma significativa em profundidades intermediárias (200–2000 m), onde processos hidrodinâmicos e a agregação com matéria orgânica favorecem o transporte vertical e a sedimentação das partículas (Zhao *et al*., 2025). Dessa forma, compartimentos menos visíveis, como o fundo do mar e a coluna d'água, representam os principais reservatórios de microplásticos no ambiente marinho (Wang *et al*., 2022).

3.3 Fontes e padrões de distribuiçãoglobal dos microplásticos

A origem desses contaminantes está associada a padrões de produção e consumo caracterizados por baixa incorporação de princípios de economia circular e gestão inadequada de resíduos (Gálvez-Blanca *et al*., 2023; Reineccius; Waniek, 2024). Além disso, fontes difusas ao longo do ciclo de vida dos produtos contribuem significativamente para a entrada de microplásticos no ambiente, incluindo o desgaste de pneus, a liberação de fibras têxteis durante a lavagem de roupas e a perda de pellets plásticos em processos industriais (Rashid et al., 2024; Napper *et al*., 2016; Hann *et al*., 2018).

A distribuição global dos microplásticos evidencia a existência de regiões de acúmulo intensivo, conhecidas como hotspots, como o Giro do Pacífico Norte e o Mar Mediterrâneo (Rynek et al., 2024). Esses ambientes apresentam dinâmicas oceanográficas que favorecem a retenção de detritos plásticos, semelhantes às observadas no arquipélago das Ilhas Canárias. A comparação com esses sistemas reforça a relevância das Canárias como área est ratégica para o estudo da poluição por microplásticos em escala regional e global (Cózar *et al*., 2014; Eriksen *et al*., 2014).

Entretanto, a distribuição dos microplásticos não se restringe à superfície oceânica. Estima-se que apenas uma fração desses materiais permaneça nas águas superficiais, enquanto a maior parte encontra-se em suspensão na coluna d'água ou depositada nos sedimentos marinhos (Eriksen *et al*., 2014; Kaandorp *et al*., 2023). Essa distribuição vertical é controlada por processos como bioincrustação, agregação com matéria orgânica e variações na densidade das partículas, que favorecem o seu afundamento.

Uma vez introduzidos no ambiente, os plásticos são submetidos a processos de degradação mecânica, fotoquímica e oxidativa, que promovem sua fragmentação progressiva em partículas menores (Andrady, 2017; Du *et al*., 2021). Esses processos dão origem aos microplásticos secundários, enquanto os microplásticos primários são produzidos intencionalmente em dimensões microscópicas (Andrady *et al*., 2019). A diversidade de formas, tamanhos e composições desses materiais influencia diretamente seu comportamento ambiental, incluindo sua mobilidade, persistência e interação com organismos.

A distribuição espacial dos microplásticos é altamente heterogênea e controlada por processos oceanográficos em múltiplas escalas. Em larga escala, mecanismos como o transporte de Ekman promovem a convergência e acumulação de partículas em regiões oceânicas específicas (Kullenberg *et al*., 2018; Kelly, 2024). Em escala regional, fatores como hidrodinâmica local, geomorfologia costeira e pressão antrópica influenciam padrões de deposição e retenção.

Ambientes insulares, como o arquipélago das Ilhas Canárias, apresentam elevada suscetibilidade à acumulação de microplásticos devido à sua inserção no giro subtropical do Atlântico Norte (Pham *et al*., 2020; Campillo *et al*., 2023). Nessa região, a deposição intensiva de resíduos plásticos em praias, águas superficiais e sedimentos tem sido amplamente documentada, configurando um cenário de crescente pressão ambiental (Herrera *et al*., 2018).

Adicionalmente, a conectividade oceânica global impulsionada por sistemas de circulação de larga escala favorece o transporte de microplásticos para regiões remotas. Evidências indicam que essas partículas já foram detectadas em ambientes considerados prístinos, como o Ártico e a Antártica, tanto por transporte atmosférico quanto oceânico (Aves *et al*., 2022; Kelly *et al*., 2020). Esses resultadosdemonstram queapoluiçãoplástica transcende fronteiras geográficas, configurando um problema ambiental de escala planetária (Emberson Marl *et al*., 2023).

3.4 Impactos ambientais e implicações ecotoxicológicas

No âmbito ecológico, os microplásticos configuram um estressor ambiental multifatorial, sendo capazes de causar impactos físicos, como lesões no trato digestório, bloqueios gastrointestinais e redução da ingestão alimentar em organismos aquáticos (Bucci *et al*., 2020). Além disso, essas partículas podem ser transferidas ao longo das cadeias tróficas

por meio de processos de bioacumulação e biomagnificação, ampliando seus efeitos em diferentes níveis tróficos (Rochman *et al*., 2015).

Além dos efeitos físicos, os microplásticos apresentam elevada relevância ecotoxicológica ao atuarem como vetores de contaminantes químicos (Campanale *et al*., 2020). Essas partículas são capazes de adsorver substâncias tóxicas presentes no ambiente, como poluentes orgânicos persistentes e metais pesados, bem como liberar aditivos incorporados à sua matriz polimérica, incluindo ftalatos e bisfenol A (BPA) (Koelmans *et al*., 2016). Esses compostos são reconhecidos como desreguladores endócrinos e podem induzir estresse oxidativo, inflamação sistêmica e danos ao DNA em organismos vivos (Płuciennik *et al*., 2024).

Além dos microplásticos, partículas em escala nanométrica, conhecidas como nanoplásticos, têm recebido crescente atenção devido à sua maior biodisponibilidade e potencial toxicidade (Shen, *et al*., 2019).

Por apresentarem dimensões inferiores a 1 µm, essas partículas possuem maior capacidade de atravessar barreiras biológicas, como membranas celulares, podendo alcançar tecidos e órgãos internos. Esse comportamento aumenta o risco de efeitos adversos em nível celular e sistêmico, representando uma preocupação emergente na avaliação dos impactos da poluição plástica (Gigault *et al*., 2018).

Em humanos, evidências recentes têm confirmado a presença de microplásticos em diferentes compartimentos biológicos, incluindo o sangue, a placenta e tecidos reprodutivos, indicando sua capacidade de distribuição sistêmica no organismo (Ragusa *et al*., 2021; Leslie *et al*., 2022). Esses achados levantam preocupações quanto aos potenciais efeitos fisiológicos a longo prazo, incluindo possíveis associações com distúrbios metabólicos e doenças neurodegenerativas.

Além dos impactos ecológicos e à saúde, a poluição plástica também apresenta interações relevantes com o sistema climático (MacLeod *et al*., 2021). Estudos recentes indicam que materiais plásticos expostos à radiação solar podem liberar gases de efeito estufa, como metano e etileno, contribuindo para o aquecimento global (Shen *et al*., 2020).

Diante disso, a intensificação da produção, consumo e descarte de materiais plásticos amplia os impactos sobre a integridade dos ecossistemas, o funcionamento dos sistemas climáticos e a saúde pública (Silva *et al*., 2021; Singh *et al*., 2016). Assim, compreender as fontes, os processos de transporte, a distribuição e os efeitos dos microplásticos torna-se

fundamental para subsidiar estratégias eficazes de monitoramento, gestão e mitigação dessa forma de poluição (Tang *et al*., 2023).

3.5 Desafios científicos e necessidade de monitoramento

A quantificação de microplásticos ainda enfrenta limitações significativas, especialmente devido à ausência de padronização nos protocolos de amostragem, identificação e análise. Diferenças nas metodologias empregadas dificultam a comparação entre estudos e podem gerar inconsistências nas estimativas de abundância e distribuição desses contaminantes, representando um desafio importante para a consolidação de dados em escala global (Hidalgo-Ruz *et al*., 2012; Lindeque *et al*., 2020).

Como consequência, a escassez de dados empíricos, especialmente em profundidade, limita a capacidade de modelagem e pode levar à subestimação da carga total de plástico no ambiente marinho (Zhao *et al*., 2025; van Sebille *et al*., 2020).

Perante o exposto, ainda persistem lacunas relevantes no entendimento dos mecanismos que controlam a distribuição dos microplásticos ao longo da coluna d'água, desde a superfície até os sedimentos profundos (Kane *et al*., 2020). Esse contexto evidencia a necessidade de investigações mais integradas, que considerem diferentes compartimentos ambientais e escalas espaciais.

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4 CAPÍTULO ÚNICO

Artigo 1: Spatiotemporal patterns of microplastic contamination in the Canary Islands (Spain): abundance, particle size and polymer composition

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Abstract

Microplastic contamination in oceanic islands emerges from interactions among local anthropogenic pressure, regional connectivity, and hydrodynamic retention. Here, we investigated the structural signature of microplastic contamination in aquatic environments of the Canary Islands, focusing on abundance, particle size, morphotype, and polymer composition across three oceanographic campaigns (RAPROCAN2312, RAPROCAN2411, and RAPROCAN2508). Surface microplastics were collected with an Avani manta trawl and characterized through fluorescence screening followed by polymer confirmation using ATR-FTIR and LDIR. A total of 780 microplastic particles were recorded. Fragments (57.9%) and fibers (40.0%) dominated the assemblage, whereas PET (36.5%) and LDPE (33.8%) were the most frequent polymers. The equivalent diameter varied widely, indicating marked size heterogeneity among the particles. The abundance of microplastics varied strongly among the campaigns and samples, with RAPROCAN2508 contributing the largest share of recorded particles and including the strongest local hotspots. The morphology and polymer composition also differed significantly among the campaigns, and the morphotype–polymer association was highly significant, with fibers closely linked to PET and fragments associated mainly with LDPE, PE, and HDPE. Multivariate analyses further revealed differences in contamination structure among the campaigns, with partial separation and compositional variation driven mainly by PET, LDPE, PE, PP, and HDPE. Overall, the results indicate that microplastic contamination in the Canary Islands is spatially aggregated, compositionally dynamic, and dominated by secondary sources, underscoring the need for monitoring strategies that integrate abundance, morphology, polymer composition, size structure, and spatial heterogeneity in oceanic insular systems.

Keywords: Oceanic islands; Morphotype; Secondary sources; Spatial heterogeneity; Hotspots; Marine debris; Hydrodynamic retention; Insular systems

1. Introduction

Plastic pollution is among the most persistent and widespread forms of contamination in marine environments. Because of the continuous increase in plastic production, the extensive

use of these materials, and their low degradability, plastic debris is now recorded from densely urbanized coasts to remote oceanic regions. In the environment, larger plastic items undergo physical, chemical, and biological weathering, generating microplastics (MPs, with diameters < 5 mm), which can persist for long periods and interact with multiple environmental compartments. In addition to their broad distribution, MPs are considered important ecological stressors because they can be ingested by organisms from different trophic levels and may also act as vectors for chemicals adsorbed onto their surfaces (Borrelle et al., 2020; Eriksen et al., 2023; Song et al., 2022).

The environmental behavior of MPs depends not only on their abundance but also on structural attributes such as particle size, shape, and polymer composition, which influence transport, residence time, weathering, and bioavailability. In oceanic systems, the horizontal and vertical distributions of MPs are controlled by interactions among currents, wind, waves, surface convergence, and mesoscale processes such that observed patterns emerge from the combined effects of sources, transport pathways, and preferential retention zones. This framework is especially relevant for oceanic islands, which can simultaneously function as interception areas for long-range transported debris, coastal accumulation zones, and nodes of regional redistribution (Cardoso and Caldeira, 2021; Vega-Moreno et al., 2024).

The Canary Archipelago is a particularly relevant case in this context. Located in the Northeast Atlantic and directly influenced by the Canary Current, the archipelago intercepts large amounts of litter transported from remote sources and is therefore especially vulnerable to marine plastic pollution (García-Regalado et al., 2024). Recent evidence indicates that the Canary Islands constitute a hotspot of oceanic plastic pollution, with very high concentrations reported for both beaches and surface waters, marked contrasts between the windward and leeward sectors, and recurrent accumulation areas associated with local hydrodynamics and marine litter windrows (García-Regalado et al., 2024). Empirical studies across the archipelago have also documented high spatial variability and recurrent accumulation areas in coastal environments (Herrera et al., 2018; Reinold et al., 2020), while recent work has shown that regional contamination patterns are shaped not only by large-scale ocean transport but also by mesoscale dynamics and water-column pathways (Vega-Moreno et al., 2024).

Regional evidence already shows that plastic pollution in the Canary Islands is strongly spatially heterogeneous. Preferential accumulation areas have been described mainly on north- and northeast-facing coasts, with consistent contrasts between the windward and leeward sectors associated with the interaction of the Canary Current, prevailing winds, and insular

geomorphology (García-Regalado et al., 2024; Schreiber et al., 2025). In these environments, fragments tend to predominate, together with white or transparent particles and polymers such as polyethylene and polypropylene, although beaches under stronger tourist pressure may also have additional contributions from local sources (García-Regalado et al., 2024; Schreiber et al., 2025). Despite these advances, important gaps remain regarding the integration of spatial distribution, particle size, and polymer composition in the aquatic environments of the archipelago. This approach is particularly relevant because abundance alone does not capture the full complexity of contamination, whereas variations in particle size and polymer signatures may reflect differences in fragmentation processes, transport pathways, and potential source inputs.

Therefore, in this study, the spatiotemporal patterns of microplastic contamination in the Canary Islands were investigated, with emphasis on abundance, particle size, and polymer composition. By integrating these descriptors, we aim to identify contamination patterns among campaigns and sampling sites and to clarify how transport, accumulation, and particle transformation shape the structural signature of microplastic contamination in an oceanic insular system strongly influenced by regional connectivity and local coastal pressure. We expected that contamination patterns would differ not only in magnitude but also in their compositional and dimensional structure, reflecting the interaction between remote inputs, local forcing, and environmental processing within the archipelago.

2. Materials and Methods

2.1. Study area and sampling

The Canary Archipelago comprises eight islands in the Northeast Atlantic, off the northwestern African coast, between 26.997° and 29.168° N and 18.489° and 12.372° W (Fig. 1). The region is influenced by the Canary Current, the eastern branch of the North Atlantic Subtropical Gyre, which contributes to the redistribution of water masses and suspended particles.

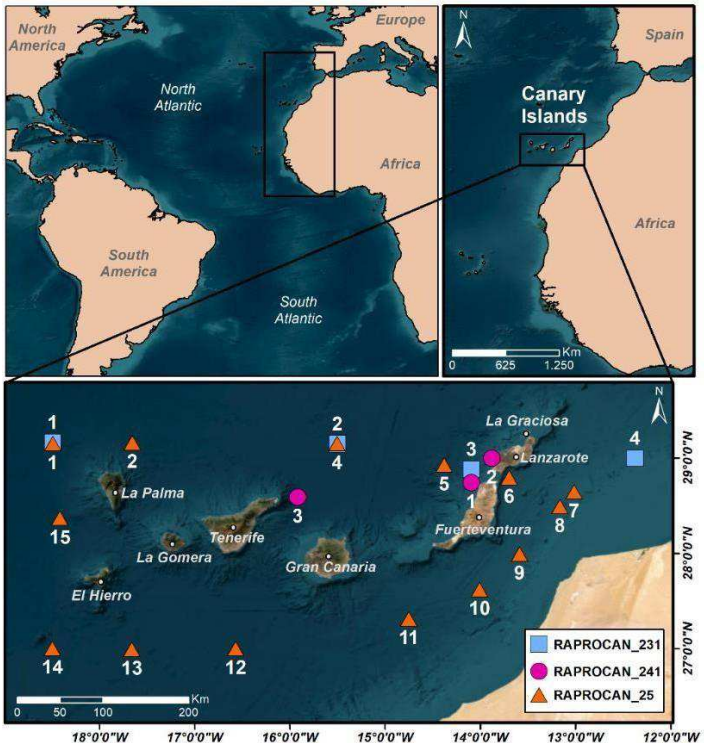

Figure 1. Location of the study area and sampling stations of the three oceanographic campaigns conducted around the Canary Islands archipelago (Spain). The upper panels show the position of the archipelago in the North Atlantic and its regional context relative to Europe and northwestern Africa. The lower panel presents the spatial distribution of the sampling stations for RAPROCAN2312, RAPROCAN2411, and RAPROCAN2508, with numbers indicating individual stations.

Sampling was carried out during three oceanographic campaigns in 2023, 2024, and 2025, hereafter referred to as RAPROCAN2312, RAPROCAN2411, and RAPROCAN2508. Surface microplastics were collected with an Avani manta trawl equipped with a 333 µm mesh net and a 0.69 × 0.14 m mouth opening. The trawl was towed at the surface, with approximately half of the mouth opening submerged, corresponding to an effective sampling depth of ~0.35 m. Tows were conducted along predefined transects at 3–4 knots for approximately 20 min, under wind speeds below 20 knots, while avoiding vessel wake and deck-washing activities.

Each transect was considered one sampling unit, totaling four transects in 2023, three in 2024, and fourteen in 2025. Effective towing distance, estimated by GPS from the start and end positions, ranged from 1052 to 2955 m, corresponding to sampled areas of 147.3–413.7 m² per transect. Full geographic coordinates are provided (see S1). After each tow, the net was

rinsed externally to concentrate retained material in the cod end, and samples were transferred to clean containers and kept frozen until laboratory processing.

2.2. Laboratory processing for microplastic extraction

Laboratory procedures were conducted under contamination-control conditions. Work surfaces and materials were cleaned beforehand, airflow and personnel circulation were minimized, operators wore cotton clothing, and all items in contact with samples were pre-rinsed. Procedural blanks were included throughout processing to assess background contamination, and blank results are summarized (see S2).

The organic fraction was removed by chemical digestion. Samples were transferred to precleaned 1 L beakers, rinsed with Milli-Q water, and treated with H_2O_2 to a final concentration of 15%. After brief magnetic stirring, samples were incubated at 50 °C for 24 h.

Density separation was then performed with saturated NaCl solution (~350 g L^{-1}, with a slight excess to ensure saturation). This approach is widely used for the recovery of low-density polymers, although denser polymers such as PET may be underestimated. Samples were transferred to separation funnels, left undisturbed for 24 h, and the supernatant was vacuum-filtered through pre-rinsed stainless-steel mesh filters (100 µm, ~47 mm diameter).

When relevant organic residues remained, an additional digestion step with sodium hypochlorite (14% active chlorine, 2–4 h) was applied. At the end of the procedure, the filtration system was rinsed with ethanol to recover residual particles adhering to the apparatus.

2.3. Microplastic identification and polymer confirmation

After filtration, the retained particles were screened by fluorescence stereomicroscopy following Nile red staining. Stainless steel mesh filters were dried, transferred to clean Petri dishes, and treated with Nile red solution before visual inspection under a Leica MZ10 F stereomicroscope equipped with LED illumination and GFP LP filters (excitation at 470 nm; emission > 515 nm). All suspected particles were photographed, measured for maximum length, and assigned to morphotype categories (fragment, fiber, film, pellet, filament, or foam). Because dark particles may show little or no fluorescence response, the filters were also inspected under nonfluorescent illumination to avoid the under detection of black or opaque particles.

Polymer identification was performed by infrared spectroscopy after visual screening. Nonfibrous particles greater than approximately 500 µm were analyzed by ATR-FTIR using a

PerkinElmer Spectrum Two spectrometer equipped with an UATR accessory. Fibers and smaller particles that could not be reliably analyzed on the ATR crystal were transferred to high-reflectance slides and analyzed using LDIR (Agilent 8700). The spectra were compared with those of the reference polymer libraries, and the polymer assignments were accepted according to the best spectral match. This sequential workflow, combining Nile Red staining, fluorescence-based screening, and complementary ATR-FTIR/LDIR confirmation, was adopted to improve the detection and identification of morphologically distinct microplastic particles.

2.4. Statistical analyses

Statistical analyses were performed to describe and compare microplastic contamination among campaigns in terms of abundance, particle size, morphotype, and polymer composition. Descriptive statistics included absolute and relative frequencies of morphotypes and polymers and summary measures of equivalent diameter. Abundance was standardized by the effectively sampled area of each transect.

Differences in particle diameter among campaigns, morphotypes, and samples were tested with Kruskal–Wallis tests, followed by Dunn's post hoc comparisons with Holm correction when significant. Differences in morphotype and polymer composition among campaigns were assessed by chi-square tests of independence. Because some categories had low frequencies, rare classes were regrouped and complemented by permutation tests.

Differences in morphotype and polymer composition among campaigns were assessed using chi-square tests of independence based on contingency tables. Because some categories showed low frequencies, complementary analyses were conducted after regrouping rare classes to improve inferential robustness. Permutation tests were also applied to the regrouped tables to assess the stability of the results under unequal frequency distributions.

Compositional structure was evaluated from sample-level abundance matrices for morphotypes and polymers using Bray–Curtis dissimilarity. Patterns were explored by NMDS, and differences among campaigns were tested with PERMANOVA and PERMDISP (999 permutations). The contribution of individual categories to between-campaign dissimilarity was examined by SIMPER. PERMANOVA and PERMDISP were performed using 999 permutations.

Compositional heterogeneity was also described at the sample level for both morphotypes and polymer classes. For this purpose, category richness (S), the Shannon index

(H′), the Simpson index (1 − D), Pielou's evenness (J′), and dominance (D) were calculated. These descriptors were not used as measures of biological diversity sensu stricto but as descriptors of the compositional structure of microplastic contamination. They were used to quantify the number of categories per sample, the balance among their relative abundances, and the concentration of composition in a few dominant morphotypes or polymers. Comparisons among the campaigns for these descriptors were performed using the Kruskal–Wallis test. All analyses were conducted in R (R Core Team, 2025) using the packages vegan, dplyr, tidyr, readxl, and ggplot2.

3. Results

3.1. General descriptive characterization of microplastics

A total of 780 microplastic particles were recorded across three campaigns: RAPROCAN2508 (n = 650; 83.3%), RAPROCAN2411 (n = 81; 10.4%), and RAPROCAN2312 (n = 49; 6.3%).

In terms of morphology, fragments predominated, accounting for 57.9% of the total (n = 452), followed by fibers, which represented 40.0% (n = 312). The remaining categories were scarce, with films accounting for 1.2% (n = 9), whereas pellets and filaments each represented 0.4% (n = 3 in both cases), and foam accounted for only 0.1% (n = 1) (Figure 2).

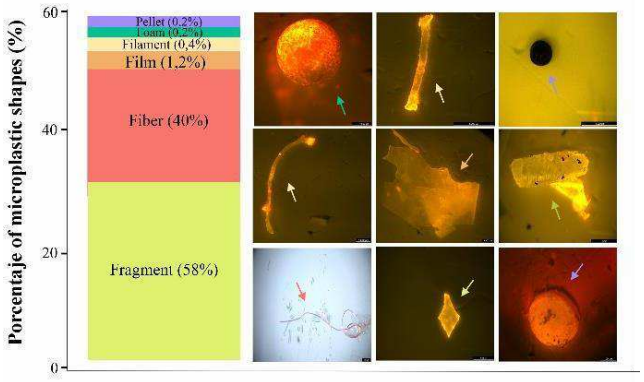

Figure 2. Relative abundance of microplastic morphotypes in the overall dataset, with representative micrographs of each category identified in the samples. The percentage values refer to the proportion of each morphotype in the total set of analyzed particles.

Polymer composition was dominated by PET (36.5%) and LDPE (33.8%), followed by PE (14.1%), HDPE (5.8%), and PP (5.3%), whereas all other polymers occurred at low

frequencies (Table 1). ATR accounted for 59.6% of the analytical records and LDIR for 40.4%. (Table 1).

Table 1. Absolute and relative frequency of polymers identified in the overall sample set (n = 780).

Polymer	N	%
PET	285	36.5
LDPE	264	33.8
PE	110	14.1
HDPE	45	5.8
PP	41	5.3
PA66	7	0.9
Zein	6	0.8
ABS	5	0.6
PEVA	4	0.5
PVC	3	0.4
PS	3	0.4
PTE	1	0.1
PE-Oxd	1	0.1
PU	1	0.1
Ethylene oxide	1	0.1
EVA	1	0.1
PET	1	0.1
Ethylene propylene copolymer	1	0.1
Total	**780**	**100.0**

Particle diameter varied widely, with an overall mean equivalent diameter of 1849.7 ± 3267.9 µm. RAPROCAN2312 showed the highest mean diameter, whereas RAPROCAN2508 exhibited the broadest size range and highest maximum value. Fibers were larger on average than fragments, whereas fragments showed the greatest dispersion (Table 2).

Table 2. Descriptive statistics of microplastic particle diameter (µm) for the overall dataset, by campaign, and by morphotype.

Group	n	Mean	Minimum	Maximum	SD
Total	780	1849.7	260.0	80662.0	3267.9
RAPROCAN2312	49	2918.3	486.0	8916.0	1953.8
RAPROCAN2411	81	1905.8	382.0	10987.0	1676.8
RAPROCAN2508	650	1762.2	260.0	80662.0	3477.8
Fiber	312	2208.6	382.0	16794.0	2066.6
Filament	3	5673.0	1696.0	10989.0	4614.8
Film	9	2306.9	419.0	5061.0	1331.4
Foam	1	1933.0	1933.0	1933.0	—
Fragment	452	1569.1	260.0	80662.0	3885.3
Pellet	3	1577.7	722.0	3276.0	1470.8

3.2. Particle abundance by sample

Microplastic abundance varied markedly among campaigns and sampling units. RAPROCAN2508 accounted for more than 80% of all recorded particles and showed the highest mean abundance per sample (46.4 ± 81.3 particles) and standardized density (0.17 ± 0.27 particles m^{-2}), followed by RAPROCAN2411 and RAPROCAN2312 (see S3).

At the sample level, abundance ranged from 3 to 319 particles. RAPROCAN2508-M6 represented an extreme hotspot, with the highest absolute abundance and density in the dataset (319 particles; 1.0523 particles m^{-2}). In contrast, several samples showed very low values, particularly RAPROCAN2508-M5, RAPROCAN2508-M7, and RAPROCAN2411-M1 (see S4).

Overall, RAPROCAN2508 combined the highest total abundance, the highest mean density, and the widest among-sample variation, indicating a strongly heterogeneous spatial distribution of microplastic contamination (Table 2; S4).

3.3. Comparison of particle size

Particle diameter differed significantly among campaigns, morphotypes, and samples. The Kruskal–Wallis test revealed significant differences among campaigns ($H = 43.81$, $p < 0.001$) and morphotypes ($H = 71.58$, $p < 0.001$). Dunn's post hoc test indicated that all campaign pairs differed significantly in particle size, whereas among morphotypes only the

fragment–fiber comparison remained significant after Holm correction, with fibers showing larger diameters than fragments (Table 8; S5–S6).

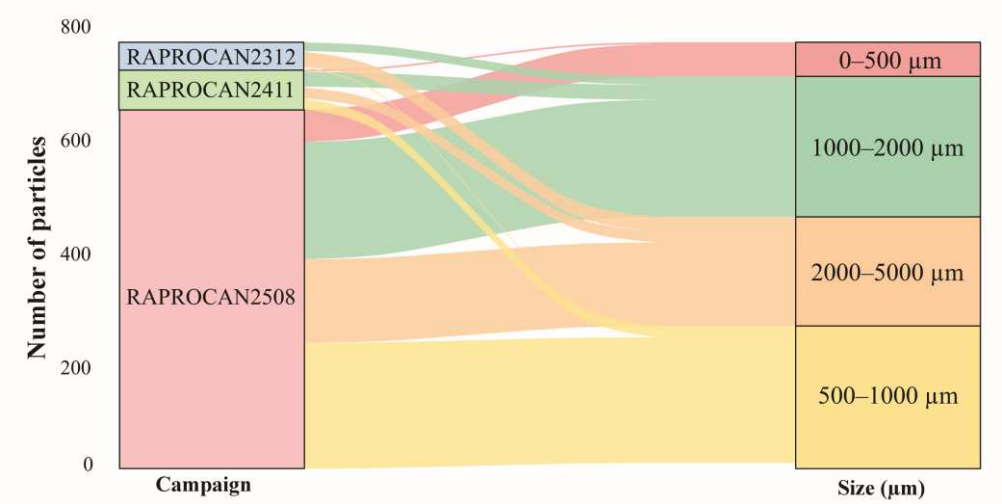

Figure 3. Sankey diagram showing the distribution of microplastic particles among size classes across the three sampling campaigns (RAPROCAN2312, RAPROCAN2411, and RAPROCAN2508). The width of each flow is proportional to the number of particles assigned to each size class within each campaign.

Size-class distribution also varied among campaigns (Fig. 3). At the sample level, diameter heterogeneity was significant ($H = 119.87$, $p < 0.001$), with ten significant pairwise contrasts, mainly involving RAPROCAN2508-M6, which showed lower median diameters than several other samples. Overall, RAPROCAN2312 had the highest mean particle diameter, whereas RAPROCAN2508 showed the widest size range.

3.4. Comparison of morphotype characteristics

Morphotype composition differed significantly among the campaigns. Considering all the morphotype categories, the chi-square test of independence indicated a significant association between the campaign and particle shape ($\chi^2 = 62.62$; $df = 10$; $p < 0.001$). However, owing to the low frequency of rare categories such as pellets, filaments, and foam, more than 60% of the cells presented expected frequencies below 5. To address this limitation, rare categories were regrouped into a single class ("Others"), whereas fragments and fibers were kept as separate categories. After regrouping, the association remained highly significant ($\chi^2 =$

55.19; df = 4; $p < 0.001$), and this result was also supported by a permutation test ($p = 0.0002$) (Table 3).

Table 3. Absolute and relative frequency of microplastic morphotypes by campaign.

Campaign	Fragment n (%)	Fiber n (%)	Film n (%)	Pellet n (%)	Filament n (%)	Foam n (%)	Total
RAPROCAN2312	16 (32.7)	31 (63.3)	2 (4.1)	0 (0.0)	0 (0.0)	0 (0.0)	49
RAPROCAN2411	51 (63.0)	21 (25.9)	5 (6.2)	2 (2.5)	2 (2.5)	0 (0.0)	81
RAPROCAN2508	385 (59.2)	260 (40.0)	2 (0.3)	1 (0.2)	1 (0.2)	1 (0.2)	650
Total	**452**	**312**	**9**	**3**	**3**	**1**	**780**

In proportional terms, RAPROCAN2312 was dominated by fibers (63.3%), whereas RAPROCAN2411 and RAPROCAN2508 were dominated by fragments, accounting for 63.0% and 59.2%, respectively. RAPROCAN2411 also showed the greatest relative contribution of rare morphotypes, especially films, pellets, and filaments. These proportional differences are illustrated in Fig. 4 and summarized in Table 3.

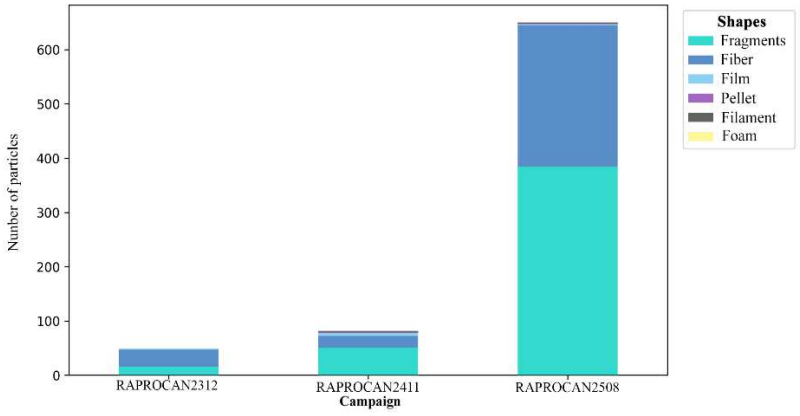

Figure 4. Distribution of microplastic morphotypes by campaign, expressed as absolute particle counts.

3.5. Comparison of polymer compositions

The polymer composition differed significantly among the campaigns. Considering polymers individually, the chi-square test indicated a highly significant association between the campaign and polymer composition ($\chi^2 = 147.84$; df = 34; $p < 0.001$). However, the high

frequency of rare polymers resulted in a large proportion of cells with expected values below 5, which reduced the robustness of the inference under this configuration. To address this limitation, the polymers were regrouped into three classes: polyolefins (PE, LDPE, HDPE, and PP), polyesters (PET), and other polymers. After regrouping, the association remained significant ($\chi^2 = 19.70$; df = 4; $p < 0.001$), and this result was also supported by a permutation test ($p = 0.001$) (Table 4).

Table 4. Absolute and relative frequency of regrouped polymer classes by campaign.

Campaign	Polyolefins n (%)	Polyesters (PET) n (%)	Others n (%)	Total
RAPROCAN2312	23 (46.9)	20 (40.8)	6 (12.2)	49
RAPROCAN2411	62 (76.5)	16 (19.8)	3 (3.7)	81
RAPROCAN2508	375 (57.7)	251 (38.6)	24 (3.7)	650
Total	**460**	**287**	**33**	**780**

Note: Polyolefins = PE, LDPE, HDPE, and PP. Polyesters = PET. The "Others" category includes the remaining low-frequency polymers. The percentage values refer to the proportion within each campaign.

In proportional terms, RAPROCAN2411 was dominated by polyolefins (76.5%), whereas RAPROCAN2312 showed a more balanced distribution between polyolefins (46.9%) and PET (40.8%), as well as the highest relative contribution of the "Others" category (12.2%). RAPROCAN2508 was also dominated by polyolefins (57.7%), with a high contribution of PET (38.6%) and a low relative contribution of other polymers (3.7%) (Table 4; Fig. 5).

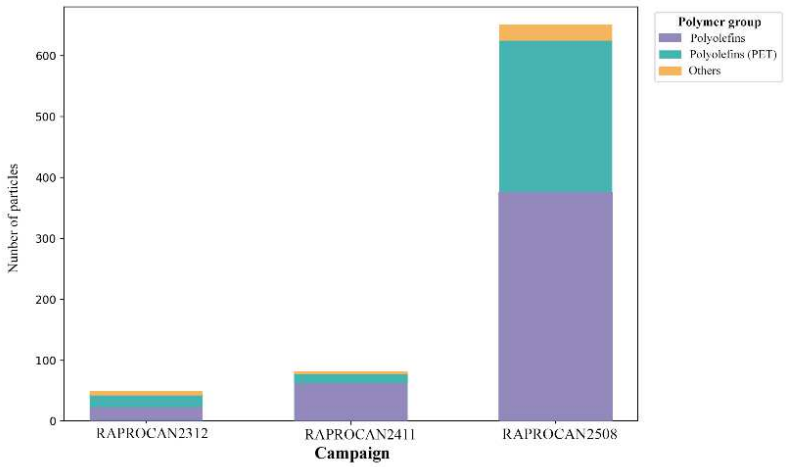

Figure 5. Relative polymer composition of microplastics by campaign, based on the regrouped classes of polyolefins, PET, and others.

3.6. Associations between morphotype and polymer

The association between morphotype and polymer was highly significant. Considering the full contingency table, the chi-square test indicated a strong dependence between the two variables ($\chi^2 = 1270.24$; df = 75; $p < 0.001$). However, the high frequency of cells with low expected values in the full table requires caution in interpretation. To reduce this limitation, the polymers were regrouped into PET, LDPE, PE, HDPE, PP, and others, and the association remained strongly significant after regrouping ($\chi^2 = 751.04$; df = 25; $p < 0.001$) (Table 5).

Table 5. Absolute frequency of the association between microplastic morphotype and polymer, considering regrouped polymer classes.

Morphotype	PET	LDPE	PE	HDPE	PP	Others	Total
Fragment	4	254	107	45	26	16	452
Fiber	283	3	1	0	10	15	312
Film	0	4	2	0	3	0	9
Pellet	0	2	0	0	0	1	3
Filament	0	1	0	0	2	0	3
Foam	0	0	0	0	0	1	1
Total	**287**	**264**	**110**	**45**	**41**	**33**	**780**

The absolute frequencies differed markedly among the morphotypes. Fibers occurred predominantly in PET (n = 283 of 312), whereas fragments were concentrated mainly in LDPE (n = 254), PE (n = 107), and HDPE (n = 45). Films were more frequent in LDPE (n = 4), PE (n = 2), and PP (n = 3), whereas filaments occurred mainly in PP (n = 2) and LDPE (n = 1). Pellets were recorded in LDPE (n = 2) and Others (n = 1), and foam occurred only in the Others category (Table 5).

Correspondence analysis (CA) revealed separation between the fibers and PET on one side and fragments associated with LDPE, PE, and HDPE on the other, whereas the films and filaments were positioned closer to the PP (Fig. 6).

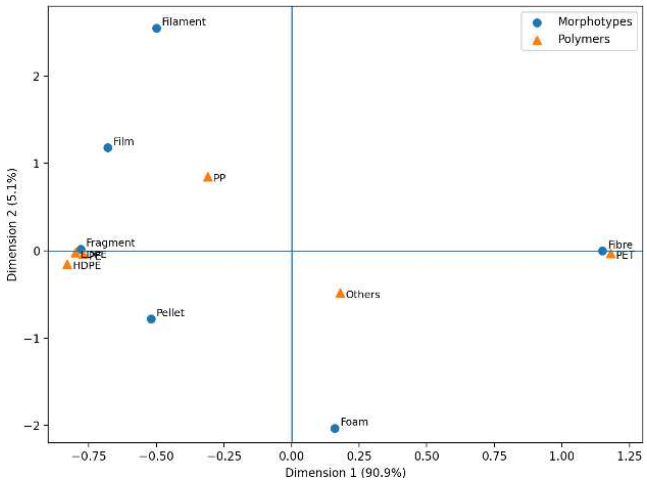

Figure 6. Correspondence analysis (CA) showing the association between microplastic morphotypes and regrouped polymer classes. The fibers were positioned closer to the PET, whereas the fragments were positioned closer to the LDPE, PE, and HDPE.

3.7. Compositional heterogeneity by sample

The compositional heterogeneity of microplastics varied among the campaigns when described on the basis of morphotype. For this purpose, category richness, the Shannon index, the Simpson index, Pielou's evenness, and dominance were used.

3.7.1. Compositional heterogeneity of morphotypes

Among morphotypes, diversity was highest in the group with the greatest mean richness (5.00 ± 2.00), Shannon (1.41 ± 0.31), Simpson (0.73 ± 0.08), and Pielou's evenness (0.92 ± 0.06), which also showed the lowest dominance (0.27 ± 0.08). RAPROCAN2312 showed intermediate values, whereas the lowest richness (4.00 ± 1.82), diversity, and evenness, together with the highest dominance (0.59 ± 0.24), were recorded in the least diverse group (see S7).

The results of the Kruskal–Wallis test indicated significant differences among the campaigns for the Shannon ($H = 6.43$; $p = 0.04$) and Simpson ($H = 6.79$; $p = 0.03$) morphotypes. No significant differences were observed for morphotype richness ($H = 3.00$; $p = 0.22$), Pielou's evenness ($H = 1.35$; $p = 0.51$), or dominance ($H = 5.32$; $p = 0.07$).

3.7.2. Compositional heterogeneity of polymers

Polymer composition varied among campaigns, with sample richness ranging from 3 to 9. RAPROCAN2411 showed the highest mean richness (5.0), Shannon (1.41), Simpson (0.73), and Pielou's evenness (0.92), and the lowest dominance (0.37). RAPROCAN2312 displayed intermediate values, whereas RAPROCAN2508 had the lowest richness (4.0), Shannon (0.78), and Simpson (0.41), together with the highest dominance (0.70).

Kruskal–Wallis tests indicated significant among-campaign differences for polymer Simpson (H = 7.68, p = 0.02) and dominance (H = 6.89, p = 0.03), but not for richness (H = 1.19, p = 0.55), Shannon (H = 5.41, p = 0.07), or Pielou's evenness (H = 5.50, p = 0.06).

3.8. Variation among samples

At the sample scale, compositional heterogeneity varied widely. Among the morphotypes, the highest Shannon index values were observed for RAPROCAN2411-M3 (0.995) and RAPROCAN2411-M2 (0.94). For polymers, the highest heterogeneity values were recorded in RAPROCAN2312-M4 (Shannon = 1.81; richness = 7) and RAPROCAN2411-M2 (Shannon = 1.68; richness = 7). In contrast, some samples, such as RAPROCAN2508-M6, which presented 9 polymers and a dominance value of 0.61, presented relatively high richness together with high dominance values.

Overall, compositional descriptors varied among samples for both morphotypes and polymers, with differences in richness, heterogeneity, and dominance across sampling units.

3.9. Temporal variation in the multivariate structure of microplastic contamination

Multivariate analysis based on the polymer abundance per sample revealed variations in the compositional structure among the campaigns. NMDS ordination revealed partial separation among groups, with the displacement of the RAPROCAN2508 samples being greater than that of the other campaigns (Fig. 7).

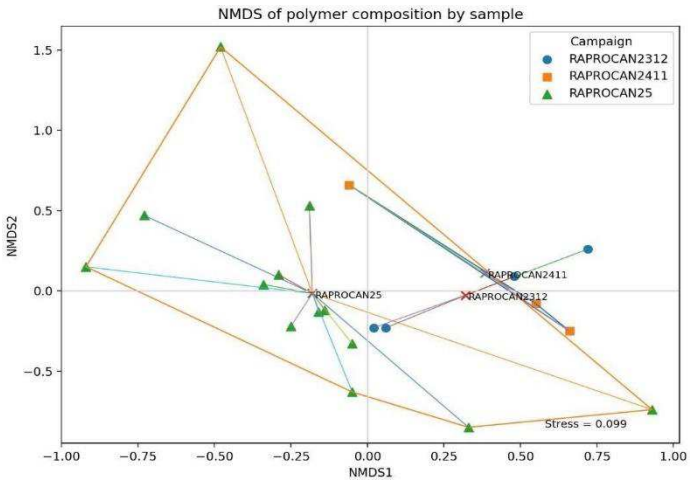

Figure 7. NMDS ordination based on polymer composition per sample using Bray–Curtis dissimilarity. Symbols represent samples from each campaign, and larger markers indicate group centroids. Stress = 0.099.

PERMANOVA indicated a significant difference in polymer composition among the campaigns (pseudo-F = 1.90; R^2 = 0.18; p = 0.033). PERMDISP was not significant (F = 2.14; p = 0.146). Compared with the other campaigns, RAPROCAN2508 showed greater mean

dispersion (Table 6).

Table 6. Results of PERMANOVA and PERMDISP based on Bray–Curtis dissimilarity.

Analysis	Source of variation	Df	Statistic	R^2	p
PERMANOVA	Campaign	2	pseudo-F= 1.90	0.18	0.033
PERMDISP	Campaign	2	F = 2.14	–	0.146

SIMPER analysis revealed that the dissimilarity among the campaigns was explained mainly by PET, LDPE, PE, PP, and HDPE. In the comparison between RAPROCAN2312 and RAPROCAN2411, LDPE, PE, PP, and PET contributed similarly to the dissimilarity. In comparisons involving RAPROCAN2508, PET and LDPE had the greatest relative contributions (Table 7).

Table 7. Main polymers contributing to the dissimilarity among the campaigns according to the SIMPER analysis.

Comparison	Polymer	Contribution (%)
RAPROCAN2312 × RAPROCAN2411	LDPE	23.46
	PE	21.12
	PP	19.77
	PET	18.71
	HDPE	7.56
RAPROCAN2312 × RAPROCAN2508	PET	43.15
	LDPE	19.74
	PP	10.66
	PE	7.48
	HDPE	5.18
RAPROCAN2411 × RAPROCAN2508	PET	36.63
	LDPE	22.83
	PE	16.57
	PP	8.90
	HDPE	6.83

4 Discussion

4.1. General overview of microplastic contamination in the Canary Islands archipelago

Microplastic contamination in the Canary Islands archipelago showed a clear structural signature across the three campaigns, defined by the predominance of fragments and fibers, the dominance of PET and LDPE, broad particle-size variation, and a major quantitative contribution from RAPROCAN2508. Overall, 780 particles were recorded, and the wide size range indicated marked dimensional heterogeneity. These findings show that contamination in the archipelago is better interpreted through the combined structure of morphotype, size, and polymer composition than through abundance alone.

This pattern is consistent with previous studies identifying the Canary Islands as a regional hotspot of marine plastic pollution, with localized accumulation shaped by oceanographic forcing (García-Regalado et al., 2024; Campillo et al., 2023). The agreement between the present dataset and earlier regional evidence reinforces that the observed contamination is not an isolated event, but part of a broader and already recognized oceanographic and anthropogenic setting. At a broader geographical scale, Martín-Lara et al. (2021) also highlighted the relevance of the Canary Islands within the current Spanish context of marine plastic pollution.

The predominance of fragments suggests an important contribution from secondary microplastics derived from the breakdown of larger debris, whereas the high frequency of fibers indicates diffuse inputs associated with textiles, urban effluents, and maritime activities. Regional evidence further indicates that much of the plastic load reaching the archipelago is shaped not only by local coastal sources but also by remote transport through the Canary Current and the North Atlantic Subtropical Gyre (García-Regalado et al., 2024). In addition, Lagrangian analyses have shown that microplastic accumulation depends on large-scale circulation as well as mesoscale features such as eddies and convergence zones (Vega-Moreno et al., 2024), while studies of the water column and deeper environments indicate that synthetic and colored cellulosic fibers remain important components of regional contamination, with polyester predominating among synthetic fibers (Rodríguez et al., 2026).

The observed pattern should therefore not be attributed exclusively to local inputs. Instead, the Canary Islands appear to function as both a receiving and a redistributing system for marine plastic debris, in which particle shape, size, and polymer type reflect not only source characteristics but also transport history, retention, and environmental transformation (García-Regalado et al., 2024; Vega-Moreno et al., 2024). In this context, the strong contribution of RAPROCAN2508, which accounted for more than 80% of all records and showed the widest size range, reinforces the view that microplastic contamination in the archipelago is structurally complex, spatially heterogeneous, and controlled by the interaction between multiple sources and oceanographic processes.

4.2. Variation in microplastic abundance among campaigns

A comparison among the campaigns revealed clear differences in the number of recorded microplastics, with RAPROCAN2508 contributing the largest share of the dataset. RAPROCAN2312 and RAPROCAN2411 totaled 49 and 81 particles, respectively, whereas RAPROCAN2508 accounted for 649 particles, representing more than 80% of all the recorded material. The same pattern was observed after standardization by sampled area, with mean densities of 0.03 ± 0.01 particles/m² in RAPROCAN2312, 0.07 ± 0.08 particles/m² in RAPROCAN2411, and 0.17 ± 0.27 particles/m² in RAPROCAN2508. However, these differences should be interpreted with caution, as the sampling effort was markedly uneven among the campaigns, and the greater contribution of RAPROCAN2508 is primarily attributable to the greater number of samples collected during that survey rather than to a confirmed temporal increase in the microplastic load.

This uneven sampling effort is central to the interpretation of the observed differences. RAPROCAN2312 included four samples, RAPROCAN2411 three, and RAPROCAN2508 fourteen, which naturally increased the likelihood of detecting a larger absolute number of particles and of capturing a broader range of local conditions, including highly contaminated sites, in the most recent campaign. For this reason, the predominance of RAPROCAN2508 should not be interpreted as direct evidence of a temporal increase in contamination across the archipelago.

Moreover, the wider spatial coverage of RAPROCAN2508 appears to have captured a broader range of contamination patterns within the sampled system. This campaign included not only the highest total abundance and the highest area-standardized values but also strong internal variation among samples, suggesting that the dataset incorporated both low-contamination sites and localized accumulation zones. In this sense, the greater contribution of RAPROCAN2508 is informative not because it demonstrates a robust temporal t rend but because it reveals how strongly estimates of microplastic load can be shaped by spatial heterogeneity within and among surveys.

This point is reinforced by the presence of exceptionally rich samples, especially RAPROCAN2508-M6, with 319 particles and a density of 1.05 particles/m², far exceeding the remaining records. Such values indicate that an important part of the intercampaign contrast was driven by the inclusion of local hotspots within the sampling structure of RAPROCAN2508. In insular marine systems, this is ecologically plausible, as episodic transport, resuspension, deposition, or retention events may produce abrupt and highly localized increases in microplastic density.

This interpretation is consistent with the regional literature. García-Regalado et al. (2024) emphasized that temporal and spatial comparisons in the Canary Islands should be approached cautiously because of methodological differences, seasonality, sampling frequency,

and high internal variability. In this sense, the present dataset fits a broader pattern already recognized for the archipelago, namely, strong heterogeneity among campaigns and locations, with estimates highly sensitive to sampling design and prevailing oceanographic conditions.

Overall, the present results are better interpreted as evidence of uneven distribution and sampling-dependent variation among campaigns than as confirmation of a temporal increase in the microplastic load. The greater contribution of RAPROCAN2508 likely reflects broader spatial coverage combined with the inclusion of local hotspots and variable accumulation conditions. Confirming a robust temporal trend will require longer time series, a more balanced sampling effort among campaigns, and integration with explanatory environmental variables such as wind, currents, coastal exposure, and local anthropogenic pressure.

4.3. Uneven distribution among samples and the occurrence of local hotspots

Microplastic abundance was strongly aggregated among samples rather than distributed along a uniform spatial gradient. Across the 21 samples, abundance ranged from 3 to 319 particles, with RAPROCAN2508-M6 clearly standing out as the main hotspot (319 particles; 1.05 particles m^{-2}), far exceeding all other records. This pattern indicates that a substantial fraction of the total plastic load was concentrated in a few localized accumulation nuclei rather than evenly distributed among transects.

This result is consistent with previous studies describing the Canary Islands as a plastic pollution hotspot marked by strong spatial heterogeneity and recurrent preferential accumulation zones in beaches and surface waters (García-Regalado et al., 2024). Similar small-scale contrasts have been reported for exposed Canary beaches (Herrera et al., 2018), for persistent beach-specific accumulation zones in Tenerife (Reinold et al., 2020), and for highly concentrated neustonic slicks in surrounding waters (Campillo et al., 2023). A comparable Atlantic-island pattern was also described for Boa Vista, Cabo Verde, where hotspots were associated with exposure and retention processes rather than homogeneous debris distribution (Sousa-Guedes et al., 2025).

The contrast observed at RAPROCAN2508-M6 is compatible with the combined effects of hydrodynamic convergence, coastal retention, shoreline orientation, and connectivity with both local and remote sources. In the Canary Islands, hotspot formation should not be interpreted simply as passive deposition or immediate proximity to emission sources, because accumulation may also reflect debris transported by the Canary Current and redistributed by regional circulation (Herrera et al., 2018; García-Regalado et al., 2024; Schreiber et al., 2025). This interpretation is reinforced by evidence that transport and fate in the region depend on both large-scale circulation and mesoscale retention processes (Vega-Moreno et al., 2024).

Area standardization reinforced rather than attenuated the hotspot pattern, showing

that the high values at M6 reflected a real increase in particle density rather than an artifact of sampled area. More broadly, the coexistence within RAPROCAN2508 of highly contaminated and very poor sites suggests a contamination mosaic in which strongly retentive sectors coexist with areas of lower residence time or greater export. Overall, the results indicate that microplastic contamination in the archipelago is spatially aggregated and hotspot-driven, and that future monitoring should explicitly account for this heterogeneity through greater spatial resolution and integration with hydrodynamic and connectivity variables.

4.4. Morphological structure of microplastics: predominance of fragments and fibers

The morphological composition was dominated by fragments and fibers, whereas films, pellets, filaments, and foam occurred only residually. This pattern indicates that contamination in the archipelago was shaped mainly by secondary microplastics generated through the fragmentation and environmental transformation of larger plastic items, rather than by a major contribution of primary plastic raw material. In marine environments, fragments and fibers are widely recognized as dominant morphotypes, reflecting the degradation of common plastic debris and the continuous release of fibrous synthetic materials.

The predominance of fragments suggests an important contribution from the breakdown of packaging, containers, films, and other plastic residues exposed to photooxidation, abrasion, and hydrodynamic stress (Andrady et al., 2022). In the Canary Islands, this interpretation agrees with regional studies showing that fragments are among the dominant forms on beaches and in surface waters and that their occurrence is associated with the interaction of remote transport, local retention, and progressive weathering of debris already circulating within the system (García-Regalado et al., 2024; Herrera et al., 2018; Reinold et al., 2020). The pattern therefore supports the view that the archipelago receives predominantly secondary microplastics in line with expectations for coastal–oceanic environments (Jola Osho et al., 2025).

The high occurrence of fibers broadens the interpretation of likely sources, pointing to inputs linked to synthetic textiles, domestic effluents, wastewater discharges, and the wear of ropes, nets, and other maritime materials. This morphotype is environmentally relevant because of its persistence, mobility, and broad interaction with aquatic compartments and organisms (Rebelein et al., 2021). In the Canary region, fibers remain important throughout the water column, reinforcing their value as indicators of diffuse and persistent contamination pathways (Rodríguez et al., 2026).

In contrast, the low occurrence of films, foam, filaments, and especially pellets suggests that these sources were secondary in the analyzed system or less persistent under the sampling conditions of this study. Because pellets are often interpreted as indicators of industrial or logistical losses of primary resin, their scarcity reinforces the view that the

observed morphological signature was driven mainly by secondary residues derived from the consumption, disposal, and environmental degradation of plastics already present in the system (Yang et al., 2021). Overall, the coexistence of abundant fragments and fibers indicates that contamination in the archipelago results from the overlap between conventional solid residues and diffuse fibrous emissions (Cesa et al., 2017), with limited evidence of a major contribution from primary industrial resin and broad consistency with recent regional syntheses (Rodríguez et al., 2025).

4.5. Polymeric signature of contamination: dominance of PET and LDPE

The polymer composition observed in this study was dominated by PET and LDPE, followed by PE, HDPE, and PP, indicating that the contamination recorded in the archipelago is strongly associated with polymers widely used in packaging, consumer containers, plastic films, and synthetic fibers. In marine environments, PE and PP are among the most frequently reported polymers because of their high global production, broad use in packaging, and high environmental persistence, whereas PET is recurrently associated with beverage containers and synthetic textile fibers. García-Regalado et al. (2024) reported that PEs and PPs predominate on beaches and in surface waters of the Canary Islands, reflecting the central role of these materials in regional plastic loading, while broader reviews also highlight the growing relevance of PET in aquatic matrices and sediments, especially in contexts influenced by synthetic fibers and urban residues.

The predominance of LDPE in the present sample set is consistent with the extensive use of this polymer in flexible packaging, bags, films, and other light materials that are highly susceptible to transport and fragmentation in the marine environment. Recent reviews indicate that PE, including both low- and high-density fractions, is among the most produced plastics and one of the most frequently detected microplastics, precisely because of its broad use in the packaging sector and its propensity to degrade and generate secondary particles. The high frequency of PET, in turn, deserves particular attention, as it may reflect the combined contribution of rigid packaging, bottles, and synthetic fibers derived from polyesters. Studies on textile emissions have shown that polyester is among the main sources of microfibers released into the environment, reinforcing the hypothesis that the strong contribution of PET in the present study is linked not only to disposable containers but also to diffuse inputs associated with the use and washing of synthetic textiles (Šaravanja et al., 2022).

This pattern partly differs from the profile more often reported for beaches and surface waters of the Canary Islands, where PE and PP tend to predominate, often in the form of white or colorless fragments. However, this difference does not weaken the present findings. In contrast, the results suggest that the analyzed system may integrate a mixture of sources and environmental trajectories different from those typically detected in exclusively beach-based

surveys or in the surface fraction more directly influenced by the transport of light floating polymers. García-Regalado et al. (2024) emphasized that contamination in the archipelago is strongly heterogeneous among compartments, islands, and hydrodynamic settings, whereas Rodríguez et al. (2026) showed that polymer signatures vary across the water column and include degraded particles compatible with oxidized PE and PP, together with polyester-rich fibrous material. This helps explain why the polymeric signature may vary substantially among compartments, campaigns, and coastal sectors of the archipelago.

From an environmental perspective, the dominance of these polymers has direct implications for particle transport, persistence, and distribution in the system. PE and PP, owing to their lower density, tend to remain at the surface or in the subsurface water layer longer, favoring regional dispersal. In contrast, because of its higher density, PET may respond differently to transport, mixing, and deposition processes, especially after weathering, biofouling, and fragmentation. Thus, the polymeric signature observed in the environment reflects not only the type of material originally introduced into the system but also the residence time and degree of particle transformation along the environmental pathway. In this context, Laursen et al. (2023) showed that even positively buoyant microplastics may settle efficiently in saline environments under flocculation-driven conditions, reinforcing that environmental fate cannot be inferred from nominal polymer density alone.

Overall, these results reinforce that microplastic contamination in the Canary Islands is dominated by polymers widely used in everyday consumption and packaging, with an additional relevant contribution from polyester-related materials. This pattern suggests that the plastic load in the system is shaped mainly by secondary sources of urban and touristic origin, interacting with transport, retention, and particle transformation processes that influence the selection and redistribution of polymers with different densities, uses, and environmental behaviors.

4.6. Integration of morphotype and polymer: evidence of multiple transformation pathways and sources

The combined interpretation of morphology and polymer composition reveals that contamination recorded in the archipelago does not result from a single pathway of entry but from the overlap of different sources and environmental trajectories. In the present study, the dominance of fragments associated with the high contribution of LDPE, PE, HDPE, and PP suggests that a large part of the plastic load derives from the secondary degradation of packaging, containers, and every day-use plastic materials. In contrast, the strong presence of PET, especially when interpreted together with the expressive occurrence of fibers, broadens the range of likely sources and suggests an additional contribution from synthetic fibrous materials.

Integrating morphotype and polymer is especially useful because it allows a more robust distinction between materials likely derived from conventional solid residues and those associated with diffuse emissions of textile or domestic origin. From this perspective, fragments dominated by polyolefins suggest mainly the fragmentation of disposable plastics and packaging residues, whereas fibers with a high PET contribution indicate a relevant influence of synthetic textiles, urban effluents, and the wear of fibrous materials. The microplastic signature recorded in the Canary Islands can therefore be interpreted as t he combined product of urban, touristic, and marine sources modulated by transport, retention, and particle transformation processes (Periyasamy and Tehrani-Bagha, 2022).

This pattern is also consistent with the regional literature. In the Canary Islands, recent studies have shown that PE and PP predominate on beaches and in surface waters, frequently as fragments, whereas studies on vertical microplastic distribution indicate that synthetic fibers are predominantly composed of polyester and that many fragments display advanced degradation features, including characteristics compatible with oxidized PE and PP (Rodríguez et al., 2026). A similar association between polyester-rich fibers and polyethylene-rich fragments was also reported for another Atlantic archipelago by Rodrigues et al. (2024), reinforcing that the coupling between shape and polymer may reflect broader contamination organization in insular systems rather than a local peculiarity.

Unlike approaches that analyze morphology and polymers separately, their integration offers a more mechanistic interpretation of contamination. In the present study, the association between fragments and polyolefins reinforces the importance of secondarily degraded solid residues, whereas the combination of fibers and PET supports the hypothesis of diffuse input from textile-origin synthetic materials. The low occurrence of pellets, foam, and other less frequent morphotypes, in turn, weakens the idea of a dominant contribution from primary industrial resin and supports the coexistence of multiple secondary pathways of entry and transformation.

4.7. Particle size structure and compositional reorganization among campaigns

The results indicate that variability among campaigns was not restricted to abundance but also involved structural reorganization of microplastic contamination. Differences among campaigns included not only the number of recorded particles, but also the relative proportions of morphotypes, size classes, and polymers, suggesting shifts in the structural signature of the plastic load over time. This interpretation is consistent with previous studies showing marked temporal and spatial variability in plastic pollution across the Canary Islands, including heterogeneous accumulation patterns and retention zones without a simple seasonal structure (Herrera et al., 2018; Reinold et al., 2020).

In this context, each campaign appears to have captured a different combination of

inputs, transport pathways, retention processes, and environmental transformation. García-Regalado et al. (2024) described the archipelago as an oceanic plastic pollution hotspot marked by strong heterogeneity among beaches, islands, and surface waters, whereas Rodríguez et al. (2026) showed that small microplastics are distributed throughout the water column, reinforcing the link between size structure, redistribution, and environmental fate. Thus, changes in the relative contribution of fragments, fibers, dominant polymers, and particle-size classes suggest that contamination in the archipelago is compositionally dynamic rather than a simple fluctuation in total load.

This compositional reorganization may reflect shifts in the relative influence of sources and environmental trajectories. Campaigns richer in fragments and polyolefins may indicate stronger contributions from secondarily degraded residues and greater surface persistence of light particles, whereas higher relative contributions of fibers and PET may suggest diffuse emissions associated with synthetic textiles, urban effluents, or fibrous materials retained under specific conditions. At the same time, the observed size spectrum may also be influenced by analytical resolution and mesh selectivity (Yang et al., 2025; Reineccius and Waniek, 2024). Overall, the results reinforce that monitoring in insular systems should go beyond total particle counts and incorporate compositional metrics, since high-abundance campaigns may also reflect stronger internal heterogeneity rather than a uniform increase in contamination across the study area (Wu et al., 2020; Reinold et al., 2020).

4.8. Environmental implications and monitoring perspectives in an oceanic insular system

Overall, the results show that microplastic contamination in the Canary Islands is structured not only by abundance, but also by composition and spatial heterogeneity. The strong contribution of RAPROCAN2508, the occurrence of local hotspots, and the predominance of fragments, fibers, PET, and LDPE indicate that the archipelago functions as both a receiving and a redistributing system for plastic particles under variable oceanographic conditions. This interpretation is consistent with García-Regalado et al. (2024), who described the Canary Islands as an oceanic hotspot of plastic pollution shaped by the interaction between large-scale forcing and local controls.

From an environmental perspective, this pattern implies uneven ecological exposure across sectors and over time. Preferential accumulation zones may subject specific habitats and organisms to contamination levels far above the regional average, especially when the load is dominated by small fragments and persistent fibers, which have high potential for ingestion and transfer among environmental compartments. The observed contamination signature also cannot be explained solely by local coastal disposal, since it reflects the combined influence of urban and tourist activities, remote inputs, and ongoing environmental transformation, in agreement with Vega-Moreno et al. (2024).

These results have direct implications for monitoring, because surveys based only on total abundance are unlikely to capture the real complexity of contamination in insular systems. Monitoring designs should explicitly incorporate morphotype and polymer composition, greater spatial resolution, and repeated temporal coverage to distinguish persistent accumulation from episodic deposition and hydrodynamic redistribution. Herrera et al. (2018) reported strong temporal variability and marked contrasts among exposed beaches in the Canary Islands, reinforcing the need for monitoring strategies that represent the true heterogeneity of the system.

5. Conclusions

The results show that microplastic contamination in the Canary Islands is spatially aggregated, compositionally dynamic, and dominated by secondary sources. The occurrence of local hotspots and the heterogeneity among campaigns indicate that the observed variability is not restricted to total abundance but also involves changes in contamination structure expressed through the combination of morphology, size, and polymer composition.

The predominance of fragments and fibers, together with the high frequency of PET and LDPE, suggests that the plastic load in the system is shaped mainly by every day-use residue, packaging materials, and diffuse emissions associated with synthetic fibers. The low contribution of pellets and other less frequent morphotypes reinforces the limited influence of primary industrial raw materials and instead points to the predominance of particles resulting from the degradation and environmental transformation of residues already present in the system.

Overall, the results indicate that microplastic dynamics in the archipelago arise from interactions among local sources, regional inputs, and particle transport, retention, and transformation processes in an oceanic insular environment. In this sense, the results of this study reinforce that assessing plastic pollution in the Canary Islands requires exceeding particle counts and incorporating, in an integrated way, morphological composition, polymer composition, size structure, and spatial heterogeneity.

Finally, the results highlight the need for monitoring programs with greater spatial and temporal resolution capable of identifying hotspots, capturing compositional changes among campaigns, and incorporating hydrodynamic and meteorological variables into the interpretation of contamination patterns.

CRediT authorship contribution statement

Jin Zhang: Writing – original draft, Visualization, Data curation. Jack Chi-Ho Ip: Writing – review & editing, Visualization, Resources. Mohamed Hamed: Writing – review & editing, Visualization, Resources. Jae-Seong Lee: Writing – review & editing, Visualization,

Resources. Jiezhang Mo: Writing – original draft, Supervision, Methodology, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Conflict of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

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SUPPLEMENTARY MATERIALS

Supplementary Materials 1- Geographic coordinates of the start and end positions of each surface manta net tow used to estimate effective towing distance and sampled area.

Campaign	Transect	Start latitude	Start Longitude	End latitude	End longitude	Distance (m)
RAPROCAN2312	1	29,1676167	-18,489633	29,1683667	-18,461983	2693
RAPROCAN2312	2	29,1538333	-15,498333	29,1508333	-15,47515	2280
RAPROCAN2312	3	28,887	-14,089817	28,8928333	-14,064667	2537
RAPROCAN2312	4	29,0019667	-12,372533	29,0051167	-12,40265	2955
RAPROCAN2411	1	28,7442333	-14,0904	28,7643333	-14,074917	2691
RAPROCAN2411	2	29,0018333	-13,8782	28,9775333	-13,883717	2746
RAPROCAN2411	3	28,5919833	-15,916217	28,5831667	-15,941917	2697
RAPROCAN25	1	29,1558385	29,1558385	29,1612539	-18,466715	2259
RAPROCAN25	2	29,1665315	-17,652066	29,166513	-17,628229	2318
RAPROCAN25	4	29,156445	-15,502853	29,1495485	-15,481095	2250
RAPROCAN25	5	28,931675	-14,377982	28,9211725	-14,358031	2267
RAPROCAN25	6	28,8018451	-13,693121	28,790833	-13,674665	2176
RAPROCAN25	7	28,6505481	-13,010194	28,6373475	-12,993167	2216
RAPROCAN25	8	28,4942352	-13,161663	28,4910937	-13,171811	1052
RAPROCAN25	9	27,9957836	-13,584957	27,9783727	-13,599298	2390
RAPROCAN25	10	27,62408	-14,005997	27,617847	-14,027492	2231
RAPROCAN25	11	27,3168324	-14,749125	27,3364162	-14,745577	2198
RAPROCAN25	12	27,0021546	-16,568083	26,9957894	-16,550342	1896
RAPROCAN25	13	26,9974005	-17,66112	27,0152283	-17,670633	2189
RAPROCAN25	14	27,0052876	-18,493957	27,0103404	-18,484859	1062
RAPROCAN25	15	28,373291	-18,416253	28,3940041	-18,412437	2325

Supplementary Materials 2- Characterization of microplastic particles in blank samples.

Campaign	Particle	Particle size (µm)	Polymer	Spectral match (HQI)	Analytical technique
RAPROCAN2311	Fragment	1465	PP	0,937	LDIR
RAPROCAN2311	Fragment	926	PA	0,913	LDIR
RAPROCAN2411	Fiber	4796	PA	0,865	LDIR
RAPROCAN2411	Fragment	1465	PP	0,937	LDIR
RAPROCAN2411	Fragment	926	PA	0,913	LDIR
RAPROCAN2508	Fiber	596	Celulosa	0,826	LDIR
RAPROCAN2508	Fiber	1778	Celulosa	0,88	LDIR
RAPROCAN2508	Fiber	1021	PET	0,905	LDIR
RAPROCAN2508	Fiber	2124	Celulosa	0,856	LDIR
RAPROCAN2508	Fiber	1467	Celulosa	0,867	ATR
RAPROCAN2508	Fragment	513	PE	0,978	ATR
RAPROCAN2508	Fragment	281	PE	0,78	ATR
RAPROCAN2508	Fragment	442	PE	0,935	ATR
RAPROCAN2508	Fragment	643	PE	0,976	ATR
RAPROCAN2508	Fragment	774	PE	0,955	ATR
RAPROCAN2508	Fragment	329	PE	0,951	ATR
RAPROCAN2508	Fragment	557	PE	0,906	ATR
RAPROCAN2508	Fragment	1331	Celulosa	0,921	ATR

Supplementary Materials 3- Abundance and density of microplastics per campaign, expressed as mean ± standard deviation, with minimum and maximum values observed.

Campaign	**Total particles**	**Mean ± standard (particles/sample)**	**Mín–Máx**	**Medium density (particles/m²)**
RAPROCAN2312	49	12,3 ± 1,3	11-14	0,03 ± 0,01
RAPROCAN2411	81	27,0 ± 30,8	8-62	0,07 ± 0,0
RAPROCAN2508	650	46,4 ± 81,3	3-319	0,17 ± 0,27

Supplementary Materials 4- Absolute abundance (number of particles) of microplastics recorded in selected samples from the RAPROCAN campaigns.

Campaign	Transect	Abundance (particles)
RAPROCAN2508	M6	319
RAPROCAN2508-M1	M1	79
RAPROCAN2411-M2	M2	62
RAPROCAN2508-M2	M2	56
RAPROCAN2508-M11	M11	49
RAPROCAN2508-M5	M5	3
RAPROCAN2508-M7	M7	4
RAPROCAN2411-M1	M1	8

Supplementary Materials 5- Results of Kruskal–Wallis tests assessing differences in microplastic particle diameter among campaigns and morphotypes. Degrees of freedom (df) correspond to the number of groups minus one. Significance levels: *** $p < 0.001$.

Factor	H statistic	Df	P-value
Campaign	43.81	2	< 0.001
Morphotype	71.58	5	< 0.001

Supplementary Materials 6- Results of Dunn's post hoc pairwise comparisons with Holm correction applied to microplastic particle diameter among campaigns. All pairwise comparisons were statistically significant ($p < 0.001$), indicating clear separation between campaigns. Significance levels: *** $p < 0.001$

Comparison	Adjested-value
RAPROCAN2312-RAPROCAN2411	<0.001
RAPROCAN2312-RAPROCAN2508	<0.001
RAPROCAN2411-RAPROCAN2508	<0.001

Supplementary Materials 7- Diversity indices by group/morphotype (mean ± standard deviation)

Campaign	Richness	Shannon	Simpson	Pielou's evenness	Dominance
RAPROCAN2508	5,00 ± 2,00	1,41 ± 0,31	0,73 ± 0,08	0,92 ± 0,06	0,27 ± 0,08
RAPROCAN2312	4,50 ± 1,73	1,19 ± 0,41	0,61 ± 0,15	0,81 ± 0,09	0,39 ± 0,15
RAPROCAN2411	4,00 ± 1,82	0,78 ± 0,49	0,41 ± 0,24	0,57 ± 0,27	0,59 ± 0,24

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