UNIVERSIDADE FEDERAL FLUMINENSE
INSTITUTO DE GEOCIÊNCIAS
PROGRAMA DE PÓS-GRADUAÇÃO EM DINÂMICA DOS OCEANOS E DA TERRA

ALAIN ALVES PÓVOA

RESÍDUOS SÓLIDOS EM PRAIAS ARENOSAS: PANORAMA DA PRODUÇÃO CIENTÍFICA AO LONGO DA COSTA ATLÂNTICA E ESTUDOS DE CASO DA MICROBIOTA A MACROBIOTA NO MUNICÍPIO DE NITERÓI, RIO DE JANEIRO, BRASIL.

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Aprovada em 15 de janeiro de 2026.

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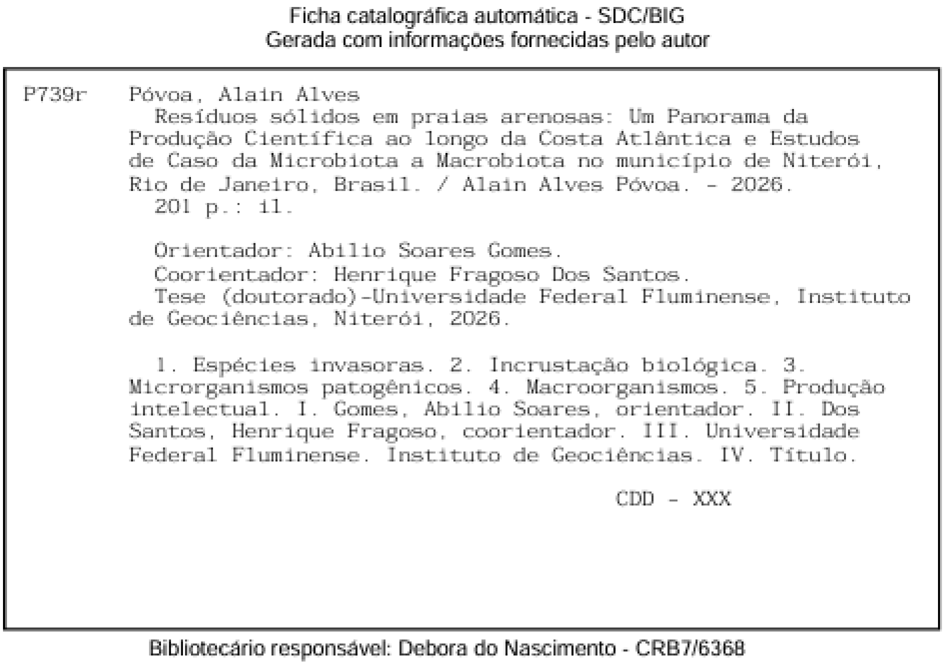
FICHA CATALOGRÁFICA



Ficha catalográfica automática - SDC/BIG
Gerada com informações fornecidas pelo autor

P739r Póvoa, Alain Alves
Resíduos sólidos em praias arenosas: Um Panorama da Produção Científica ao longo da Costa Atlântica e Estudos de Caso da Microbiota a Macrobiota no município de Niterói, Rio de Janeiro, Brasil. / Alain Alves Póvoa. - 2026.
201 p.: il.

Orientador: Abilio Soares Gomes.
Coorientador: Henrique Fragoso Dos Santos.
Tese (doutorado)-Universidade Federal Fluminense, Instituto de Geociências, Niterói, 2026.

1. Espécies invasoras. 2. Incrustação biológica. 3. Microrganismos patogênicos. 4. Macroorganismos. 5. Produção intelectual. I. Gomes, Abilio Soares, orientador. II. Dos Santos, Henrique Fragoso, coorientador. III. Universidade Federal Fluminense. Instituto de Geociências. IV. Título.

CDD - XXX

Bibliotecário responsável: Debora do Nascimento - CRB7/6368

AGRADECIMENTOS

Agradeço, em primeiro lugar, à fé — essa força silenciosa e poderosa que, independentemente de religião ou doutrina, revela-se sempre presente e valiosa, especialmente nos momentos mais desafiadores da vida.

À minha mãe, Severina, dedico toda a gratidão que palavras jamais alcançarão traduzir por completo. Seu amor constante, renovador e incondicional foi como um farol que me guiou em diversos momentos da vida. Ao meu pai, Américo (in memoriam), minha eterna admiração e saudade. Dele herdei o amor pelas praias e pelo mar. Seu legado permanece vivo em mim, principalmente em minhas memórias.

Estendo meus agradecimentos com profundo carinho a todos os membros da minha família, cujo apoio, mesmo nos mais diversos momentos do cotidiano, foi essencial para que esta trajetória fosse possível, mesmo sem saber o que significa o doutorado.

Aos amigos que dividiram comigo os desafios e as alegrias do cotidiano — Luiza Reis, Filippe Schulz, Igor Henud, Renan Amorim, Peter Prado, Lucas Vinicius, Mariana Tavares, Rafael Trindade, Carlos Sigmaringa, Fernanda Saleme e Bernardo Brandão — minha gratidão pela presença firme, pelas conversas sinceras, pelos momentos de descontração e por todo o companheirismo que suavizou os passos dessa longa caminhada acadêmica.

Sou grato também aos colegas do Laboratório de Microbiologia e Microbiotecnologia Ambiental: Emily Magalhães, Katheriny Pereira, André Canellas e Vanessa Janoni, que foram fundamentais na preparação do material para extração de DNA e as análises da bioinformática.

Aos amigos conquistados nos laboratórios da Universidade Federal do Estado do Rio de Janeiro (UNIRIO) — Antônio Rodrigues, Gabriel Martins e Pedro Lucas Freire — deixo meu apreço pelo companheirismo, pelas risadas e pela leveza que trouxeram ao meu cotidiano.

À Caroline de Andrade e ao Ludson Ázara, pela amizade que soube transcender a distância geográfica, pelo acolhimento constante e pela demonstração de que a presença genuína se manifesta na qualidade dos vínculos. Cada encontro foi marcado por alegria sincera e momentos de agradável convivência.

Aos meus orientadores, Abilio Soares-Gomes (orientador) e Henrique Fragoso dos Santos (coorientador) agradeço por cada conselho, cada leitura atenta, cada palavra de incentivo e por não perderem a paciência diante das minhas inquietações. Vocês foram guias

fundamentais, não apenas no aspecto técnico, mas também no amadurecimento do meu pensamento científico.

Aos especialistas que colaboraram com a identificação das espécies, minha gratidão genuína: Fábio Pitombo e Rodrigo D'Almeida (cirripédios), Ana Carolina Almeida (briozoários), Igor Mihayra e Vanessa Amaral (moluscos bivalves), Carlos Sigmaringa (moluscos gastrópodes), Andrielle Rodrigues e Ana Cláudia Brasil (poliquetas) e Humberto Fortunato (esponjas). As contribuições foram indispensáveis para a solidez científica deste trabalho.

Aos Laboratórios de Ecologia de Sedimentos e de Microbiologia e Microbiotecnologia Ambiental, ambos da Universidade Federal Fluminense, agradeço por terem sido verdadeiras casas acadêmicas. Cada capítulo desta tese carrega um pouco da história que vivi nesses ambientes, repletos de trocas, aprendizados e descobertas.

Ao CNPq/Capes, pelo suporte financeiro por meio da bolsa de estudos, meu sincero reconhecimento. Essa ajuda foi fundamental para viabilizar os trabalhos de campo e garantir a continuidade da pesquisa.

Ao Programa de Pós-Graduação em Dinâmica dos Oceanos e da Terra da Universidade Federal Fluminense, minha gratidão pela oportunidade de cursar o doutorado e pelo apoio que permitiu levar minha pesquisa a eventos científicos relevantes, como o XV e o XVI Encontro de Bioincrustação, Ecologia Bêntica e Biotecnologia, o XX Congresso Latino-Americano de Ciências do Mar e o II Simpósio de Ecologia e Conservação de Praias Arenosas.

Agradeço à Universidade Federal Fluminense por proporcionar um ambiente acadêmico enriquecedor, pela pluralidade de pessoas e saberes, e pelas amizades que nasceram nesse contexto e que certamente seguirei cultivando ao longo da vida.

Por fim, reconheço que a verdadeira essência da vida se revela na capacidade de equilibrar o conhecimento científico com a sensibilidade humana. A biologia dos seres, o amor pela natureza e a conexão profunda com os animais são fontes inesgotáveis de inspiração. Foi mergulhando nas profundezas da vida marinha que compreendi, com mais clareza, o valor da resiliência, da diversidade e da interdependência entre todas as formas de vida. Cada organismo observado, cada fragmento analisado, trouxe uma lição — sobre sobrevivência, adaptação e conexão.

Este trabalho é, portanto, um reflexo do que sou: alguém em constante busca por entender o mundo, respeitando suas complexidades e celebrando sua beleza.

A vida ensina e o tempo traz o tom
Pra nascer uma canção
Com a fé o dia-a-dia encontro solução
Encontro a solução
Quando bate a saudade eu vou pro mar
Fecho os meus olhos e sinto você chegar
(Cidade Negra)

RESUMO

Diferentes tipos de resíduos sólidos acumulados em ambientes costeiros, especialmente nas praias arenosas, podem atuar como substratos para a colonização de diferentes organismos, desde microrganismos até macrorganismos. Essa colonização pode ocasionar diversos impactos ecológicos como a introdução de espécies invasoras e a disseminação de patógenos para organismos marinhos e seres humanos. Esta tese apresentou como objetivo geral avaliar a diversidade, a composição e os impactos ecológicos e sanitários de organismos associados a diferentes tipos de resíduos sólidos, considerando o papel das propriedades físico-químicas dos substratos na colonização biológica. A tese foi estruturada em três capítulos independentes com metodologias distintas. O primeiro capítulo consistiu em uma revisão cientométrica dos estudos sobre resíduos sólidos em praias arenosas do Atlântico, destacando a heterogeneidade metodológica e as lacunas geográficas existentes com ênfase no gerenciamento costeiro e um destaque para o papel das mudanças climáticas. Esse estudo apresentou um alto número de publicações foi identificado, com o Brasil como principal produtor científico, baixa participação dos Estados Unidos, predominância do plástico como resíduo, complementaridade entre bases de dados, metodologias não uniformes e riscos climáticos ainda pouco considerados. O segundo capítulo investigou a presença de comunidades microbianas aderidas a diferentes tipos de resíduos (plástico, madeira, vidro e alumínio) e sedimento, revelando a ocorrência de bactérias potencialmente patogênicas demonstrando uma distinção da comunidade microbiana de madeira e outros tipos de resíduos em praias estuarinas e oceânicas. Os principais resultados deste capítulo deram destaque para a madeira, que apresentou maior riqueza de possíveis patógenos e espécies ligadas à microincrustação, além de uma clara diferenciação da comunidade microbiana em relação ao sedimento em praias estuarinas e oceânicas. O terceiro capítulo abordou a composição da macrofauna incrustada em resíduos sólidos coletados em uma baía urbana tropical e em áreas costeiras adjacentes do sudoeste do Atlântico, identificando espécies nativas, exóticas, criptogênicas, muitas das quais apresentam potencial invasor para a região bem como as diferentes propriedades físico-químicas que podem influenciar no assentamento larval das espécies nos diferentes tipos de resíduos. Os resultados reforçam que as características físico-químicas dos substratos influenciam diretamente os padrões de incrustação, afetando tanto a diversidade biológica quanto os riscos ambientais associados à dispersão de organismos. A compreensão dessas interações é essencial para orientar ações de monitoramento e gerenciamento costeiro que considerem não apenas a quantidade, mas também o tipo de resíduo presente em praias arenosas.

Palavras-chave: Espécies invasoras, Incrustação biológica, Microrganismos patogênicos, Macrorgansimos, *Rafting*.

ABSTRACT

Different types of marine litter accumulated in coastal environments, particularly on sandy beaches, can act as substrates for the colonization of a wide range of organisms, from microorganisms to macroorganisms. This colonization may generate several ecological impacts, including the introduction of invasive species and the dissemination of pathogens to marine organisms and humans. The general objective of this thesis was to evaluate the diversity, composition, and ecological and sanitary impacts of organisms associated with different types of marine litter, considering the role of the physicochemical properties of substrates in biological colonization. The thesis was structured into three independent chapters using distinct methodologies. The first chapter consisted of a scientometric review of studies on solid waste on Atlantic sandy beaches, highlighting methodological heterogeneity and existing geographical gaps, with emphasis on coastal management and the role of climate change. This chapter revealed a high number of publications, with Brazil as the main contributor, low participation by the United States, plastic as the predominant waste type, complementarity among databases, non-uniform methodologies, and climate-related risks still poorly addressed. The second chapter investigated microbial communities attached to different types of waste (plastic, wood, glass, and aluminum) and to sediment, revealing the presence of potentially pathogenic bacteria and clear differences between microbial communities associated with wood and those found on other types in estuarine and oceanic beaches. The main results highlighted wood as the substrate with the highest richness of potential pathogens and species associated with microfouling, as well as a marked differentiation of microbial communities between wood and sediment in both environments. The third chapter addressed the composition of macrofouling fauna on solid waste collected from a tropical urban bay and adjacent coastal areas in the southwestern Atlantic, identifying native, exotic, and cryptogenic species, many with invasive potential, and evaluating how different physicochemical properties of substrates influence larval settlement across types. Overall, the results reinforce that the physicochemical characteristics of substrates directly influence fouling patterns, affecting both biological diversity and the environmental risks associated with organism dispersal. Understanding these interactions is essential to support monitoring actions and coastal management strategies that consider not only the amount, but also the type of litter present on sandy beaches.

Keywords: *Fouled species*, *Invasive species*, *Macroorganisms*, *Pathogenic microorganisms*, *Rafting*.

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ARGs	Antibiotic Resistance Genes – genes de resistência a antibióticos presentes em microbiomas de lixo marinho.
ETE	Estação de Tratamento de Esgoto
CCI	Clean Coast Index – índice de limpeza de praias baseado na quantidade de lixo marinho.
MLFO	Marine Litter with Fouled Organisms – lixo marinho colonizado por organismos.

SUMÁRIO

1. INTRODUÇÃO GERAL

1.1 ÁREA COSTEIRA E PRAIAS ARENOSAS

A costa brasileira apresenta uma extensão de aproximadamente 8.500 quilômetros, desde a desembocadura do rio Oiapoque, no Amapá, até a foz do arroio Chuí, no Rio Grande do Sul e 200 milhas náuticas a leste (MMA, 2025). Esta extensa faixa litorânea abrange uma grande diversidade de ambientes, totalizando cerca de 514 mil quilômetros quadrados, dos quais aproximadamente 324 mil quilômetros quadrados correspondem ao território dos 395 municípios em 17 estados banhados pelo Oceano Atlântico (MMA, 2025). Esta área é reconhecida como Patrimônio Nacional pela Constituição Federal de 1988 (Brasil, 1988).

A costa brasileira apresenta elevado valor ambiental, ecológico e socioeconômico, a qual desempenha diversas funções como a conservação da biodiversidade, a provisão de serviços ecossistêmicos e o suporte a atividades econômicas essenciais, como o turismo, a pesca e o transporte marítimo, entre outros (Kirillova *et al.*, 2014; Corrêa *et al.*, 2021). Apesar de sua importância, essa região enfrenta uma série de desafios provenientes de impactos naturais ou antrópicos (Corrêa *et al.,* 2021). Diversos impactos como a erosão costeira, a urbanização desordenada, a poluição e as variações do nível do mar afetam diretamente a integridade dos ecossistemas litorâneos como as praias arenosas (Marques; Nicolodi, 2021; MMA, 2024).

As praias arenosas representam o ecossistema litorâneo mais comum em escala global, sendo particularmente vulneráveis às mudanças ambientais e às intervenções humanas (Filho *et al.,* 2014; Lercari, 2023). Essas praias são formadas por depósitos de sedimentos não consolidados acumulados predominantemente pela ação das ondas, rios, marés, onde processos dinâmicos e contínuos de erosão e acreção são observados (McLachlan; Brown, 2006; Côrte *et al.*, 2023). Esses ambientes litorâneos são caracterizados por sua alta dinamicidade e instabilidade morfológica, em constante transformação sob a influência de fatores naturais como a energia das ondas, a ação dos ventos, as correntes marítimas e as variações no nível do mar (McLachlan; Brown, 2006; Amaral *et al.*, 2023).

As praias possuem diferentes tipos de classificação, uma vez que podem ser identificadas em relação ao seu perfil geomorfológico, ao nível de intensidade de energia e morfodinâmica de ondas (Short, 1999; Nordstrom; Jackson, 2012; Postigloni *et al.,* 2025). O perfil geomorfológico das praias arenosas é composto por diversas faixas, comumente denominadas zonas: pós-praia (*backshore*), estirâncio (*foreshore*), face de praia (*beachface*), antepraia (*shoreface*), zona de surfe, zona de arrebentação e zona de espraiamento (Figura 1)

(Muehe, 1995; Short, 1999; Souza *et al.*, 2005). Podem ser classificadas em três tipos principais, com base em suas características morfológicas e na dinâmica das ondas: refletivas, dissipativas e intermediárias (Wright; Short, 1984; Short *et al.*, 2020) (Figura 2).

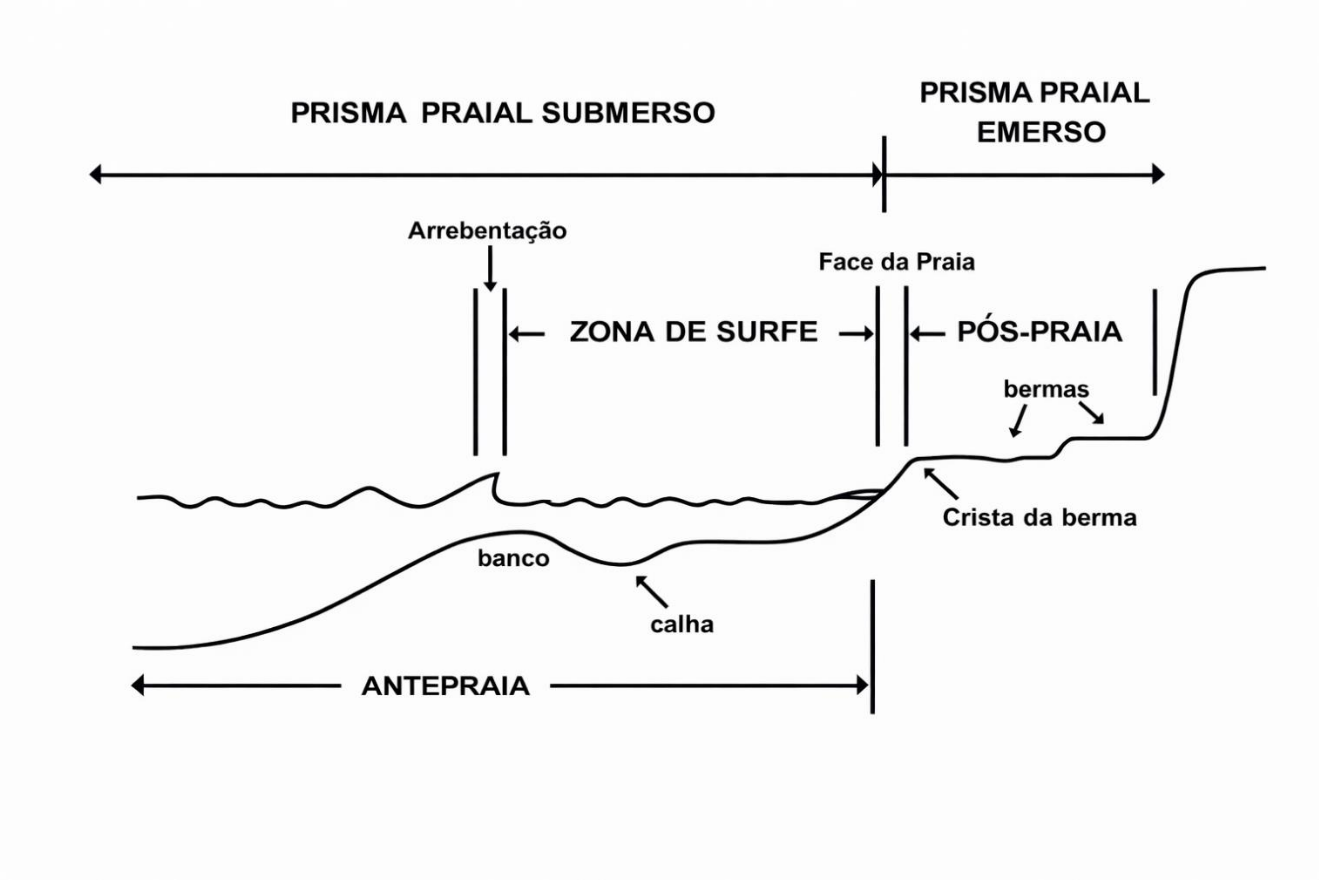
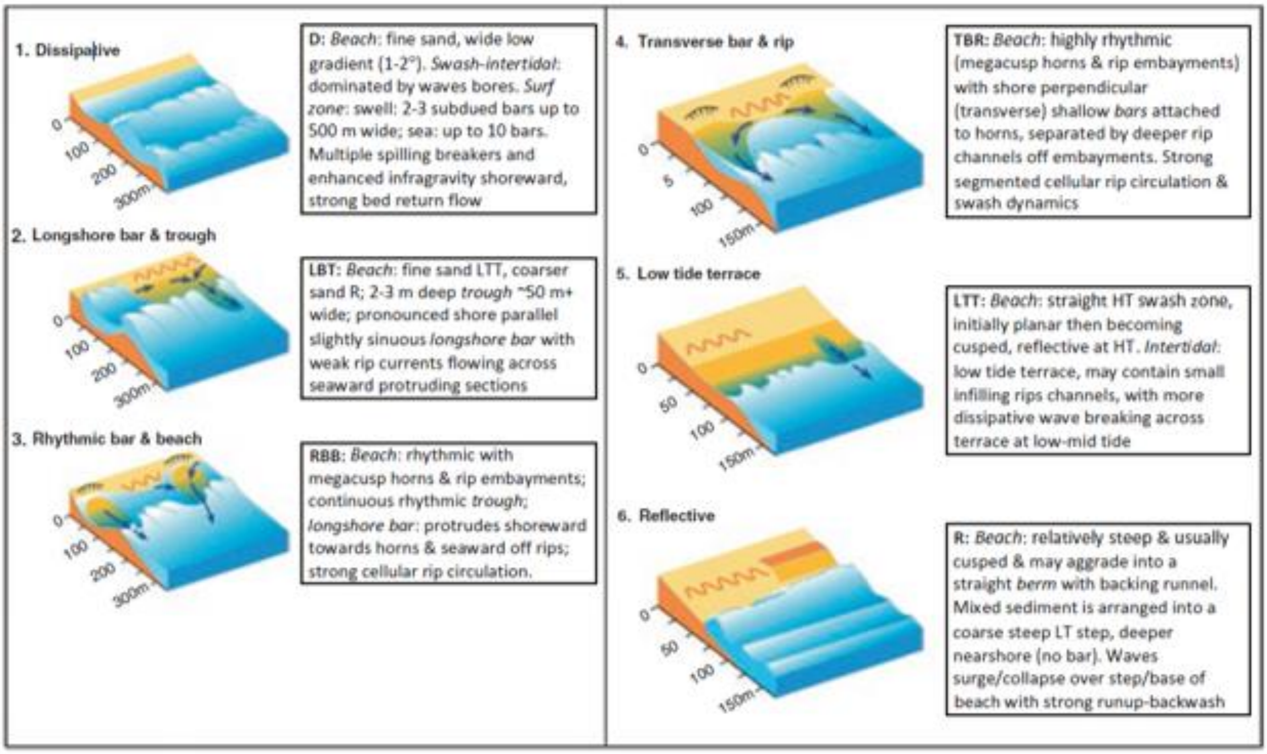


Figura 1 - Representação esquemática das zonas das praias.

Fonte: Zona Costeira (zonacosteira.bio.ufba.br/praia.html).



D: *Beach*: fine sand, wide low gradient (1-2°). *Swash-intertidal*: dominated by waves bores. *Surf zone*: swell: 2-3 subdued bars up to 500 m wide; sea: up to 10 bars. Multiple spilling breakers and enhanced infragravity shoreward, strong bed return flow

LBT: *Beach*: fine sand LTT, coarser sand R; 2-3 m deep *trough* ~50 m+ wide; pronounced shore parallel slightly sinuous *longshore bar* with weak rip currents flowing across seaward protruding sections

RBB: *Beach*: rhythmic with megacusp horns & rip embayments; continuous rhythmic *trough*; *longshore bar*: protrudes shoreward towards horns & seaward off rips; strong cellular rip circulation.

TBR: *Beach*: highly rhythmic (megacusp horns & rip embayments) with shore perpendicular (transverse) shallow *bars* attached to horns, separated by deeper rip channels off embayments. Strong segmented cellular rip circulation & swash dynamics

LTT: *Beach*: straight HT swash zone, initially planar then becoming cusped, reflective at HT. *Intertidal*: low tide terrace, may contain small infilling rips channels, with more dissipative wave breaking across terrace at low-mid tide

R: *Beach*: relatively steep & usually cusped & may aggrade into a straight *berm* with backing runnel. Mixed sediment is arranged into a coarse steep LT step, deeper nearshore (no bar). Waves surge/collapse over step/base of beach with strong runup-backwash

Figura 2 – Principais tipos morfodinâmicos das praias.

Fonte: Zona Costeira (zonacosteira.bio.ufba.br/praia.html).

Outra classificação relevante das praias distingue entre aquelas de alta e baixa energia, com base na intensidade das ondas incidentes e nos fatores ambientais que modulam o transporte e a deposição de sedimentos (Short, 1999; Davis-Júnior; Fitzgerald, 2009; Short; Klein, 2016). As praias de alta energia são caracterizadas pela presença de dunas e sedimentos que variam de areia grossa a cascalhos, com declive acentuado e íngreme, com ondas grandes, com zona de arrebentação larga e zona de espraiamento intensa (Davis-Júnior; Fitzgerald, 2009) As praias de baixa energia são caracterizadas por a areia fina, com o declive suave, com ondas pequenas, com zona de arrebentação estreita e espraiamento curto (Tabela 1) (Davis-Júnior; Fitzgerald, 2009; Vieira-de-Jesus *et al.*, 2023).

Tab. 1. Características de praias de alta e baixa energia.

Zona Litorânea	Praia de Alta Energia	Praia de Baixa Energia
Pós-praia	Presença de dunas e sedimentos que variam de areia grossa a cascalhos com erosão evidente	Superfície plana com sedimentos finos que variam de silte a areia fina e vegetação densa.

Estirâncio	Declive acentuado	Declive suave
Face de praia	Íngreme	Suave
Antepraia	Sedimentos grossos	Argila e silte
Zona de surfe	Ondas grandes	Ondas pequenas
Zona de arrebentação	Larga	Estreita
Zona de espraiamento	Espraiamento intenso	Espraiamento curto

Fonte: O autor, 2025.

As praias ainda podem ser classificadas em estuarinas e oceânicas (Nordstrom; Jack, 2012; Postigloni *et al.*, 2025). As praias estuarinas são ambientes costeiros influenciados por processos fluviais e marinhos, tipicamente localizadas perto de estuários onde águas salobras e alta variabilidade ambiental resultam da ação das marés e da vazão fluvial (Nordstrom; Jackson, 2012). Em contraste, as praias oceânicas estão voltadas para o oceano aberto apresentando condições mais estáveis e salinas, com menor influência continental, e maior influência de ondas (Postigloni *et al.*, 2025).

As praias também atuam como ecótones, ou seja, áreas de transição entre o ambiente terrestre e marinho, as quais são essenciais para a manutenção da biodiversidade (McLachlan; Brown, 2006; Amaral *et al.*, 2023). As praias são locais de forrageamento, nidificação e descanso para uma ampla gama de organismos marinhos e terrestres, além de contribuírem para o equilíbrio ecológico costeiro (Defeo; McLachlan, 2005; Amaral *et al.*, 2023)

A integridade ecológica e atratividade turística têm sido ameaçadas por impactos antrópicos, como o crescimento populacional desordenado, a expansão urbana e a poluição proveniente de diversas fontes como as domésticas, as industriais e as urbanas que afetam cada vez mais as praias arenosas (Defeo; McLachlan, 2005; Barboza *et al.*, 2016; Amaral *et al.*, 2023). A falta de infraestrutura adequada e de estratégias eficazes de ordenamento costeiro agravam esses riscos, comprometendo desta forma a conservação da biodiversidade e a funcionalidade desses ecossistemas (Pereira *et al.*, 2003; Zacarias *et al.*, 2011; Corrêa *et al.*, 2021). Nesse contexto, a inclusão das praias em estratégias integradas de gerenciamento costeiro, no âmbito municipal, estadual e federal, é essencial para garantir sua proteção e uso sustentável (Botero *et al.*, 2014; Fanini *et al.*, 2020).

A análise sistemática do panorama costeiro é uma ferramenta essencial para diagnosticar os impactos antrópicos e avaliar os riscos associados à perda de atratividade dessas áreas, o que fornece subsídios técnicos para um gerenciamento mais eficaz (Kirillova *et al.*, 2014; Corrêa et al., 2021). A necessidade de estudos científicos que subsidiem ações de gerenciamento integrado, monitoramento contínuo e conservação eficaz da área costeira brasileira é ainda mais urgente diante do cenário de mudanças climáticas e intensificação das pressões antrópicas (Kirillova *et al.*, 2014).

As praias do estado do Rio de Janeiro estão inseridas na ecorregião marinha do Atlântico Sudoeste Tropical (Spalding *et al.*, 2007), uma das mais impactadas por atividades antropogênicas ao longo da costa brasileira (Videla; Araújo, 2021; Póvoa *et al.*, 2024), com com cerca de 80% da população do estado vivendo em áreas costeiras (Andreatta *et al.*, 2009). A região enfrenta desafios ambientais significativos, especialmente, no que diz respeito, à poluição por resíduos sólidos em ambientes praiais, afetando a qualidade ambiental e os usos sociais e econômicos dessas áreas como turismo, pesca, entre outros (Andrades *et al.*, 2018; Videla; Araújo, 2021; Póvoa *et al.*, 2024).

1.2 POLUIÇÃO POR RESÍDUOS SÓLIDOS EM PRAIAS ARENOSAS

A poluição ambiental é definida como a introdução pelo homem de substâncias ou formas de energia no meio ambiente em concentrações superiores aos níveis naturais, o que resulta em diversos impactos aos ecossistemas e à saúde humana (Bergallo *et al.*, 2024). Dentre os diferentes tipos de poluição, a por resíduos sólidos têm ganhado destaque devido ao aumento significativo do seu volume e à sua persistência no ambiente (Altinpinar, 2025).

Os resíduos sólidos podem ser definidos como "qualquer material sólido, persistente, fabricado, processado, descartado ou abandonado" (Cheshire *et al.*, 2009; Angiolillo *et al.*, 2015), que podem apresentar origem terrestre e marinha (Munari *et al.*, 2016, Altinpinar, 2025). Os resíduos provenientes de fontes terrestres chegam aos ambientes costeiros por meio de esgotos, rios, ventos ou do descarte inadequado da população durante atividades recreativas; os de origem marinha são provenientes de atividades pesqueiras, industriais e de navegação, sendo lançados ao mar de forma acidental ou intencional (Angiolillo *et al.*, 2015; Munari *et al.*, 2016).

As praias localizadas em regiões dominadas pelas principais correntes oceânicas, ventos ou inseridas em baías são mais propensas ao acúmulo de resíduos sólidos (Póvoa *et al.*, 2022; Póvoa *et al.*, 2024). Esses materiais são transportados pela ação das marés e ondas de tempestades associadas a frentes frias, provenientes principalmente dos quadrantes Sul e Sudoeste no estado do Rio de Janeiro (Macedo *et al.*, 2019; Póvoa *et al.*, 2022a). A atuação desses quadrantes estende-se até a Região dos Lagos. Em Arraial do Cabo ocorre um processo de ressurgência local, intensificado pelos ventos de nordeste, que promovem o deslocamento das águas superficiais da plataforma continental e favorecem a intrusão de massas de água mais frias e profundas (Júnior, 1995). A configuração da linha de costa condiciona a proximidade de isóbatas mais profundas ao litoral, favorecendo processos de ascensão de águas frias. Esses processos atuam na redistribuição dos resíduos ao longo da coluna d’água, possibilitando que materiais originalmente depositados em maiores profundidades atinjam a superfície. Adicionalmente, variações na orientação costeira estão relacionadas ao aumento da densidade de resíduos (Júnior, 1995; Pereira, 2025). Na região Norte do Estado, na região de Farol de São Tomé, ocorre uma mudança na orientação da linha de costa com predomínios de ventos de Norte e Nordeste, que possivelmente modifica o sentido do transporte dos resíduos (Machado, 2010).

Os principais tipos de resíduos observados nas praias costeiras incluem plásticos, madeiras, metais e vidros (Cheshire *et al.*, 2009; Andrady, 2015). Durante as operações de limpeza das praias, itens como guimbas de cigarro e fragmentos de plásticos são frequentemente encontrados (Andrady, 2015). A pandemia de COVID-19 contribuiu significativamente para o aumento do consumo e descarte de produtos plásticos, como máscaras, luvas e óculos de proteção, intensificando ainda mais o problema da poluição por resíduos plásticos nas praias (De-la-Torre *et al.*, 2021; Ribeiro *et al.*, 2021; Rangel *et al.*, 2024). Globalmente, estima-se que, a cada ano, entre 86 a 150 milhões de toneladas de resíduos plásticos sejam descartadas nas praias globalmente a cada ano, com posterior fragmentação desses resíduos em partículas menores (Turra *et al.*, 2020).

A fragmentação de resíduos plásticos resulta na formação de microplásticos, partículas entre 1 e 5 milímetros, e de nanoplásticos, que variam entre 1 e 1000 nanômetros. Estes fragmentos se integram às cadeias tróficas e podem afetar seres humanos, uma vez que já foram encontrados na corrente sanguínea, na placenta humana, entre outros (Castro *et al.*, 2020; Imsaurriaga *et al.*, 2024). Além disso, os plásticos e outros resíduos podem ser transportados por longas distâncias no oceano, sendo retidos em giros oceânicos ou ficando à deriva por décadas, o que amplia seu impacto ecológico, social e estético (Rech *et al.*, 2018; Andrades *et al.*, 2018).

A presença de resíduos sólidos nos ambientes costeiros acarreta impactos significativos, tanto em nível econômico, social e ambiental (Turra *et al.*, 2020). Diversos impactos ambientais são observados como a ingestão de resíduos por organismos marinhos, o que pode prejudicar sua locomoção, alimentação e respiração. Em vertebrados marinhos, como aves, répteis e mamíferos, o consumo destes resíduos ao confundir com sua alimentação pode ocasionar impactos nos sistemas fisiológicos e promover a desregulação endócrina de diferentes organismos (Gall; Thompson, 2015; Donovaro *et al.*, 2026).

Esses diferentes resíduos sólidos, especialmente os plásticos, podem servir como substratos para a colonização de organismos bentônicos, como espécies incrustantes, que colonizam estes materiais, transformando-os em recifes artificiais (Rech *et al.*, 2018; Póvoa *et al.*, 2021, 2022a). Esses resíduos e os organismos neles aderidos podem ser transportados por correntes oceânicas para novas áreas, em um fenômeno ecológico conhecido como *rafting* (Rech *et al.*, 2016; Póvoa *et al.*, 2022; Abelouah *et al.*, 2024). O *rafting* em resíduos sólidos atua como um vetor de espécies invasoras, que, ao competir com a fauna nativa e predar organismos locais, pode ocasionar um desequilíbrio ecológico (Thiel; Guttow, 2005; Mantelatto *et al.*, 2020; De-la-Torre *et al.*, 2023). Além disso, fatores físico-químicos dos resíduos, como sua cor, composição química, forma geométrica, tipo de polímero e a orientação de sua superfície podem influenciar na colonização das espécies nos resíduos (Rech *et al.*, 2021; Póvoa *et al.*, 2021; De-la-Torre *et al.*, 2023).

Estes mesmos resíduos também funcionam como substratos para a colonização de microorganismos patogênicos ou não (Audrézet *et al.*, 2021; García-Gómez *et al.*, 2021; Magalhães *et al.*, 2024). O plástico é o principal substrato estudado, formando uma comunidade microbiana conhecida e denominada de plastisfera (Zettler *et al.*, 2013; Audrézet et al., 2021; García-Gómez *et al.*, 2021). Outros materiais, como madeira e alumínio podem atuar como substrato para a colonização destes microorganismos, formando um composto de bactérias, vírus, algas e diatomáceas que podem ser transportados de um local para outro usando os resíduos como vetores (Naudet *et al.*, 2025). Além disso, nestes diferentes tipos de resíduos podem ser encontradas bactérias que podem contribuir como hotspot, ou seja, pontos críticos para a presença de genes de resistência devido à alta atividade microbiana (Magalhães *et al.*, 2024).

No litoral do estado do Rio de Janeiro, diversas praias enfrentam problemas graves relacionados à poluição por resíduos sólidos, especialmente na Região Metropolitana, que recebem efluentes de rios altamente poluídos e resíduos provenientes de fontes terrestres e marítimas (Baptista-Neto; Fonseca, 2011; Silva *et al.*, 2022). O estado possui praias voltadas para o mar aberto e outras situadas em baías, bem como também apresentam praias estuarinas e oceânicas, as quais são afetadas pela constante presença de resíduos sólidos (Macedo *et al.*, 2019; Póvoa *et al.*, 2022; Póvoa *et al.*, 2025).

2. OBJETIVOS

2.1. OBJETIVO GERAL:

Analisar a ocorrência, caracterização e os impactos dos resíduos sólidos em praias arenosas do Atlântico, com ênfase na Baía de Guanabara e na Região Oceânica de Niterói, considerando sua composição, degradação, fontes, interações biológicas e condicionantes ambientais, visando subsidiar ações de gestão e mitigação ambiental costeira.

2.2. OBJETIVOS ESPECÍFICOS:

Os objetivos específicos são apresentados de acordo com os capítulos:

2.2.1 Capítulo 1:

- Caracterizar temporalmente o período de publicações sobre resíduos sólidos em praias arenosas do Atlântico;
- Avaliar o volume de estudos com resíduos sólidos e os principais periódicos publicados com estudos em praias arenosas do Atlântico;
- Comparar as metodologias descritas utilizadas em estudos sobre resíduos sólidos em praias do Atlântico;
- Identificar os principais resíduos sólidos encontrados em praias arenosas do Atlântico citados na literatura;
- Determinar pontos positivos e negativos em relação à pesquisa com resíduos sólidos, propondo soluções para minimizar o impacto destes materiais em praias na costa atlântica.

2.2.2 Capítulo 2:

- Identificar, qualificar e quantificar os diferentes microrganismos associados a quatro tipos diferentes de resíduos sólidos em praias da Baía de Guanabara e da Região Oceânica de Niterói;
- Identificar os microrganismos presentes nos diferentes tipos de resíduos até o menor nível taxonômico;
- Associar os microrganismos encontrados nos diferentes tipos de resíduos sólidos a possível patogenicidade em organismos marinhos e humanos;
- Comparar os microrganismos encontrados nos resíduos sólidos com os presentes no sedimento.

2.2.3 Capítulo 3:

- Identificar, qualificar e quantificar os diferentes tipos de resíduos sólidos e aqueles resíduos com organismos incrustantes encontrados em praias na Baía de Guanabara e Região Oceânica de Niterói.
- Relacionar as principais fontes de resíduos como nível de limpeza das praias em relação aos resíduos sólidos nas praias estudadas;
- Identificar taxonomicamente os organismos presentes nos diferentes tipos de resíduos até o menor nível taxonômico possível e identificar o estágio populacional de invasão biológica;
- Analisar a relação entre as diferentes cores dos resíduos sólidos e os organismos incrustantes nas praias de estudo;
- Avaliar a composição química dos diferentes tipos de resíduos sólidos;
- Avaliar o estágio de degradação por meio do formato geométrico e orientação da superfície (lisa, rugosa) dos resíduos sólidos com organismos incrustantes que chegam às praias pesquisadas;

3. HIPÓTESES

Hipótese 1: As praias arenosas na costa atlântica apresentam uma distribuição desigual de estudos.

Hipótese 2: As comunidades microbianas associada aos resíduos sólidos são distintas em relação ao tipo de material e entre praias estuarinas e oceânicas.

Hipótese 3: A deposição de resíduos sólidos e aqueles com organismos incrustantes são distintos entre praias de alta energia e de baixa energia. As características físico-químicas dos resíduos com organismos incrustantes também são distintas entre estes tipos de praias.

4. ÁREA DE ESTUDO

A área de estudo é representada por algumas praias localizadas na Baía de Guanabara e na Região Oceânica do município de Niterói, na Região Metropolitana do Rio de Janeiro. Essas praias são especialmente impactadas pela poluição por resíduos sólidos, com praias urbanizadas historicamente afetadas (Baptista-Neto; Fonseca, 2011; Silva *et al.*, 2016; Silva *et al.*, 2022). O município figura entre os melhores do Brasil em saneamento básico, uma vez que mais de 90% do esgoto é coletado e aproximadamente 95% é tratado em Estações de Tratamento de Esgoto (ETEs). Ainda assim, persistem fontes difusas de poluição com potencial de afetar a qualidade ambiental costeira (Bernardino e Franz, 2016; de Seixas Filho, 2020; Prefeitura de Niterói, 2025).

Entre esses fatores de fontes difusas estão ligações clandestinas, falhas pontuais no sistema, cargas oriundas da drenagem urbana, deposição de resíduos sólidos, turismo intenso e processos de ocupação urbana acelerada e deposição de resíduos por meio dos rios (Baptista-Neto; Fonseca, 2011; Bernanrdino e Franz, 2016; Silva *et al.,2022*). Assim, apesar dos elevados índices de saneamento, a combinação entre pressões urbanas e limitações operacionais do sistema podem contribuir para o acúmulo de resíduos e para degradação ambiental em praias do município de Niterói (Baptista-Neto; Fonseca, 2011).

As praias da Baía de Guanabara, como Icaraí, São Francisco, Flechas e Charitas, possuem características de baixa energia, com sedimentos que variam de areia fina a média e ondas predominantemente provenientes dos quadrantes sul e sudoeste, com ressacas após a passagem de frentes frias (Silva *et al.*, 2016). Algumas dessas praias, como Flechas e Icaraí, são classificadas como de baixa energia, mas apresentam uma pequena dinâmica devido à orientação para o mar aberto (Silva *et al.*, 2016). Dentre as praias da Baía de Guanabara, Icaraí e São Francisco podem ser classificadas como praias estuarinas devido a influencia de rios ou esgotos que desaguam nestas praias com alta atividade antropogênica (Magalhães *et al.*, 2024).

As praias da Região Oceânica, como Piratininga, Camboinhas e Itacoatiara, são caracterizadas por alta energia especialmente durante eventos de ressacas, com sedimentos predominantemente de areia grossa (Silva *et al.*, 2016; Magalhães *et al.*, 2024). A praia de Itaipu, protegida por ilhas em sua enseada, apresenta características de praia de baixa energia (Eccard *et al.*, 2017). A variação nas características morfodinâmicas das praias influencia o acúmulo de resíduos sólidos, bem como o uso turístico e dos frequentadores de praias e a distribuição da vegetação (Silva *et al.*, 2016; Silva *et al.*, 2022).

5. ESTRUTURA DA TESE

Esta tese foi organizada em três capítulos, apresentados sob a forma de artigos científicos. O Capítulo 1 investiga o estado atual do conhecimento sobre a presença de resíduos sólidos em praias arenosas ao longo da costa atlântica, destacando os principais avanços, lacunas e desafios nessa área de estudo por meio de um estudo bibliométrico.

O Capítulo 2 investiga a presença de microrganismos patogênicos associados a diferentes tipos de resíduos sólidos. Este capítulo tem como objetivo a relação entre os resíduos sólidos e os riscos microbiológicos destes à saúde pública e ambiental.

O Capítulo 3 apresenta uma análise quali-quantitativa dos resíduos sólidos encontrados na linha de maré, no qual aborda a composição, origem e distribuição desses materiais. Além disso, explora a colonização de diversos organismos em diferentes tipos de resíduos sólidos, com ênfase no plástico, correlacionando as características físico-químicas desses materiais (cor, composição química, grau de degradação, forma geométrica, orientação da superfície e tipo de polímero). Por fim, este capítulo avalia o papel dos resíduos como potenciais vetores para a dispersão de espécies exóticas e invasoras.

Esta tese buscou abordar, de maneira abrangente, as interações entre resíduos sólidos, biodiversidade e saúde ambiental, contribuindo para o avanço do conhecimento científico e para o desenvolvimento de estratégias de manejo sustentável em ambientes costeiros.

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6. Capítulo 1:

Ocean and Coastal Research

ORIGINAL ARTICLE

http://doi.org/10.1590/2675-2824072.23181
ISSN 2675-2824

Marine litter on Atlantic Ocean sandy beaches: Current state of knowledge by scientometric analysis and proposal for discussion of amelioration by coastal management

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Abstract

This study aimed to conduct a comprehensive review of marine litter of Atlantic sandy beaches. We performed a bibliometric analysis from 1970 to 2023 to identify patterns, flaws, and knowledge gaps. A total of 185 studies were found but only 126 were included in the analysis according to exclusion criteria adopted. The earliest studies on Atlantic beaches were registered in the 1980s, being Marine Pollution Bulletin, the major journal. Among the countries bordering the Atlantic Ocean, the highest number of studies were carried out in Brazil, Portugal, Mexico, and Spain. A significant finding that emerged from our study was the lack of standardized methodology adopted for studying anthropogenic litter on sandy beaches. This lack of standardization makes it difficult to compare results across different years and areas, highlighting the need for the development of new techniques and means to standardize future studies. Our study also discussed strategies for minimizing the presence of litter on beaches via coastal management and climate changes. It emphasized the importance of review studies in identifying gaps and guiding integrated and shared actions across the Atlantic region. Overall, this comprehensive review provides valuable insights into the status of anthropogenic litter in beaches of the Atlantic and highlights the need for standardization and collaborative efforts to address this persistent problem. By integrating scientific research

with effective coastal management strategies, we can strive towards reducing anthropogenic litter and preserving the health and beauty of the Atlantic sandy beaches and worldwide.

Keywords: Beach litter monitoring, Coastal zone, Environmental management, Plastic pollution

1. Introduction

Sandy beaches are one of the most common types of coastal environments worldwide and are characterized by the presence of sandy grains (Defeo and McLachlan, 2005). The formation of sandy beaches is influenced by several factors such as waves, tides, and sediment sources, among others (Park *et al.,* 2021). Sandy beaches provide important ecological functions and are habitats for numerous species of organisms. They play a significant role in coastal protection, acting as natural barriers against coastal erosion and land flooding by storm tide events (Defeo and McLachlan, 2005). Additionally, sandy beaches are important recreational and tourism destinations, attracting millions of visitors (Defeo and McLachlan, 2005; Barboza *et al.,* 2016).

Human population growth, the real estate market, urban and industrial pollution, and marine litter are some of the factors that threaten the integrity of sandy beaches around the world. To preserve sandy beaches, it is crucial to implement sustainable coastal management practices, promote environmental conservation, and educate the public about the importance of preserving these valuable ecosystems (Andrades *et al.,* 2020; Fanini *et al.,* 2020).

Regarding litter, approximately 2.5 billion tons are generated annually across the planet (Williams and Rangel-Buitrago, 2019), and a large part of them have sandy beaches as its final destination (Rangel Buitrago *et al.,* 2020). The presence of marine litter on both beaches, sands, and seawater is considered one of the indicators of the Anthropocene in the stratigraphic register (Zalasiewicz *et al.,* 2016; Rangel-Buitrago *et al.,* 2019).

Beaches can receive litter from different sources and transport agents like rivers, sewages, winds, and improper disposal, and from economic activities such as fishing, the oil industry, and aquaculture (Munari *et al.,* 2015; Araújo *et al.,* 2018; Rangel-Buitrago *et al.,* 2020; Póvoa *et al.,* 2022a). The local dynamics play important roles in the permanency of litter on the beaches such as the transport via tides and winds (Ryan *et al.,* 2009; Prevenious *et al.,* 2018). Beaches that are more influenced by currents and winds have a greater potential for the accumulation of marine litter, such as exposed beaches when compared to sheltered ones, influenced mainly by the action of cold fronts, currents, storms, waves, and winds and energy dynamics (Park *et al.,* 2021; Póvoa *et al.,* 2022a).

Marine litter is defined as all synthetic or processed material, discarded or abandoned on beaches that can be classified based on their type: plastic, anthropogenic wood, glass, and fabrics, among others (Cheshire *et al.,* 2009). Approximately 8 million tons of litter reach the ocean basins and are subsequently deposited on sandy beaches (Williams and Rangel-Buitrago, 2019). Plastic is one of the most common types of anthropogenic litter, being a long-living and hardly decomposing material. It can persist in the environment for decades or even centuries, causing long-term harm to sandy beaches (Andrades *et al.,* 2018; GESAMP, 2020). Plastic bags and food packaging, indeed among the most common items found on sandy beaches, constitute approximately 80% of the litter (Topçu *et al.,* 2013; Thiel *et al.,* 2013). The plastic on sandy beaches is fragmented by wind, solar radiation, and microbial action, and can be found in different shapes and sizes, including microplastics (Andrady, 2015; Waring *et al*, 2018; Castro *et al.,* 2020).

The impacts of marine anthropogenic litter on human health, social, economic, and environmental aspects are relevant issues. They range from physical injuries to the transmission of diseases, and from decreased tourism to increased costs for beach cleaning and restoration efforts. It is essential to reduce and properly manage litter to mitigate these consequences and protect both human and environmental health (Erkes-Medrano *et al.,* 2015; Rangel-Buitrago *et al.,* 2020; GESAMP, 2020).

Climate change and marine litter are intricately linked, particularly evident along coastlines where their impacts converge. Rising temperatures and extreme weather events driven by climate change intensify storminess and runoff, consequently increasing the influx of litter into marine environments. Moreover, marine litter, predominantly plastics, exacerbates the vulnerability of coastal ecosystems to climate change by undermining their resilience (Lincoln *et al.,* 2022).

Studies on Atlantic Ocean beaches report the presence of marine litter in terms of abundance and geographic distribution, litter accumulation, and correlation between precipitation and abundance; however, to the best of our knowledge, there is no comprehensive review focusing on their entire coastline (Videla and Araújo, 2021; Lima *et al.,* 2022; Anastacio *et al.,* 2023). To fill this gap, we compiled data from studies conducted with marine anthropogenic litter on Atlantic beaches since the 1970s. In this context, one of the techniques used by review studies is the bibliometric network analysis, which is considered a useful tool to assess trends and patterns in the scientific literature, aiming to identify trends and gaps in several relevant topics (Sorensen and Jovanović, 2021).

Bibliometric network analysis is a quantitative method that involves analyzing the relationships between scientific publications in terms of their citations and co-citations. This technique allows researchers to map the knowledge domain of a specific topic by identifying key papers, influential authors, and research clusters (Serenko *et al.*, 2010; Sorensen and Jovanović, 2021). In the context of review studies, bibliometric network analysis can provide valuable insights into the current state of a research field. This information can aid researchers understand the evolution of the topic over time and identify gaps or areas that have received less attention (Serenko *et al.,* 2010). Additionally, bibliometric network analysis can reveal patterns and trends in the literature, allowing them to gain a comprehensive overview of the existing literature, identify key papers and authors, and uncover trends and gaps in the research field (Serenko *et al.,* 2010; Sorensen and Jovanović, 2021). Therefore, bibliometric network analysis is considered a useful tool to assess trends and patterns in the scientific literature to identify trends and gaps in various relevant topics (Sorensen and Jovanović, 2021).

In this sense, this study conducted a survey of the current state of knowledge of studies on Atlantic sandy beach marine litter using scientometrics to identify possible gaps, as well as to propose solutions for reducing litter presence on beaches via coastal management strategies.

2. Methods

2.1 Processing of the bibliographic review

The bibliographic searching was conducted in the Scopus and Pubmed databases, covering 53 years, from 1970 to 2022. The studies were selected in the 1970s, as it was when the first were published, aiming to observe the evolution of these in relation to the theme over time. Studies on marine litter have contributed to understanding its complexity and developing solutions to combat it since the 1970s, particularly due to the rise of plastics as a serious issue, prompting research into mitigation strategies. The search was performed using the following keywords in combination: "TITLE-ABS-KEY (((sandy beach*) AND ("anthropogenic litter" OR "marine litter" OR "marine debris" OR "beach litter" OR "litter" OR "plastic") AND ("Atlantic")))". We used the bibliometrix package in the R interface to analyze the gathered literature (Linnenluecke et al., 2020). The bibliometrix package is an open-source tool developed in R that facilitates bibliometric analysis of scientific data, offering a wide range of resources to examine scientific output and provide insights into trends and relationships across various research fields (Linnenluecke et al., 2020). This package provides tools for bibliometric analysis, allowing for the evaluation and visualization of scientific publications (Linnenluecke, *et al.*, 2020).

Out of a total of 185 studies retrieved, 126 articles (52 and 77 retrieved from Scopus and Pubmed, respectively) were included in the analysis. The other 59 studies were excluded in this review because they corresponded to conference abstracts, theses and dissertations, and monographs. This study considered surveys conducted only on sandy beaches. Studies carried out in the pelagic or other ecosystems were also discarded.

This study aimed to address several research questions related to marine litter on Atlantic Ocean beaches. Questions include the period during which studies have been conducted, the main journals that have published such studies, the leading researchers in this field of knowledge, the most studied regions along the Atlantic coast, the types of marine anthropogenic litter commonly found on these beaches, and if there is a standardized methodology adopted in such studies. Moreover, the study draws inspiration from a previous review study conducted by Póvoa *et al*. (2021) on the topic of rafting in marine litter worldwide. In addition to exploring these research questions, this study also delves into the impacts of litter on beaches in the context of coastal management and climate change.

Based on the findings from the scientometric analysis, a solution or recommendations for coastal management was proposed, aiming to identify activities and measures that can effectively minimize the presence of marine litter on Atlantic Ocean beaches. This may include strategies such as public awareness campaigns, improved waste management systems, beach clean-up initiatives, and regulations to prevent littering. The proposed solution was based on scientific evidence and best practices identified via scientometric analysis. It aimed to contribute to the sustainable management of coastal areas and the reduction of anthropogenic litter, ultimately leading to cleaner and healthier Atlantic beaches.

2.2 Processing of metrics used

Lotka's Law, proposed by Alfred Lotka in 1926, was used in this study to analyze the scientific production of authors. It aims to determine how each author contributes to the advancement of research. The law states that the proportion of authors with a certain number of articles, “x,” is a fraction of those who have written only one article, and this fraction follows a power-law distribution of (1/x^a), in which “a” is a constant usually equal to 2. This law aids measure the impact of citations and identify prolific authors in a specific field (Lotka, 1926).

We also used the h-index proposed by Hirsch (2005). Its purpose is to measure the impact of the main journals in the study area. The number of publications, “h,” that have received at least “h” citations, determines the h-index. For example, if a journal has five publications and each received at least five citations, its h-index would be five (Hirsch, 2005).

The above-mentioned metrics aid quantifying the scientific impact and contribution of authors and journals, respectively, in the study area. Lotka’s Law provides insights into the productivity and impact of individual authors, whereas the h-index focuses on the impact of journals based on their citation counts.

3. Results and Discussion

The 126 studies analyzed included four review articles (Ivar do Sul and Costa, 2007; Monteiro et al., 2018; Andrades et al., 2020; Videla and Araújo, 2021). The four reviews were included because they met the eligibility criteria of the study, namely thematic relevance to marine litter in coastal environments, compliance with the defined period, and contribution to the identification of research trends and methodological approaches (Ivar do Sul and Costa, 2007; Videla and Araújo, 2021). Among these four reviews, one is on the presence of marine litter in the Caribbean and Latin America (Ivar do Sul and Costa, 2007). Monteiro *et al.* (2018) evaluated the presence of plastic on Atlantic Ocean beaches, whereas Andrades *et al.* (2020) and Videla and Araújo (2021) evaluated published studies and made recommendations regarding litter pollution in the coastal area of Brazil. These four reviews contribute to the understanding of marine litter pollution in coastal areas, providing insights into the sources, distribution, and impact of marine litter, particularly plastic, in the Caribbean, Latin America, and Brazil.

The main keywords reported in the literature were environmental monitoring, bathing beaches, plastic, waste products/analysis, and Atlantic Ocean (**Fig.1**). In this study, although Atlantic was the focal keyword, we found studies from the Baltic Sea. This suggests that the literature on marine litter could include studies from various geographical regions, including closed or semi closed seas near the Atlantic Ocean.

Fig. 1. Map of the keywords retrieved from the bibliometric analysis.

The query << "beach debris" >> points out that scientific interest in this topic is relatively recent. This study considered several studies, especially in the past, which may not have clearly used "beach litter" and/or "marine litter," as also demonstrated by Cesarano et al. (2021) in a review of the presence of marine litter on beaches around the world.

The results below are organized into different sections that cover the timeline of the research on Atlantic beaches. This includes the temporal period, main journals, main researchers, countries, main types of litter studies, main methodologies, and a discussion focused on coastal management in the scenario of climate change as suggestions for improvement in coastal management.

3.1 Temporal Period of Studies with Marine Litter on Beaches

The first studies dated back to the 1980s, the first being in 1982 and the last in 2022. The increase in production and consumption of different types of artificial materials since the 1970s has generated enormous amounts of litter used by human populations, mainly plastic. From 2010, there has been a notable increase in the number of articles published on the subject (**Fig.2**).

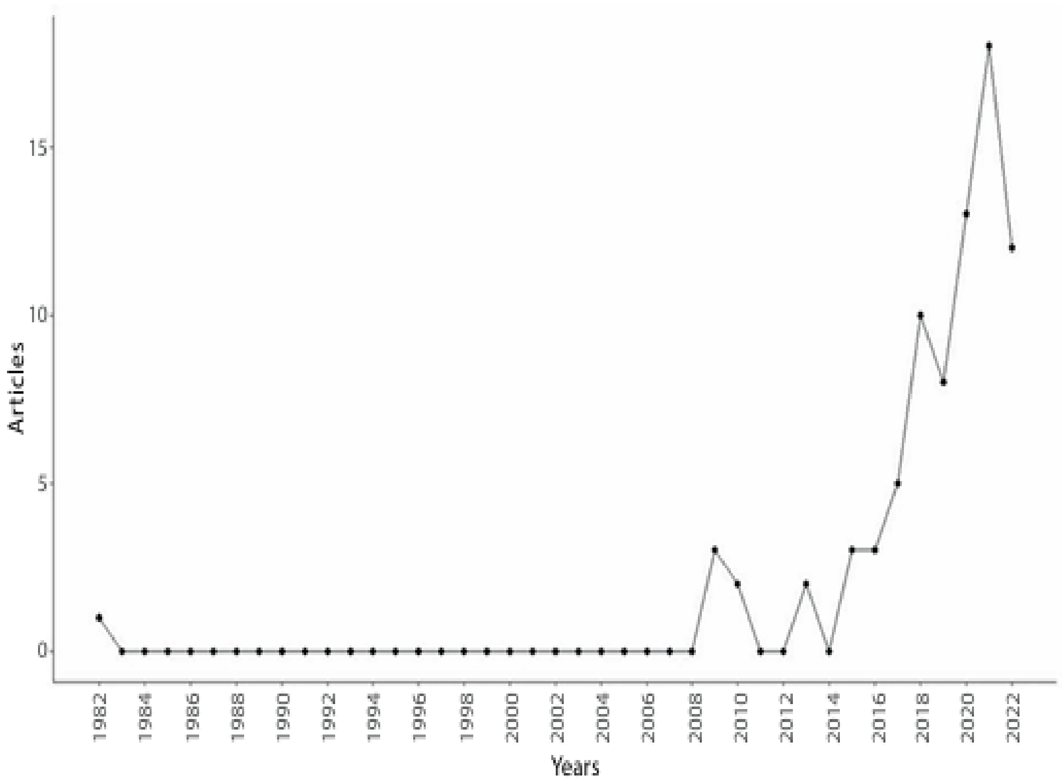

Fig.2. Bibliographic production on marine litter sand beaches by year in Atlantic Ocean.

According to Ivar do Sul and Costa (2007), beaches are one of the places that present the largest number of studies with marine litter since it is an ecosystem that is part of everyday life. Educational campaigns and cleaning activities are commonly carried out on beaches. Moreover, the simplicity of sampling design for several studies, as well as the greater accessibility, makes beaches suitable places for marine litter surveys.

A remarkable increase in marine litter studies on beaches was observed from 2010 to 2023, representing 90.4% of the total. There is a clear increase in studies since 2010 that continue to advance until present times, as pollution by marine litter affects beaches all over the world (Videla and Araújo, 2021; Póvoa *et al.*, 2021; Cesarano *et al.*, 2021). The increase in the number of studies that continues in this decade (2021 – 2030) might also be result of an entire decade focused on efforts to raise awareness of the population regarding the ocean (Gacutan *et al.*, 2022). Overall, the increase in studies from 2010 to 2030 reflects a growing recognition of the detrimental impacts of marine litter on coastal ecosystems and a concerted effort to better understand and address this issue. It highlights the global commitment to protect the ocean and the urgent need to mitigate litter pollution to ensure the health and sustainability of coastal environments (Gacutan *et al.,* 2022).

Recent studies still demonstrate the greater presence of marine litter, but this depends on the location and its characteristics, as well as seasonality. In some countries, depending on the topography, rocky shores show the highest debris density, followed by sandy beaches (Iñiguez *et al.,* 2016)

3.2 Main Journals

The main journals were found linked to the areas of "Environmental Structure Science disciplines," "Earth and Planetary Sciences," and "Agrarian and Biological Sciences," the same areas found by Cesarano *et al.* (2021). The Marine Pollution Bulletin published 49 studies (59.8%), followed by Science of the Total Environment, with 9 studies (11%), 7 studies in Marine Environmental Research and 6 in Environmental Pollution (8.5% and 7.3% respectively), while remainder journals published less than 6 articles.

The study of Videla and Araújo (2021) observed the number of studies in the Brazilian Atlantic from 2010 to 2020. They found that the Marine Pollution Bulletin and the Journal of Integrated Coastal Zone Management published most studies, corroborating the present study. It should be noted that the Journal of Integrated Coastal Zone Management was not cited in the bibliometric analysis but when searched separately, it was found to be one of the journals with the highest number of studies. However, there was a notable difference in the number of studies published in the Marine Pollution Bulletin compared to the other journals. This suggests that the Marine Pollution Bulletin is the leading journal specialized on the subject, as it presented a higher number of studies conducted both in Brazil and in the entire Atlantic Ocean context. This discrepancy in the number of studies among journals implies that researchers and scholars in the field of marine pollution and coastal zone management prefer to publish their f indings in the Marine Pollution Bulletin. This could be due to the journal's reputation, impact factor, or specialization in the subject matter. The journal is specialized in documenting marine pollution and introducing new ways of measuring and analyzing different types of pollution. Moreover, this journal conducted a special issue on litter pollution on beaches and in the marine environment around the world that could improve the number of publications. This journal mainly reflects the importance attributed by European and Asian countries to the collection of litter on their beaches, especially in the Atlantic and North Pacific, the world region of greatest production and disposal of waste (Cesarano *et al.,* 2021). The journal predominantly features research conducted by experts in the fields of oceanography, geomorphology, and marine biology. These professionals contribute their expertise to understanding the ecological implications of marine pollution and proposing strategies for its mitigation (Pauna et al., 2019; Sorensen and Jovanović, 2021).

3.3 Main Researches

The more prolific authors are Andriolo (7 studies) and Golçalves (7 studies), followed by Bessa (5 studies), Garcia-Vazquez (5 studies), and Sobral (5 studies). Of these, E. Garcia-Vazquez is the one that have been publishing for a longer period, with the first study published in 2018, but all continue to study the subject until the present moment. Regarding Lotka's Law, behavior similar to the law was found at the end of the scientific production of waste on beaches, with two authors producing seven studies (proportion of 0.008) and 134 authors producing only one (proportion of 0.556). This proportion of 0.556 is different from the normal behavior of the law, and this result is probably because the subject is not published by other than specialists in the subject. In the image below, the dotted line represents the theoretical behavior of Lotka's Law, whereas the complete line represents the analyzed works (**Fig. 3**).

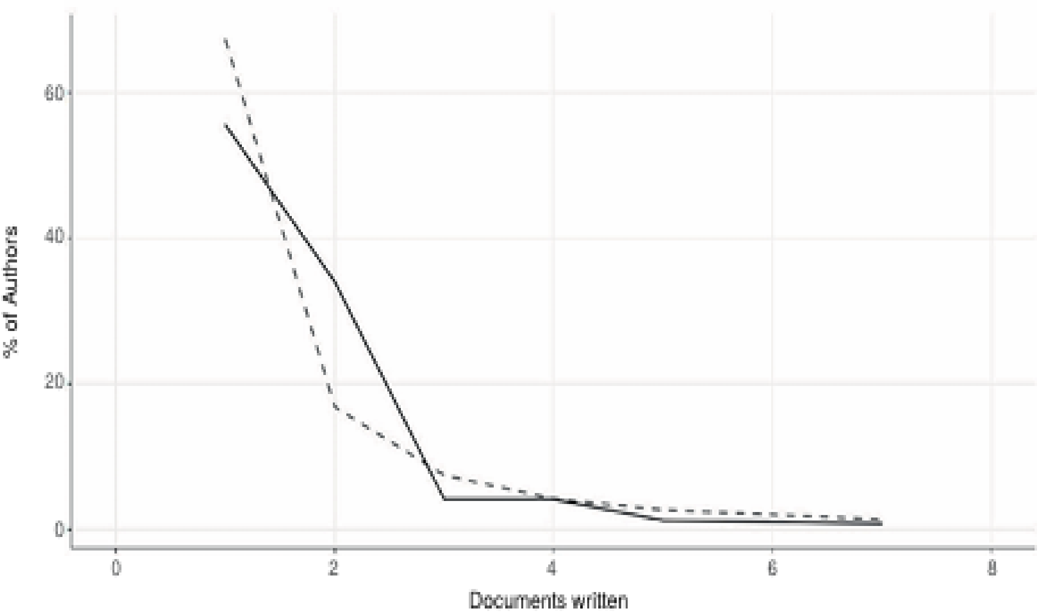

Fig.3. Influence of frequency of distribution of scientific production. The dotted line represents the theoretical behavior of Lotka's Law, while the full line represents the analyzed works.

The use of metrics such as Lotka’s Law and the h-index has the advantage of valuing influential studies, rather than those who publish a lot but their works are soon forgotten and those who publish few highly cited articles (Kelly and Jennions, 2006). The number of citations of a study is used as a proxy for its importance, being considered as a measure of the impact on science (Bornmann and Marx, 2014). The citation is used as a way of evaluating the areas that need development (Bornmann and Marx, 2014).

About the method used for finding papers, we noticed that not all the articles were indexed by Scopus, thus they had to be added manually, meaning that the use of a single database is not enough to contemplate all articles on the subject. Burnham (2006) compared two databases, Scopus and Web of Science (WOS), and concluded that they complement each other; He also suggested that, although WOS presented a greater range of years (since 1945 versus 1960), the use of one or other is interchangeable—some queries had more results on WOS, whereas others on Scopus.

3.4 Countries

Brazil, Portugal, Norway, and Argentina are the countries with the highest number of studies on marine litter on Atlantic sandy beaches. The country with the highest number of corresponding authors is Brazil, with 46 publications representing 56.1% of the studies, followed by Portugal with 31 studies (37.8%), and Norway with 12 studies (14.6%) (**Fig.4**). Interestingly, only four studies were found in the Atlantic of the United States (US) but there are more studies on marine litter conducted in the Pacific Coast of the US. Although the authors are affiliated with Australian institutions, the investigations were conducted in the Atlantic Ocean.

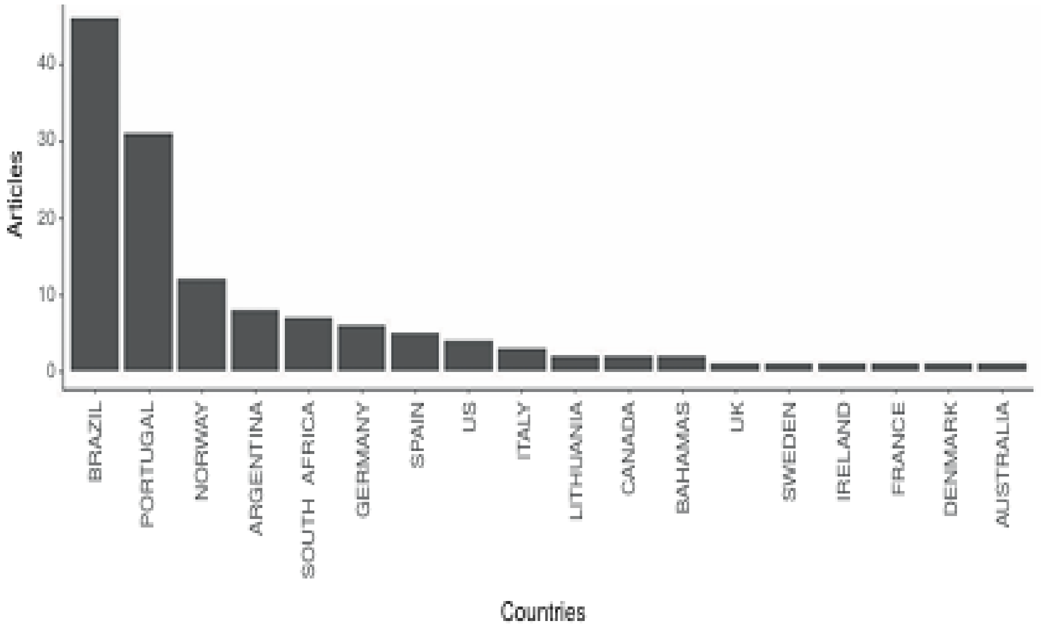

Fig.4. Main countries publishing on beach marine litter in the Atlantic Ocean.

The University of Oviedo, in Spain, showed the highest productivity, with 22 studies with authors from Oviedo, followed by the Federal University of Paraná with 16 studies. Publications by the University of Oviedo began in 2018, with 7 publications, indicating the possible emergence of a study group on the subject in that year. The US authors were pioneers on the subject in the Atlantic, publishing the first study in 1982, although it remained until 2010 without publishing additional papers. According to Cesarano *et al.,* (2021), in relation to worldwide distribution, Spain and Brazil are the countries with most studies on marine litter; however, the US and Spain studies carried out in the Pacific and the Mediterranean were not considered, as they are countries also bathed by these basins in addition to the Atlantic.

The discrepancy in the number of studies found in the present study compared to Cesarano *et al.* (2021) is due to several factors. This study focuses on macrolitter on sandy beaches (plastics, anthropogenic wood, glass, fabrics, among others), excluding studies on microplastics, stomach content analysis, and natural woody debris.

Cesarano *et al*. (2021) found 443 studies on the topic in Atlantic beaches of the US. In the Scopus database, we found 336 studies, of which 107 corresponded to conference abstracts, theses and dissertations, and monographs. These studies were reviewed one by one to determine if they fit the theme and on which coast they were conducted. Conference abstracts, theses and dissertations, monograph was excluded from this study since it is not peer reviewed and is not always as reliable as journal-published articles, although some authors advocate for its analysis (Conn *et al.*, 2003). However, it is also more difficult to retrieve (Mahood *et al.*, 2013), so it was excluded to ensure that the documents included in this work were peer reviewed, ensuring that most studies had a certain degree of quality and research standardization.

Moreover, it was found that a scientific database provides the number of studies by country used in the article. This information was obtained before detailed inspection to exclude articles outside the theme, as indicated in the article. Of the 336 articles, 262 (77.98%) were outside the theme, 33 (9.82%) were conducted in beaches on the West Coast of the US, 21 (6.25%) were about microplastics (from both the West and East Coasts), 11 (3.27%) were on the theme but along the East Coast, and 8 (2.38%) were already in our results.

Interestingly, some articles on the theme classified by Scopus as from the US were not actually conducted in the US (Santos et al., 2009, Pieper et al., 2019; Rangel-Buitrago et al., 2019;). This happens because Scopus assigns the country based on the authors' addresses, meaning that if an article has at least one author from the US, it is credited as American scientific production. However, we ensured that the studies included in the analysis were conducted in our study area by reviewing them one by one.

The discrepancies in the number of studies indicated by Cesarano *et al.* (2021) can also be attributed to the use of different keywords in the query. For example, Cesarano *et al.* (2021) used "waste" as a synonym for litter. Our query found 229 articles on Scopus, in which 24 were classified as American production but only four were actually from the Atlantic coast of the US (16.67%). Cesarano et al. (2020) found 447 productions out of a total of 1,765, with 73 fitting the topic (16.33%). In other words, although the efficiency of both queries is the same, our set of results is easier to analyze. If we excluded "Atlantic" from the query, we would have fewer articles (1,340) to refine but probably the same results. Moreover, most off-topic results in Cesarano *et al.* (2020) were influenced by the keyword "waste" (Walsh; Waliczek, 2020; Resendiz *et al.,* 2019; Adell *et al.,* 2016), which refers to litter but also other types of pollutants in the literature.

The high number of studies conducted in Spain and Brazil is probably related to the great population density of these countries, although Brazil's population (216.4 million citizens) is about fourfold that of Spain (48.8 million citizens). This result could reflect a high number of studies such as prestigious academic institutions, diverse ecosystems, and interest by researchers from all over the world, in addition to being countries frequented by tourists (Videla and Araújo, 2021; Herrera *et al.*, 2023). As popular tourist destinations, these countries attract a significant number of visitors, especially during the summer season when beach activities are prevalent. This influx of tourists, coupled with intense port activity, has contributed to the deposition of waste in their coastal areas (Videla and Araújo, 2021; Herrera *et al.,* 2023).

The situation regarding marine litter on Atlantic beaches in the US is concerning due to the lack of studies conducted on this issue. With a population of 331.9 million people, the high population density contributes to the improper disposal of waste by beachgoers and inadequate waste management practices. This problem is not unique to the US, as Brazil also faces similar challenges (personal observation). In Brazil, over 79 million tons of solid waste are produced annually, with 6.3 million tons not being properly collected (ABRELIPE, 2019). As a result, a significant portion of this litter ends up in the ocean, further exacerbating the problem (Videla and Araújo, 2021). This highlights the need for increased research and effective waste management strategies to protect the Atlantic beaches in both countries.

Portugal has implemented various technological solutions for marine litter monitoring on its beaches. For instance, studies conducted by Andriolo *et al*. (2021); Gonçalves et al. (2020a, 2020b) have highlighted the use of drones, remote sensing imaging equipment, and satellites to streamline the monitoring process. These technologies help minimize the sampling effort and enable monitoring of different beach areas. They also provide insights into the volume of the litter deposited and help researchers identify its presence on sandy beaches. This early detection allows relevant authorities to take timely actions for waste management (Gonçalves *et al.*, 2020 a, b; Andriolo *et al.*, 2021;). Portugal's significant tourist industry adds further complexity to the waste management challenges faced by these beaches. Portugal has leveraged technological advancements in waste monitoring to tackle the challenges associated with waste management on its beaches. By utilizing drones, remote sensing imaging equipment, and satellites, the country has been able to reduce sampling efforts and monitor various beach sites, as well as track the volume of litter deposited. These efforts are particularly important given the high number of tourists visiting popular coastal destinations in Portugal (Gonçalves *et al.*, 2020a, 2020b, Andriolo *et al.*, 2021).

The lack of research on marine litter on the African Atlantic is concerning, as it hinders our understanding of the extent and impact of pollution in that continent (Tavares *et al.*, 2020; Abelouah *et al.*, 2021). The issue of marine litter on African beaches is particularly alarming, considering the significant pollution levels observed. The lack of large research centers and the less developed status of the countries in Africa contribute to the limited studies. Marine litter pollution is a pressing environmental problem globally, and Africa is no exception. The Atlantic coast of Africa faces numerous challenges, including the accumulation of plastic bottles, bags, and other debris on its beaches (Ryan, 2009; Ryan et al., 2021). This marine litter comes from various sources, including local communities, shipping and fishing industries, and even ocean currents that carry debris from distant locations (Tavares *et al.,* 2020; Abelouah *et al.,* 2021).

3.5 Main Types of Marine Litter

Several studies have reported the presence of marine litter on Atlantic beaches (Rangel-Buitrago *et al.,* 2019 Andriolo *et al.,* 2021; Póvoa *et al.,* 2022a). The various types of litter deposited on sandy beaches can reach the marine environment through river currents, daily tidal fluctuations, accidental discharges into the open seas, or accidents involving drilling platforms, fishing, and maritime activities such as commercial, sports, and recreational navigation (Hidalgo-Ruz and Thiel, 2015; Munari *et al.,* 2016; Hidalgo-Ruz *et al.,* 2018).

The main type found on the Atlantic beaches is plastic (Table S1), as all studies reported that plastic is the main type of litter found (Rangel Buitrago *et al.,* 2018; Andriolo *et al.,* 2021; Póvoa et al., 2021; Póvoa *et al.,* 2022a). Brazil and the European Union, both located facing the Atlantic, are among the top 20 countries that mismanage different plastic litter, according to a study by Jambeck *et al*. (2015). The spread of plastic waste has been driven by the growth in the production and use of plastic, supported by linear economic models that have not prioritized integrated waste management (Geyer *et al.,* 2017; Lebreton *et al.,* 2019). Plastic is widely used in modern everyday life due to its durability, resistance, malleability, and low cost (Chesire *et al.,* 2009; Gregory, 2009; Castro *et al.,* 2020). However, this widespread use has led to plastic becoming the predominant type of litter found on beaches around the world. Over time, plastic litter can degrade and become microplastics, which are plastics smaller than 5 millimeters (Castro *et al.,* 2020; da Silva *et al.,* 2022). This type of plastic contaminant is persistent in the marine environment and readily bioavailable for a wider range of organisms along the food chain (De-la-Torre *et al.,* 2023).

The main items collected during clean-up campaigns on Atlantic beaches include cigarette butts, plastic, glass, and paper, all of which reflect behavioral aspects of society

(Póvoa *et al.,* 2021). Cigarette filters are the second most common item found on sandy beaches around the world, including Atlantic beaches, which are most likely incorrectly disposed of by beachgoers (Araújo and Costa, 2019; Araújo *et al.,* 2022). These butts are inaccessible to conventional cleaning services due to their small size, low weight, and color, which causes them to mix in the lower layers of beach sand and make it diffcult to collect (Silva *et al.,* 2018).

Other litter types such as wood, glass, and paper are also found on Atlantic beaches and are reported in several studies (Mantelatto *et al.,* 2020; Póvoa *et al.,* 2022a). The presence of these items is related to tidal deposition (Póvoa *et al.,* 2022 a), as well as consumption by beachgoers (Póvoa *et al.,* 2022 b). The consumption habits of individuals visiting the beach can lead to the generation of such litter. For example, people may bring drinks in glass bottles, food wrapped in paper, or wooden utensils for picnics or barbecues. The study by Perez et al. (2018), carried out on Camboinhas beach, in the municipality of Niterói, for example, found a greater quantity of napkins in kiosk areas. Improper disposal or accidental loss of these items can result in their presence on the beach (Dias Filho *et al.,* 2011; Timbó *et al.,* 2019; Póvoa et al., 2022b).

3.6 Methodologies used with marine litter on Atlantic beaches and proposals reported in the literature for standardization

The topic will be organized into three subtopics, which are data collection methodologies and the need for standardization, the diversity of types of marine litter and their influences, and the incorporation of new technologies and investment challenges.

3.6.1 Data collection methodologies and the need for standardization

The studies were carried out with various methodologies. A total of 56 studies focused on monitoring marine litter (53.3%), 22 studies used a quali-quantitative analysis (21.0%), 14 focused on the environmental perception (13.3%), eight aimed at studying rafting on marine litter (7.6%), and four encompassed tourism (3.8%) (**Fig.5**).

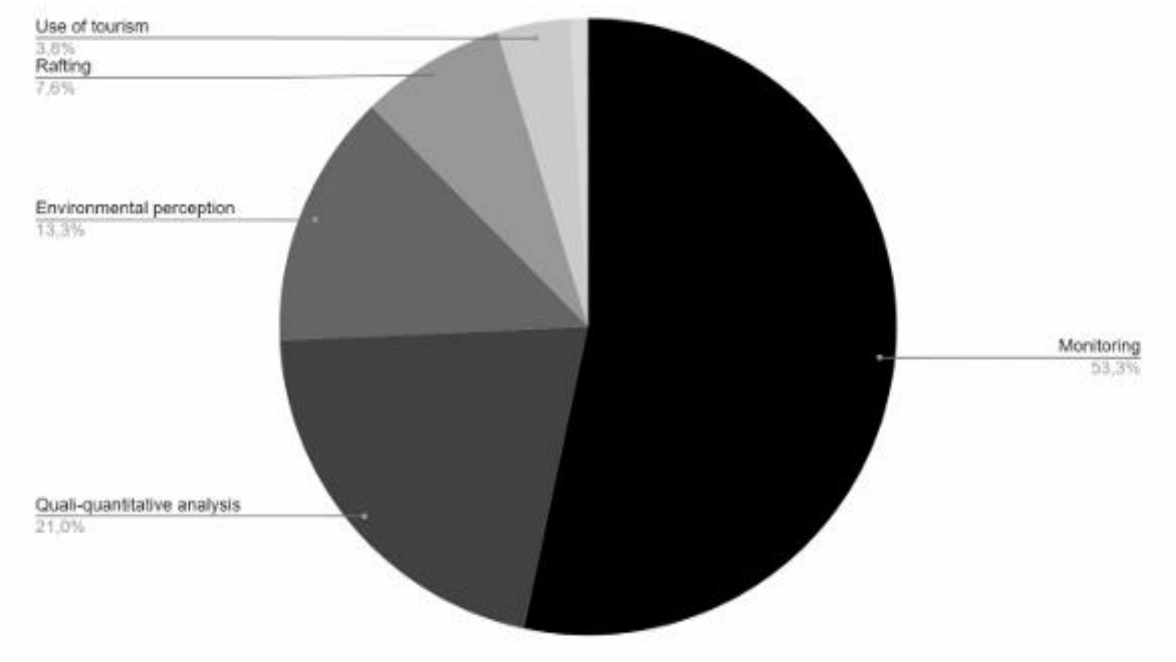

Fig.5. Main subjects studied marine litter on Atlantic beaches.

Upon reviewing the selected studies, the lack of standardization for data collection became evident for data collection across studies. Most marine litter is collected along the entire length of the beach or just in specific areas, but it is separated, while some weigh and others do not (Rech *et al.*, 2018). Most studies are carried out with manual collection coupled with random selection on beach sands, and few of them present delimitation of areas or transects, without considering the type of tide and sampling time, limiting themselves only to actions and occasional cleaning. Beach cleaning events are not effective strategies as they do not involve transect sampling (Weslawski and Kotwicki, 2018; Póvoa *et al.,* 2021). Due to these factors, we suggest that future studies standardize methodologies regarding data collection time, sampling hours, post-storm and surf-cleaning actions, and manual data collection. However, Fleet *et al.* (2021) recommend that marine litter categorization should be photographed and digitally documented using a code provided by the authors.

Future studies should consider the standardization of different methodological approaches, such as collections along sandy beaches at the highest daily tide line for the concentration of marine litter by replicas and triplicates, primarily considering the ends of the beaches since these are the places that most receive litter by tidal action (Póvoa *et al.,* 2021, 2022a). However, the middle of the beach receives litter from the tides, as well as from the regulars themselves (Póvoa *et al.,* 2022b). Moreover, digital approaches are needed to facilitate data collection in the local (De-la-Torre *et al.,* 2023). The COVID-19 pandemic has introduced new types of marine litter, such as personal protective equipment (PPE), including gloves and facemasks, to beaches (Costa *et al.,* 2023). These items need to be properly identified and included in a standardized glossary to ensure consistent reporting and classification (Fleet *et al.,* 2021; De-la-Torre *et al.,* 2023).

3.6.2 Methodological variation regarding types of marine litter

Studies examining marine litter on beaches employ various classifications, often dependent on the diversity of types encountered. This variability can be attributed to differences in sampling design, contamination sources, and sampling efforts (Rees and Pond, 1995; Velander and Mocogni, 1999). The lack of consistency in methodologies poses a challenge when attempting direct comparisons between studies conducted in the Atlantic and those in other oceans globally. Notably, researchers like Ivar do Sul and Costa (2007), as well as Videla and Araújo (2021), have contributed to the body of knowledge in this field. However, the divergent objectives and methods employed in these studies further contribute to the absence of standardized methodologies. This lack of uniformity underscores the importance of establishing consistent approaches for better comparability and a more comprehensive understanding of marine litter across diverse regions (Appendix 1).

3.6.3 Incorporation of new technologies and investment challenges

Recent research has revealed the adoption of advanced technologies like drones and remote sensing images for monitoring marine litter on sandy beaches. This insight is drawn from a study conducted on beaches in Portugal (Gonçaves *et al.,* 2020a; Gonçalves *et al.,* 2020b; Andriolo *et al.,* 2021). Drones are predominantly employed in beach areas, focusing on plastic waste, whereas remote sensing captures images targeting the presence of accumulated waste in specific beach locations (Salgado-Hermanz *et al.,* 2021).

However, it is worth noting that less developed countries, including Brazil, Uruguay, Argentina, the Caribbean, and African nations, face obstacles due to limited financial resources, technology, and a shortage of specialized personnel. This situation emphasizes the need for increased efforts from both local governments and research agencies, as observed personally. Addressing these challenges is crucial to ensure that these technological solutions can be effectively implemented more widely, thereby enhancing beach monitoring and cleanup initiatives globally (personal observation).

3.7 Discussion of marine litter in relation to coastal management with a focus on climate change

The lack of waste management on Atlantic beaches is a significant problem that requires the involvement of various stakeholders (Ivar do Sul and Costa, 2007). These stakeholders include legislators, scientists, and representatives of large companies from different sectors, as well as industries, organized civil society, members of conservation units, fishermen, and aquaculturists. It is important to establish partnerships among these actors across the Atlantic, including countries in South, Central, and North America, Europe, and Africa, in order to effectively manage coastal waste (like paper).

Coastal management planning should involve quantifying periods with higher waste abundance, as well as identifying the main sources of pollution and activities that contribute to the increase of litter deposition. By understanding these factors, appropriate strategies can be developed to mitigate and eliminate waste deposition and pollution in the medium- and long-term (Silva *et al.,* 2018; Mghili *et al.,* 2023). It is crucial to prioritize environmental education and increase awareness among the population regarding the protection of coastal and marine environments. This can help foster a sense of responsibility and encourage individuals to take action to reduce litter generation and promote sustainable practices (Silva *et al.,* 2018; Timbó *et al.,* 2019).

Other practical and community measure are the activities of cleaning beaches that are performed periodically, this action promotes the instant reduction of marine litter and allows employees to exercise their environmental protection and sustainability ideas (Póvoa *et al.* 2022 b). Moreover, climate change should also be observed in this process together with coastal erosion and the increase in sea level (Lincoln *et al*, 2022; Andriolo and Gonçalves, 2022).

Climate change is an elementary factor in the distribution, source, and degradation of marine litter, also contributing to the spread of several exotic species that can become invasive when they invade ecosystems (Lincoln *et al*, 2022). This process of climate change influences the intensity and frequency of rainfall (Masson-Delmotte *et al.,* 2018), which, consequently, increases the entry of litter into waterways due to the lack of adequate drainage of urban surfaces, which results in an increase of fragments (Hitchcock, 2020).

The rise in sea level, with the aforementioned events, causes erosion and retreat of the global coastline. Coastal erosion can exhume buried waste and make it available in the coastal environment (Andriolo and Gonçalves, 2022). In addition to these factors, the vegetation associated with these environments captures and holds marine litter that is discarded irregularly and can return to the aquatic environment (Andriolo and Gonçalves, 2022). Climate change can influence the litter decomposition process due to high temperatures, exposure to sunlight, and abrasion, which alters the persistence of this material in the environment (Deng *et al.*, 2021). Further, degradation releases pollutants that affect organisms associated with these systems, which causes different environmental and economic impacts, especially in vulnerable communities that depend on the coastal environment as a source of livelihood (Tudor and Williams, 2021).

These risks must be considered to guide, coordinate, and monitor anthropogenic litter management, planning, and actions, as effectively addressing the combined impacts of litter and climate change requires a comprehensive approach. Therefore, correlating global issues such as climate change and marine litter is essential to mitigate damage to marine biodiversity and society (Lincoln *et al.*, 2022). The response to this problem must be global, urgent, and coordinated (Farrelly *et al.*, 2020).

Legislation and policies related to marine anthropogenic litter present in coastal environments are linked to the generation and dissemination of these materials, neglecting efforts to mitigate these wastes in coastal environments (UNEP, 2016). Therefore, currently, actions aimed at the production and disposal of products are even more relevant to prevent inappropriate disposal (UNEP, 2016). Inaction in resolving marine anthropogenic litter in coastal environments has environmental and socioeconomic costs (Brouwer *et al.*, 2017). In this context, decreasing production and increasing plastic removal has been suggested as the main way to dispose of plastic litter (Hohn *et al.*, 2020). Even so, global strategies and actions are needed to be put into practice by policymakers and stakeholders on this issue (Burt *et al.*, 2020; Canning-Clode *et al.*, 2020). However, tackling the problem of marine anthropogenic litter requires global cooperation and coordinated efforts. Policymakers and stakeholders must come together and implement strategies and actions on a global scale. Collaborative initiatives can help in sharing knowledge, best practices, and resources to address the issue effectively (UNEP, 2016; Hohn *et al.*, 2020; Burt *et al.*, 2020; Canning Clode *et al.*, 2020).

4. Conclusion and Recomendations

The countries bathed by the South Atlantic, especially those in Africa, demand a greater need for public policy management applied to the management of coastal environments. The application of effective methodologies for comparing different coastal areas can provide valuable insights into the best practices for managing these environments. By examining successful case studies and comparing them with current practices, policymakers can identify areas for improvement and implement strategies that are more effective. The better utilization of present technologies can greatly enhance the management of coastal environments. Utilizing advanced monitoring systems, satellite imagery, and data analysis tools can provide real-time information on coastal health and aid in identifying potential threats or areas of concern.

Creating environmental perception via engagement with multiple actors in society is also essential. Coastal management should involve the participation and input of various stakeholders, including local communities, industries, and governmental organizations. Engaging these stakeholders in the decision-making process and raising awareness about the importance of coastal conservation can lead to a more holistic and sustainable approach to management.

ACKNOWLEDGMENTS

The authors would like to thank the reviewers for their contributions and suggestions. This study was supported by Coordination for the Improvement of Higher Education Personnel (CAPES), Brazil.

AUTHOR CONTRIBUTIONS

A.A.P.: Conceptualization, Investigation, Formal analysis, Funding acquisition, Methodology, Visualization, Writing- Original Draft; Writing – Review & Editing. L.R.S.: Investigation, Formal analysis, Methodology, Writing – Original Draft; Writing – Review & Editing. I.R.H.: Investigation, Methodology; Writing – Original Draft; Writing – Review & Editing. G.E.D.L.T.: Writing – Review & Editing. A.S.G.: Supervision, Validation, Visualization, Writing – Review & Editing.

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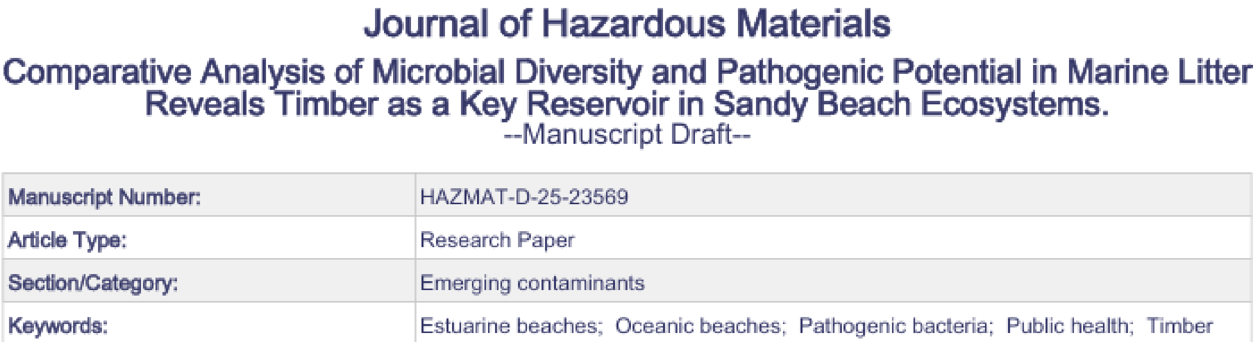
8. CHAPTER 2



Journal of Hazardous Materials

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--Manuscript Draft--

Manuscript Number:	HAZMAT-D-25-23569
Article Type:	Research Paper
Section/Category:	Emerging contaminants
Keywords:	Estuarine beaches; Oceanic beaches; Pathogenic bacteria; Public health; Timber

Comparative Analysis of Microbial Diversity and Pathogenic Potential in Marine Litter Reveals Timber as a Key Reservoir in Sandy Beach Ecosystems.

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Abstract: Many materials create new habitats for microbial colonization and the persistence of potentially pathogenic bacteria. Despite this, comparative studies addressing the microbial diversity and pathogenic potential across different types of marine litter remain scarce. This study investigated microbial communities associated with plastics, aluminum, and timber collected from the strandline of two types of beaches. Amplicon sequencing of the 16S rRNA gene revealed that bacterial community structure and diversity varied primarily according to substrate type rather than beach environment. Nevertheless, all types of marine litter evaluated hosted rich and diverse bacterial communities, with several taxa recognized as potential pathogens of both marine organisms and humans. Timber supported the richest, most diverse, and most specific microbiome, including a high number of taxa known to contain potential pathogens. Among these, *Flavobacterium, Mycobacterium, Pseudoalteromonas, Acinetobacter,* and *Staphylococcus* were particularly notable, as they are recognized pathogens of both marine organisms and humans, representing potential ecological and sanitary risks. These findings highlight that marine litter on sandy beaches functions as a selective substrate influencing biofilm formation, microbial dispersal, and the persistence of pathogens in coastal ecosystems. Timber, in particular, emerges as an underrecognized reservoir for microbial diversity and resistance genes, warranting greater attention in marine pollution and public health monitoring.

Keywords: Estuarine beaches, Oceanic beaches, Pathogenic bacteria, Public health, Timber.

1. Introduction

Estuarine beaches are coastal environments influenced by both fluvial and marine processes, typically located in sites where brackish waters and high environmental variability result from tidal action and river discharge (Nordstrom and Jack, 2012). In contrast, oceanic beaches face the open ocean, exhibiting more stable and saline conditions with less continental influence (Postigloni *et al.*, 2025). Both types of beaches are susceptible to the accumulation of marine litter, deposited either by tidal rhythms or by local anthropogenic activities among other causes (Silva *et al.*, 2019; Magalhães *et al.*, 2024).

Marine litter is a global environmental concern due to its impacts on public health and the economy, particularly because it affects sandy beaches, which are vital for tourism a major economic activity in many coastal regions (Wright *et al.*, 2013; Videla and Araújo, 2021). Tourism activities often contribute to the accumulation of marine litter through increased waste generation and improper disposal, exacerbating pollution problems on these beaches (Abalansa *et al.*, 2020).

Marine litter is defined as synthetic materials that have been processed, discarded, or abandoned in various environments, such as beaches (Cheshire *et al.*, 2009), and can have both terrestrial and marine sources (Munari *et al.*, 2016; Póvoa *et al.*, 2022). Terrestrial sources include sewage discharges, river and wind inputs, and improper disposal by beachgoers (Munari *et al.*, 2016; Póvoa *et al.*, 2022), while marine sources come from economic activities such as fishing, oil spills, aquaculture, and tidal transport (Angiolillo *et al.*, 2015; Munari *et al.*, 2016; Póvoa *et al.*, 2022).

The principal types of marine litter found on beaches are plastics, timber, aluminum, and glass (Cheshire *et al.*, 2009; Andrady, 2015), with plastics being the most abundant, persistent, and extensively studied due to their widespread distribution and environmental impact. Plastic is the most found litter due to its lightness, durability, and resistance to corrosion, along with its low cost, which drives large-scale production (Magalhães *et al.*, 2024). These litters degrade due to physical, chemical, and biological factors, such as solar radiation, wind, and exposure time on the beaches (Wright *et al.*, 2020; Audrézet *et al.*, 2021). However, the degradation time can be prolonged for certain materials, which may persist in the environment for decades or even longer. In some cases, such as rubber, the degradation time is still largely unknown (Barnes *et al.*, 2009; Guajardo and Andler, 2024).

The accumulation of artificial materials on sandy beaches provides substrates for microbial colonization, including pathogens such as bacteria, fungi, and viruses of sanitary importance (Zettler *et al.*, 2013; Lacerda *et al.*, 2020; Magalhães *et al.*, 2024; Mishra *et al.*, 2024). Once attached to these surfaces, microorganisms often transition from a planktonic to a sessile lifestyle, forming complex biofilms that enhance their persistence in the environment. Microorganisms within biofilms are embedded in an extracellular matrix composed of exopolysaccharides (EPS), secreted proteins, and extracellular DNA (eDNA), acting as "molecular glue" for the biofilm structure (Joern *et al.*, 2025). Marine biofilms colonize biological and inert surfaces in the oceans and are mainly composed of virus, bacteria, archaea, diatoms, and fungi all of which secrete EPS for adhesion and protection (Dang and Lovell, 2016).

The formation of biofilms provides evolutionary advantages for microorganisms, such as better access to nutrients, resistance to environmental hazards, and beneficial microbial interactions (Battin *et al.,* 2016). However, it can also result in negative impacts for humans, resulting in biofouling on ships and marine infrastructures, as well as the persistence of pathogenic microorganisms and antibiotic-resistant bacteria (Watnick and Kolter, 2000; Cottingham *et al.,* 2003; Magalhães *et al.,* 2024).

Among the various substrates found in coastal environments, plastic has become the most extensively studied due to its ubiquity and capacity to support diverse microbial assemblages. The concept of the "plastisphere" describes the colonization of plastic polymers by a wide range of microorganisms forming distinct biofilm communities (Zettler *et al.,* 2013; Amaral-Zetler *et al.,* 2021). Within these materials, common microbial species identified include *Arcobacter*, *Pseudomonas*, *Salmonella*, and *Vibrio* (Muniz *et al.,* 2019; Magalhães *et al.,* 2024; Cheng *et al.,* 2024). Studies indicate that plastic surfaces facilitate the colonization of pathogens capable of causing severe gastrointestinal infections in humans. This represents public health risk, as marine ecosystems being a natural habitat of numerous microorganisms that can harbor disease-causing pathogens that may also affect marine species (Pereira *et al.,* 2008; Zettler *et al.,* 2013; Muniz *et al.,* 2019).

Although less abundant than plastics, aluminum is also found in coastal environments and may act as a substrate for microbial colonization. Owing to its metallic nature and potential for ion release, aluminum can influence biofilm composition and select for metal-resistant taxa, yet its role in shaping marine litter microbiomes remains poorly explored (Sancy *et al.,* 2015). Similarly to plastic, timber undergoes physical and chemical degradation such as abrasion, weathering, mechanical damage that fragments it, allowing prolonged drift and eventual deposition along sandy beach strandline, where it can also harbor and spread resistance genes (Gracía *et al.,* 2018; Rech *et al.,* 2018). However, despite its abundance in coastal debris, timber remains one of the least-studied substrates within the context of marine litter microbiology. Very few studies have examined its microbial colonization, biofilm development, or potential to act as a reservoir for pathogens and antimicrobial-resistance genes (Destoumieux-Garzón *et al.,* 2018).

Timber may offer favorable conditions for microbial growth and biofilm formation (Rech *et al.,* 2018), as well as for the accumulation of organic and inorganic pollutants, such as antibiotics and biocides, that can promote resistant bacteria and facilitate the horizontal transfer of antimicrobial-resistance genes (ARGs), ultimately fostering the proliferation of resistant microorganisms (Ben-Haddad *et al.,* 2025; Rangel-*Buitrago et al.,* 2021; Zhang *et al.,* 2020).

Given the ecological relevance of these processes and the limited knowledge about microbial colonization across different litter types, especially on sand beach, a broader comparative approach is needed to assess how various substrates, such as plastic, aluminum, and timber, support biofilm formation and harbor potential pathogens. This study therefore investigated the presence of biofilms and potential pathogenic microorganisms in different types of marine litter accumulated on the beach strandline and comparing them with the bacteria found in sediment.

The innovation of this study lies in the fact that, to the best of our knowledge, no prior research has detected microrganisms and potential pathogens on different types of marine litter, as most studies have focused solely on plastics. The specific objectives of this study were: (i) To identify, qualify, and quantify the relative abundance of different microorganisms associated with distinct types of marine litter found in estuarine and oceanic beaches in a sub-tropical site; (ii) To associate microorganisms found on different types of marine litter with pathogenic potential and (iii) To compare microorganisms found in marine litter with those in sediments. The hypothesis of the study is that the microbiome differs between the types of marine litter and the sediment in the estuarine and oceanic beaches.

2. Material and Methods

2.1 Study Area and Experimental design

The present study was conducted on beaches within Guanabara Bay (estuarine beaches) and the nearby Oceanic Region (oceanic beaches) of Niterói, Rio de Janeiro, Brazil, encompassing estuarine and oceanic beaches. The population of the municipalities surrounding Guanabara Bay located in southeastern Brazil is approximately 8.5 million inhabitants (IBGE, 2022).

Guanabara Bay and its surrounding areas are internationally recognized as one of the most polluted coastal systems in the world, due to the high input of untreated sewage, industrial effluents, and especially marine litter, as extensively documented in the literature (Baptista-Neto and Fonseca, 2011; Soares-Gomes *et al*., 2016; Castro *et al*., 2020). Alarming concentrations of marine litter have placed the bay among global pollution hotspots (Soares-Gomes *et al*., 2016). Its 4,000 km² drainage basin, fed by 45 rivers and channels, transports large amounts of waste from densely urbanized areas (Kjerfve *et al*., 1997; Baptista-Neto and Fonseca, 2011; Silva *et al*., 2016). Marine water circulation, driven by tides and ocean current intrusion, reaches as far as the Rio–Niterói Bridge and Paquetá Island, contributing to the dispersion of pollutants throughout the system (Silva *et al*., 2016; Soares-Gomes *et al.*, 2016).

The local climate is tropical, characterized by high temperatures and humidity (Chen and Chen 2013). It is home to conservation units such as the Serra da Tiririca State Park and the Itaipu Marine Extractive Reserve (Timbó *et al*., 2019). The Oceanic Region encompasses a variety of coastal ecosystems, including sandy beaches, lagoons, rocky shores, mangroves and restinga vegetation (Leite *et al.*, 2021; Silva *et al*., 2022).

For this study, two beaches located in both Guanabara Bay and two in the Oceanic Region were selected- Icaraí (Estuarine Beach 1 - 22◦ 54′ 26″ S; 46◦ 06′ 45″ W) and São Francisco (Estuarine Beach 2 - 22◦55′ 04″ S; 43◦05′ 41″ W); Piratininga (Oceanic Beach 1 - 22◦95′ 48″ S; 43◦08′ 31″ W) and Itaipu (Oceanic Beach 2 - 22◦97′ 11″ S; 43◦04′ 59″ W), respectively (**Fig.1**). The selection of these beaches was based on their orientation relative to the predominant South and Southwest winds (Godoi et al., 2011) and ocean currents that may influence the destination of pollutants, such as marine litter accumulating along the debris line after cold fronts, swells, and waves originating from the South and Southwest (Silva *et al*., 2016).

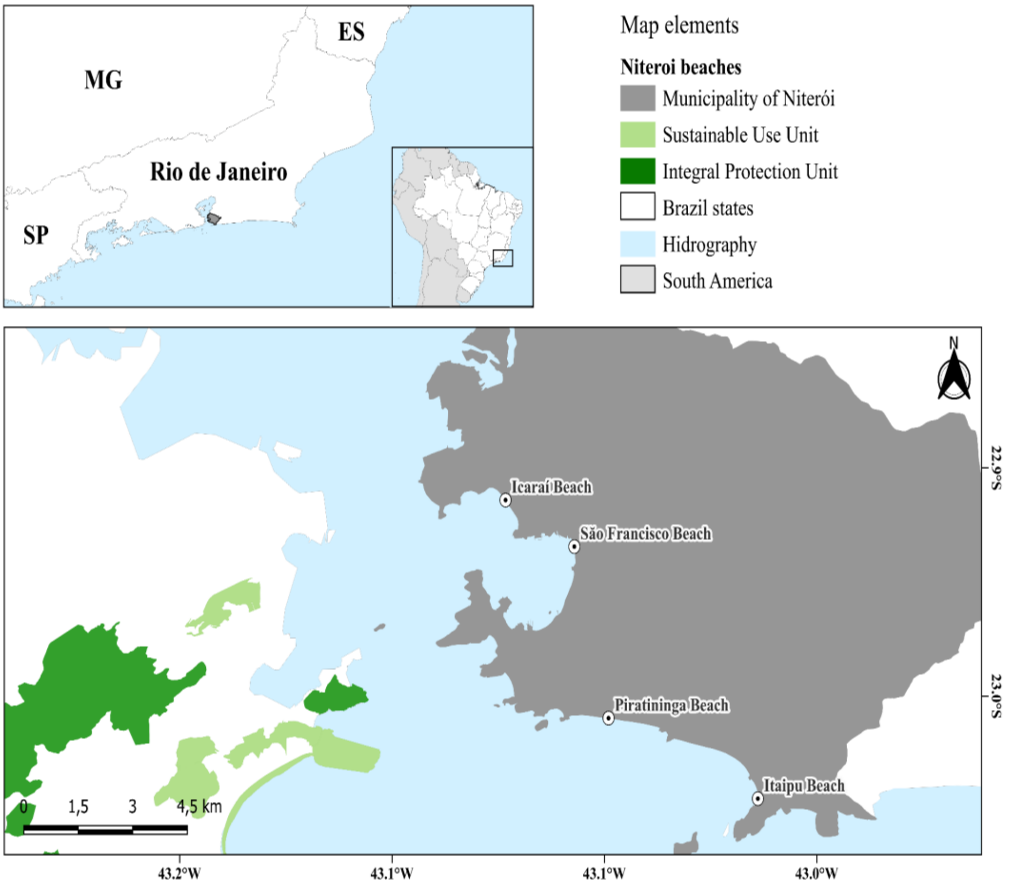

Fig.1. Geographical location and pictures of the studied beaches.

2.2 Sample Characterization and Processing

Marine litter (plastic, timber, metals, and glass) and sediment were collected along the beach strandlines in an area of 1 m² between the years 2023 and 2024. Sediment samples were collected within a 1 m² area at 10 cm intervals using small core tubes, and the material was subsequently transferred and pooled into a larger tube. Samples were taken from three sites on the beach: the extremes and the middle section.

The marine litter samples were stored in plastic bags, while sediment samples were placed in tubes. These samples were stored in an insulated container with ice to prevent contamination and transported to the laboratory for refrigeration, following the methodology outlined by Magalhães *et al.* (2024). The storage and transport protocol aimed to preserve the integrity of the samples and minimize the risk of external microbial contamination, ensuring reliable results in subsequent laboratory analyses (Silva *et al.*, 2019).

In the laboratory, the samples were used distilled water, following the method used by Silva *et al*. (2019), except for sediment and timber. The timber samples were cryogenically ground using liquid nitrogen.

The different types of marine litter were fragmented into smaller pieces and placed in small tubes, weighed to 0.3 grams for the next step of DNA extraction preparation.

2.3 DNA Extraction and Sequencing

The PowerSoil® DNA Isolation Kit (MOBIO, Qiagen, USA) was used for DNA extraction from 0.3 g of plastic, aluminum, glass, wood, and sediment samples, following the manufacturer's instructions. The extracted DNA was quantified using a Qubit fluorometer (ThermoFisher, USA). The variable V4–V5 region of the 16S rRNA gene was targeted for amplification using primers 515F and 909R (Apprill *et al.*, 2015). Amplicon sequencing was conducted using the MiSeq platform (Illumina, San Diego, CA, USA).

2.4 Data Analysis

The generated sequences were analyzed using QIIME 2 (version 2024.5) (https://qiime2.org/). After demultiplexing with the q2-demux plugin, reads were quality filtered and chimeras were removed using DADA2 (q2-dada2) (Callahan et al., 2016). High-quality sequences were transformed into Amplicon Sequence Variants (ASVs) per group using vSEARCH (Rognes *et al.*, 2016). Representative sequences were aligned against the Silva reference database, and singletons, chloroplast, and mitochondrial sequences were excluded from the dataset prior to downstream analyses (Quast *et al*., 2012). Alpha diversity was assessed using the Shannon index (H'), considering the microbial diversity present in different types of materials collected along the strandline, including sand and marine litter.

We compiled a dataset comprising 72 bacterial genera potentially linked to diseases in marine organisms (BGPM) as described by Magalhães et al. (2024), and 292 bacterial genera identified as potentially associated with human diseases (BGPH) as described by Jurelevicius et al. (2021).

2.5 Statistical analysis

Statistical analyses were conducted in R (version 4.4.2). The Phyloseq Package (version 1.50.0) was used to assess diversity (alfa-diversity) per sample and differential twenty taxa relative abundance per sample (McMurdie; Holmes, 2013).

To assess the variations between the different types of samples and beaches were evaluated using a PERMANOVA (Permutational Multivariate Analysis of Variance) and the microbioma ordination was performed by nMDS (Non-Multidimensional Scale) based on Bray–Curtis similarities. The Kruskal-Wallis test ($p < 0.05$) was performed using PAST Statistical Software v. 4 was applied to assess differences among groups of beaches, marine litter and sediment (Kelly *et al.*, 2015).

3. Results

To explore how microbial assemblages respond to different marine litter substrates, this study examined microbial communities associated with different types of marine litter and sediments collected from estuarine and oceanic beaches. The results are presented in three main sections: (i) comparisons of microbial richness, diversity, and community composition across substrates and environments; (ii) the distribution of core and substrate-specific ASVs to assess microbial overlap and selectivity; and (iii) the identification of potential pathogenic taxa related to marine litter and their possible implications for environmental and public health.

3.1 Substrate-Driven Differences in Microbial Diversity, Richness and Composition

Microbial diversity varied according to the type of substrate and the environment (estuarine or oceanic beach). Glass was not analyzed due to low DNA concentrations, which prevented more identification that is precise.

Timber and sediment exhibited the highest species richness, particularly in oceanic beaches, whereas aluminum and plastic showed lower Observed ASVs index values. Regarding the Shannon index, timber also displayed the highest diversity values, followed by aluminum (**Fig.2**).

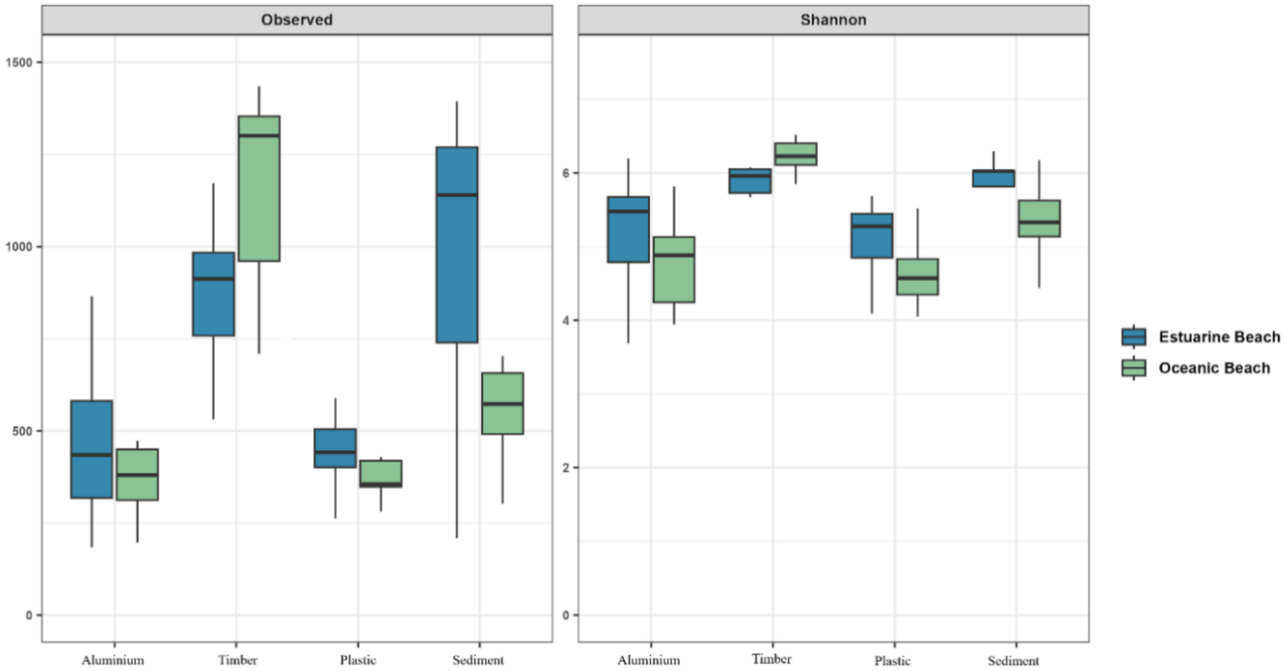

Figure 2. Alpha-diversity measures of the marine litter and sands in the strandline (A) Shannon diversity per sample index (B).

The microbioma composition varied significantly between the types of material ($p = 0.03$; $p < 0.05$; Stress = 0.18). Non-metric multidimensional scaling (NMDS) analysis revealed that the microbial community associated with timber is likely distinct from that found in sediment (**Fig.3 A**). No significant differences were observed in the microbioma structure between estuarine and oceanic beaches ($p = 0.27$; $p > 0.05$; Stress = 0.18). Non-metric multidimensional scaling (NMDS) analysis revealed the microbial communities of the beaches are similar (**Fig.3 B**).

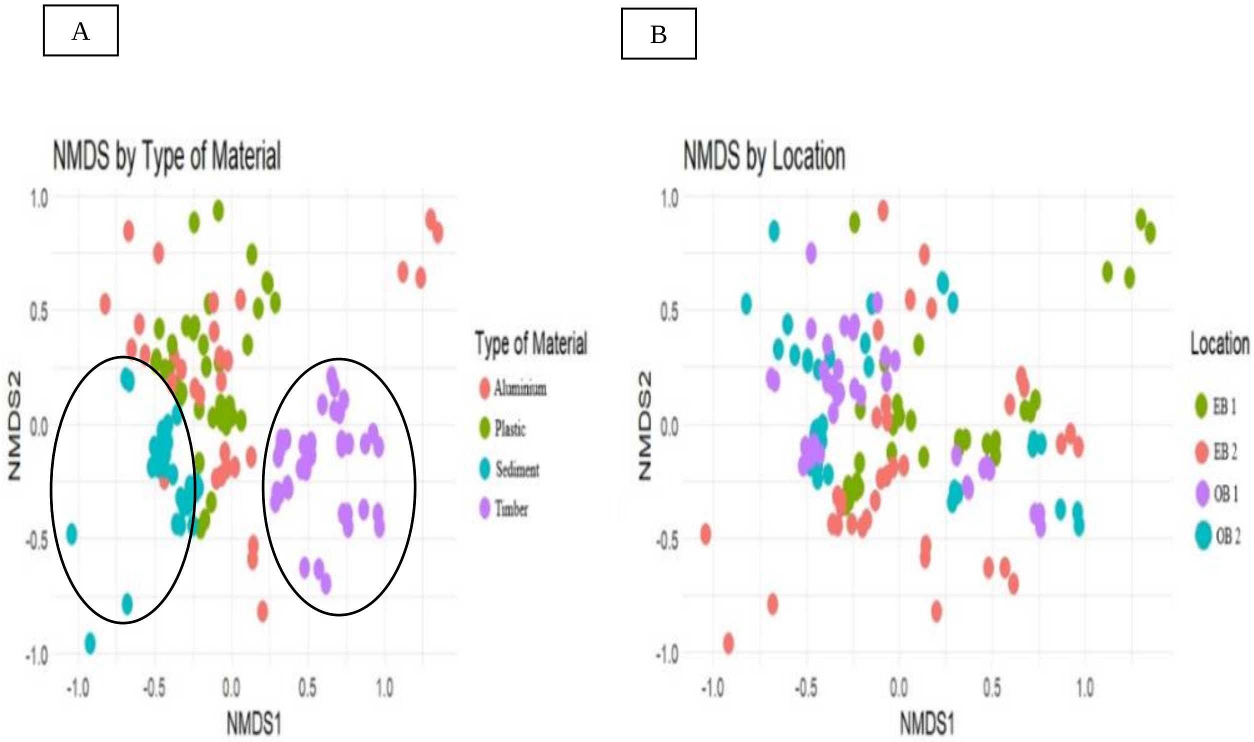

Figure 3. Non-metric multidimensional scaling (NMDS) ordination of microbiome associated with by type of material (Red Circle – Aluminium, Green Circle – Plastic, Blue Circle – Sediment, Purple Circle – Timber) (A) and by location (B (Green Circle - Estuarine Beach 1, Red Circle - Estuarine Beach 2, Purple Circle - Oceanic Beach 1, Blue Circle - Oceanic Beach 2). Stress A and B: 0.18.

3.2 Variation in Microbial Composition Across Marine Litter and Sediment Substrates

Approximately 30,000 ASV's were found associated with different types of marine litter and sediment. They were identified at the levels of family, class, and genus, but not at the species level.

The most abundant bacteria in marine litter and sediment were *Rhodobacteraceae*, *Flavobacteriaceae*, Gammaproteobacteria, *Alteromonadaceae*, and *Erythrobacter*. The genus *Woeseia* was also dominant in sediment samples (**Fig. 4)**. In the aluminum samples, the most abundant bacterial families were *Rhodobacteraceae* and *Flavobacteriaceae*. Timber samples exhibited a dominance of Rhodobacteraceae, Flavobacteriaceae, and Sphingomonadaceae. Plastic samples were primarily colonized by *Rhodobacteraceae*, *Flavobacteriaceae*, and *Erythrobacter*. In sediment samples, the prevalent bacterial groups included *Rhodobacteraceae*, *Flavobacteriaceae*, Gammaproteobacteria, and the *Woeseia* sp. was observed with a high relative abundance in sediment samples (**Fig.4**).

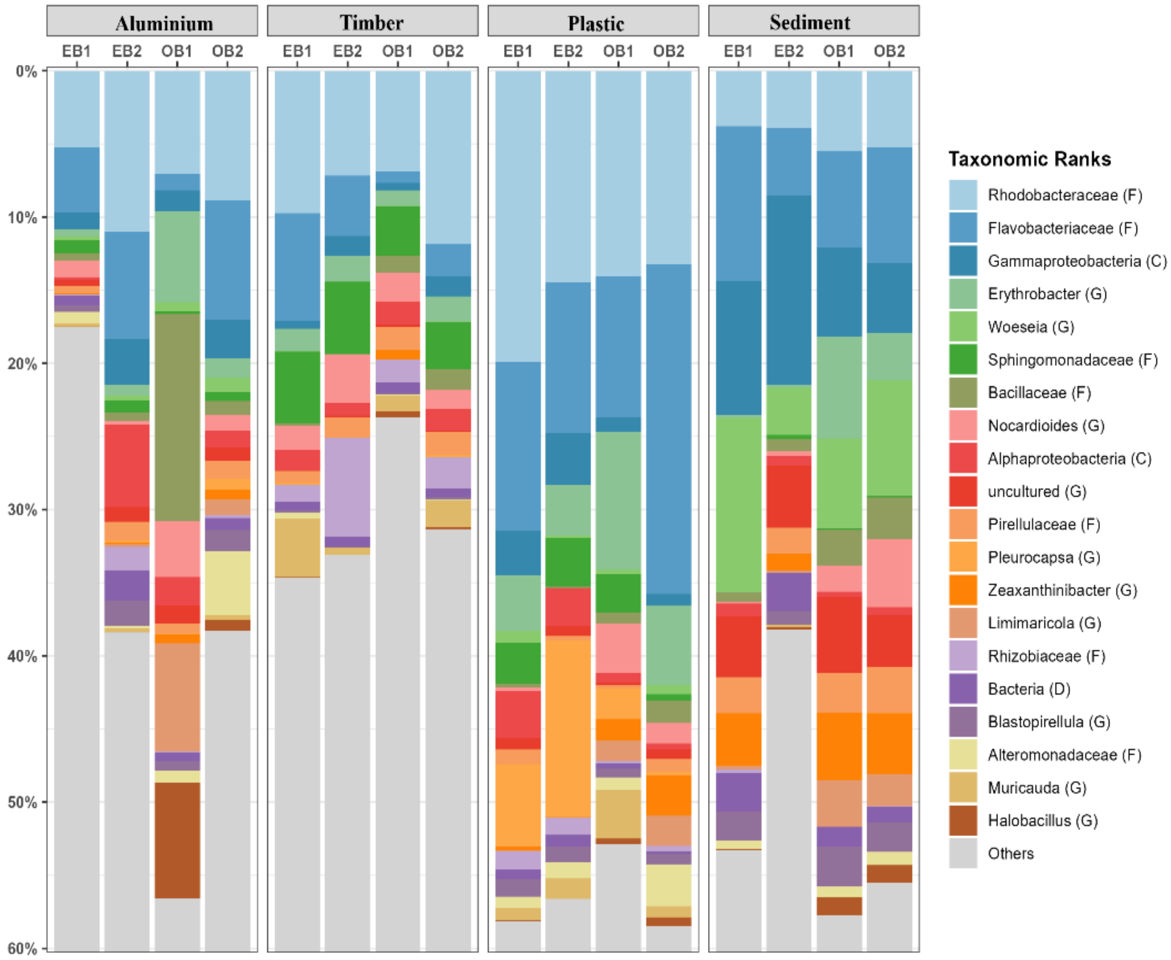

Fig.4. Relative abundance of bacterial (%) in marine litter and sediment from estuarine and oceanic beaches. The abbreviations F, C, and G indicate that the bacteria were identified at the family (F), class (C), and genus (G) taxonomic levels, respectively. The abrreviattions EB 1, EB 2, OB 1, OB 2 indicates Icaraí, São Francisco, Piratininga and Itaipu, respectively.

3.3 Distribution of Core and Substrate-Specific Amplicon Sequents Variants Across Marine Litter Types

To better understand how microbial communities are structured across different types of marine litter, we examined the distribution of Amplicon Sequence Variants (Amplicon Sequence Variants) among substrates. This analysis allows us to identify whether distinct materials harbor unique bacterial assemblages or share a common microbial core capable of colonizing multiple surfaces.

Timber showed the highest exclusive ASVs types of marine litter analyzed with 11.255 ASVs, followed by 4664 from sediment, 4301 from aluminum and 3204 from plastic. A total of 638 were shared between plastic and timber, 580 were common between plastic and aluminum, 552 between aluminium and timber and 522 between plastic, aluminium and timber. For instance, *Saprospiraceae* and *Psychrobacter* sp. were exclusively associated with timber. In aluminum samples, *Comamonadaceae* and *Desulfosporosinus* were predominant, whereas plastic substrates harbored *Nocardioides* and *Xanthobacteraceae* (**Fig.5).**

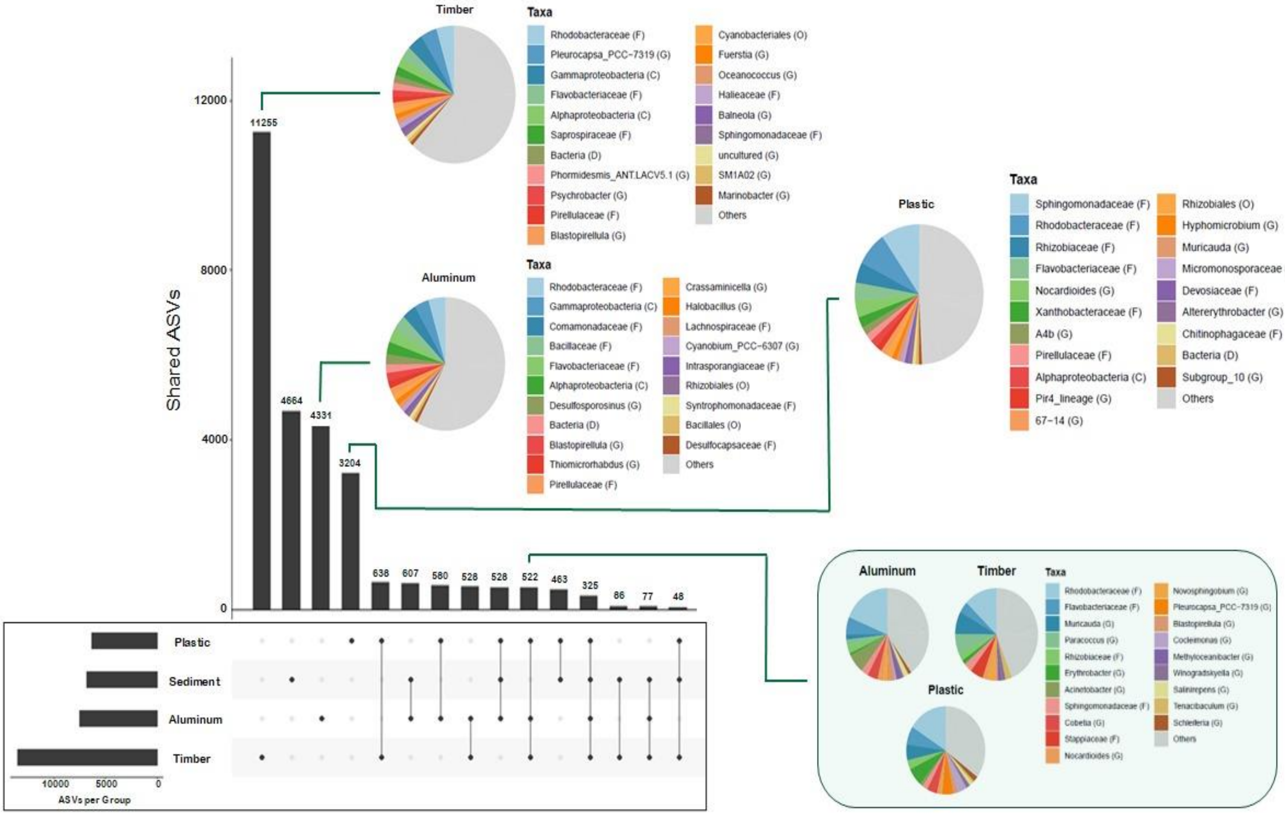

Fig.5. Number of ASV (Sequence of Amplification Variation) per group sharing among different types of marine litter and sediment.

3.4 Potential Pathogenic Assemblages Associated with Marine Litter and Sediment Substrates

The findings highlight that both the type of marine litter and the beach environment strongly influenced the composition of potential pathogenic communities. The analysis revealed that the assemblage of potential pathogens for marine species varied according to the type of marine litter. In aluminum, the most representative genus were *Pseudoalteromonas*, *Mycobacterium*, *Acinetobacter* and *Staphylococcus* in timber *Flavobacterium*, *Mycobacterium*, *Acinetobacter* and *Legionella* and in plastic, *Pseudoalteromonas*, *Flavobacterium*, *Acinetobacter*, *Staphylococcus* and *Pseudomonas* Finally, in sediment, the predominant genera were *Pseudoalteromonas* and *Halomonas* (**Fig. 6 A**).

The analysis of potential human pathogens revealed marked differences among types of marine litter and sediment. In aluminum, the most representative genera were *Mycobacterium*, *Acinetobacter* and *Staphylococcus* in timber, *Flavobacterium*, *Mycobacterium*, and *Paracoccus* and in plastic, *Flavobacterium*, *Acinetobacter*, *Staphylococcus*, *Pseudomonas* and *Legionella*. In sediment, the most representative taxa were *Flavobacterium*, *Mycobacterium* and *Halomonas* (**Fig. 6 B**).

The analysis of potential human pathogens revealed marked differences among types of marine litter and sediment. In aluminum, the most representative genera were *Mycobacterium*, *Acinetobacter* and *Staphylococcus*. In timber, the predominant groups were *Flavobacterium*, *Mycobacterium* and *Paracoccus*. In plastic, the dominant genera included *Flavobacterium*, *Acinetobacter*, *Staphylococcus*, *Pseudomonas*, *Legionella* and sediment, the most representative taxa were *Flavobacterium*, *Mycobacterium* and *Halomonas* (**Fig. 6 B**).

In estuarine beaches, *Shewanella*, *Mycobacterium* and *Pseudoalteromonas* in EB1 dominated the BGPM microbioma (Icaraí), while *Aquimarina*, *Acinetobacter*, and *Staphylococcus* dominated in EB2 (São Francisco). *Flavobacterium*, *Mycobacterium*, *Legionella*, *Acinetobacter*, *Pseudomonas* and *Staphylococcus* dominated the BGPH microbioma. In EB1, *Flavobacterium*, *Mycobacterium* and *Legionella* were the predominant genera, whereas in EB2, *Acinetobacter*, *Pseudomonas* and *Staphylococcus* were more abundant. Notably, EB2 also harbored a higher number of sediment exclusive bacteria (**Appendix 2 – Fig.1**).

In oceanic beaches, *Moraxella*, *Pseudomonas* and *Legionella* in OB1 dominated the BGPM microbioma (Piratininga) while *Shewanella*, *Lactococcus*, *Flavobacterium*, and *Mycobacterium* predominated in OB2 (Itaipu). *Flavobacterium*, *Mycobacterium* and *Coxiella* dominated the BGPH microbioma. In OB1, *Coxiella*, *Legionella* and *Corynebacterium* were the most abundant, whereas in OB2, *Flavobacterium* and *Mycobacterium* predominated (**Appendix 2 – Fig.2**).

Overall, the findings highlight that both the type of marine litter and the beach environment strongly influenced the composition of potential pathogenic communities.

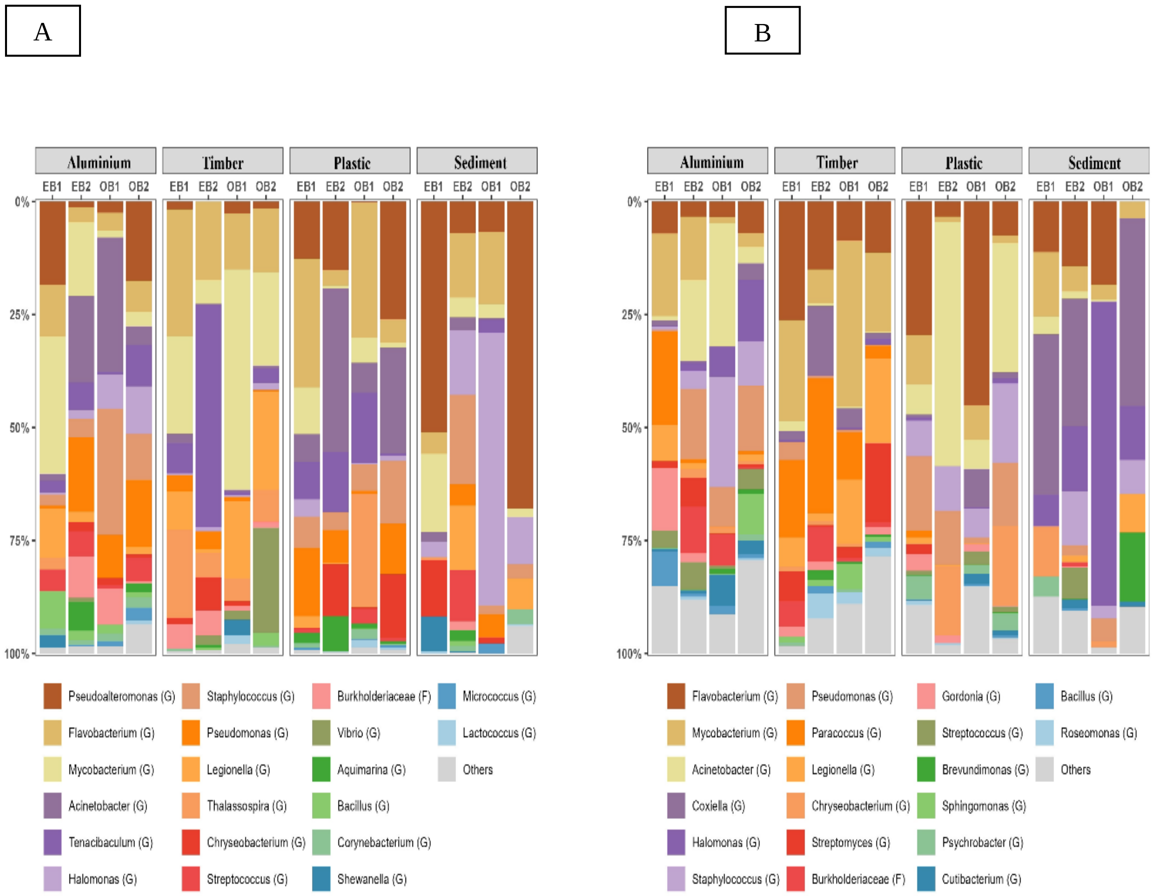

Figure 6. Potential assemblage of pathogens for marine species (A) and humans (B). The abbreviations F, C, and G indicate that the bacteria were identified at the family (F), class (C), and genus (G) taxonomic levels, respectively. The abrreviattions EB 1, EB 2, OB 1, OB 2 indicates Icaraí, São Francisco, Piratininga and Itaipu, respectively.

4. Discussion

The results of this study provide new insights into how different types of marine litter act as selective substrates shaping microbial community structure, diversity, and potential pathogenicity. Our findings show that the physicochemical properties of the substrate, rather than the beach environment (estuarine or oceanic), are the primary drivers of microbial assemblage composition. Among the analyzed materials, timber emerged as a particularly important substrate, supporting the richest and most diverse bacterial communities. Despite its abundance in coastal debris, timber remains one of the least-studied components of marine litter, and its role in harboring biofilms and potential pathogens has been largely overlooked in the literature. This discussion is therefore organized into four main topics: (i) variations in microbial abundance across substrates and sediments; (ii) the composition and functional roles of the microbiome in relation to substrate type; (iii) the occurrence and ecological relevance of potential pathogens affecting marine organisms and humans; and (iv) the unique microbial dynamics associated with timber, highlighting its ecological importance and potential health risks.

4.1 Substrate-Driven Patterns of Microbial Abundance and Diversity

Alpha diversity analyses indicated that microbial diversity was mainly influenced by substrate type rather than by environmental setting (estuarine or oceanic beach). Timber and sediment exhibited the highest species richness, particularly in oceanic beaches, whereas aluminum and plastic showed lower values in the Observed ASVs index. In terms of the Shannon index, timber also displayed the highest diversity, followed by aluminum. These findings highlight the strong influence of substrate type in shaping microbial assemblages, with certain substrates supporting more diverse and complex communities.

Statistical analyses confirmed significant differences in microbial communities according to substrate type. NMDS ordination revealed a clear separation between timber and sediment, indicating that their contrasting physicochemical properties drive distinct microbial assemblages. Timber, rich in lignocellulose, promotes the growth of microorganisms specialized in decomposing complex organic compounds (Magalhães *et al.*, 2024; Ben-Haddad *et al.*, 2025; Lacerda *et al.*, 2025). In contrast, marine sediments, characterized by heterogeneity and vertical gradients in oxygen and nutrients, sustain stratified and metabolically diverse communities (Liu *et al.*, 2022). Interestingly, no clear differences in microbial composition were detected between estuarine and oceanic beaches, consistent with Magalhães *et al*. (2024), who observed no significant variation in plastisphere between these environments within the same region.

The porous structure, rich organic composition, and resistance to moisture and degradation of timber provide stable microhabitats that favor biofilm formation (Okino *et al.*, 2005; Silva *et al.*, 2019; Walker *et al.*, 2020). These conditions facilitate colonization by lignocellulolytic microorganisms under both oxic and anoxic conditions, resulting in richer and more diverse bacterial communities (Coons *et al.*, 2021). Conversely, smooth surfaces such as glass and flexible plastics tend to hinder microbial adhesion, limiting biofilm development and reducing microbial retention (Hall-Stoodley *et al.*, 2004; Zhao *et al.*, 2023), which may explain the lower diversity typically observed on these materials and the challenges in detecting sufficient genetic material in metagenomic analyses (Tsuji *et al.*, 2022).

4.2 Structure and Composition of the Marine Litter Microbiome

The bacterial families *Flavobacteriaceae, Rhodobacteraceae,* and the genus *Erythrobacter*, *Pleurocapsa* and the class Gammaproteobacteria play central ecological roles in marine environments, particularly within biofilms and sediments (Dyksma e*t al*., 2018; Polner *et al.*, 2019). *Flavobacteriaceae* are key colonizers of marine biofilms, capable of degrading organic matter and utilizing extracellular polymers produced by primary colonizers (Magalhães *et al*., 2024). This family, one of the largest in the phylum Bacteroidota (Zhao *et al*., 2023), is widely distributed across water columns, sediments, algae, marine habitats, and various types of marine litter (Alejandre-Colomo *et al*., 2021; Seo *et al.*, 2021). Many *Flavobacteriaceae* species are opportunistic pathogens of humans and fishes (Zhang *et al*., 2016) and serve as hosts and carriers of antibiotic resistance genes (ARGs) in different ecosystems, including marine litter (Wang *et al.*, 2022; Magalhães *et al.*, 2024). Their adaptability ensures persistence across diverse aquatic environments, including plastics (Tulloch *et al*., 2024).

Rhodobacteraceae, the most prevalent family in marine ecosystems, dominate biofilms and sediments and represent a promising source for novel antibiotic discovery (Polhner *et al*., 2019; Magalhães *et al.*, 2024). These bacteria are involved in biogeochemical cycles, such as carbon and sulfur cycling, and exhibit high adaptability to environmental abundant class in marine ecosystems, contributing to organic matter remineralization, variability (Hamamoto *et al*., 2024). Similarly, Gammaproteobacteria constitute a diverse and particularly during phytoplankton blooms, and playing essential roles in nutrient cycling (Francis *et al*., 2021). The genus *Erythrobacter* is commonly found in nutrient-rich coastal environments, including sediments and plastics (Li *et al*., 2017; Giulizia *et al*., 2025).

Pleurocapsa has been identified as a recurrent component of biofilms on plastic surfaces, often forming amorphous masses alongside other cyanobacteria such as *Calothrix*, covering up to 3.5% of submerged plastic surfaces (Dussud *et al.*, 2018). Members of the *Alteromonadaceae* family, including *Alteromonas*, are gram-negative marine bacteria widely distributed in aquatic environments and associated with organic particles such as decomposing wood and nutrient-rich sediments (Brzeszcz *et a*l., 2018; Barbe *et al*., 2024). *Alteromonas macleodii*, for example, forms aggregates with chitin particles, enhancing particulate organic matter degradation (López-Pérez and Rodriguez-Valera, 2014). These bacteria play key roles in organic waste breakdown and biogeochemical cycling, with their metabolic versatility making them important contributors to marine microbial ecology (Barbe *et a*l., 2024).

Pirellulaceae are abundant in marine environments, especially in biofilms on plastic, where they establish stable communities. Their metabolic versatility allows utilization of a wide range of organic compounds, emphasizing their ecological significance in plastic-associated microbial communities (Oberbeckmann *et al.*, 2014). *Sphingomonadaceae* foud in timber that study, are well-known colonizers of natural surfaces, particularly submerged wood, where they form stable biofilms and degrade complex compounds such as lignin, cellulose, and hemicellulose — key components of wood (Catão *et al*., 2019; Briand *et al*., 2022). Their ability to tolerate environmental fluctuations, including changes in salinity and nutrient availability, makes them essential players in wood biodegradation and carbon cycling in coastal ecosystems (Briand *et al*., 2022).

4.3 Shared and Distinct Bacterial Assemblages Among Marine Litter Substrates

The results of ASV distribution among the analyzed substrates demonstrate the strong influence of substrate type on microbiome structure in marine environments. Timber exhibited the highest number of ASV types, reflecting its ecological versatility and capacity to host diverse microbial assemblages (Walker *et al*., 2020). In addition, bacterial taxa unique to each substrate were identified. These findings highlight that, beyond supporting a diverse core microbiota, each substrate may also act as a selective niche for specific bacterial groups. Notably, Rhodobacteraceae and Flavobacteriaceae were the most abundant taxa and were consistently shared among different substrates, including plastic, aluminum, and timber, suggesting that these families are well adapted to colonize a wide range of marine surfaces (Polhner *et al*., 2019, Seo *et al*., 2021).

The high number of ASVs shared between plastic and timber, as well as between plastic-aluminum, and others such as plastic-aluminium-timber, indicates that, despite their distinct physicochemical characteristics, these substrates may select for partially overlapping microbial communities. Moreover, the substantial number of ASVs shared among timber, plastic and aluminum across all types of marine litter, reinforces the hypothesis that marine litter functions as a vector for microbial dispersal across different environments (Amaral-Zettler *et al*., 2020; Zettler *et al*., 2013).

The main bacterial groups identified in this study and the key substrates where they most commonly establish biofilms in marine and coastal environments are summarized in **Table 1**.

Tab.1. Bacteria and mains substrates of biofilms.

Bacteria	Main Substrates of Biofilm	References
Flavobacteriaceae	Aluminium, Plastic, Timber and Sediment	Alejandre-Colomo et al., 2021; Seo et al., 2021
Rhodobacteraceae	Aluminium,Plastic, Timber and Sediment	Polhner et al., 2019
Gammaproteobacteri*a*	Sediment	Ramos-Mendóza et al., 2024
Erythrobacter	Plastic and Sediment	Giulizia et al., 2025
Pleurocapsa	Plastic	Dussud et al., 2018
Pirellulaceae	Plastic	Oberbeckmann et al., 2014
Sphingomonadaceae	Timber	Catão et al., 2019; Briand et al., 2022
Woeseia	Sediment	Hoffmann et al., 2020

This overlap is consistent with the co-occurrence of key bacterial families identified in this study, such as *Flavobacteriaceae, Rhodobacteraceae,* and Gammaproteobacteria, which were detected across multiple substrates. Their metabolic versatility and ecological roles in biofilm formation and organic matter degradation likely contribute to the observed patterns of ASV sharing, highlighting the importance of both substrate type and microbial functional traits in structuring marine microbial communities. The persistence and physicochemical properties of these materials facilitate the formation of complex biofilms, with potential implications for environmental and public health (Wang *et al.*, 2022). Therefore, understanding the microbial dynamics associated with different types of marine litter is essential for assessing ecological risks and developing effective monitoring and mitigation strategies to combat marine pollution (Magalhães *et al.*, 2024).

Overall, these findings indicate that substrate type, environmental conditions, and microbial functional traits collectively shape the composition and diversity of marine microbial communities. The overlap of ASVs among different substrates and environments suggests that marine litter not only provides habitat for diverse microorganisms but also serves as a conduit for their dispersal, potentially facilitating the spread of both beneficial and opportunistic or pathogenic bacteria across marine ecosystems.

4.4 Marine Litter as a Reservoir for Potential Pathogenic Bacteria

Among the main bacterial groups adhering to different types of marine litter and sediment, members of *Flavobacteriaceae, Rhodobacteraceae, Gammaproteobacteria, Pirellulaceae,* and *Sphingomonadaceae* are recognized as pathogenic or potentially pathogenic. In particular, *Flavobacteriaceae, Rhodobacteraceae,* and *Pirellulaceae* are considered opportunistic pathogens of humans and fishes (Meyer *et al.*, 2010; Zhang *et al.*, 2016; Xiang *et al.*, 2018). Some taxa within *Flavobacteriaceae* have demonstrated resistance to multiple antibiotics, enhancing their pathogenic potential and raising concern for both public and environmental health (Zhang *et al.*, 2020).

Within *Gammaproteobacteria*, several genera such as *Vibrio, Pseudomonas*, and *Aeromonas* are known to cause diseases in humans and aquatic organisms, including wound infections, gastrointestinal illnesses, and systemic infections, particularly under immunosuppressed conditions or in aquaculture systems (Vázquez-Rosas-Landa *et al.*, 2017; Ramos-Mendóza *et al*., 2024). Members of the *Sphingomonadaceae* detected in timber in this study have been implicated in human infections, especially in nosocomial environments, underscoring their clinical relevance (Song *et al*., 2022).

The presence of these taxa supports the idea that pathogenic bacteria associated with marine organisms often act as opportunistic agents under environmental stress (Offret *et al*., 2016; Yoo *et al*., 2025). This overlap between marine and human pathogens highlights the dual risk posed by these bacteria, as several species can cause severe diseases in both humans and animals (Saviola and Bishai, 2006; Petersen *et al*., 2021). For example, *Pseudoalteromonas* species have been reported to cause skin lesions and opportunistic infections in fishes, mollusks, and humans (Offret *et al.*, 2016; Dubert *et al.*, 2017), while *Mycobacterium* is responsible for mycobacteriosis in fishes, including necrosis and weight loss, and for tuberculosis, Hansen's disease, lymphadenitis, and pulmonary and cutaneous infections in humans (Austin and Austin, 2016).

Other clinically relevant taxa include *Acinetobacter*, linked to septicemia and wound infections in fishes and mollusks, and nosocomial infections and bloodstream infections in humans (Sun *et al*., 2023; Muleskhova *et al*., 2025). *Staphylococcus* causing ulcerative lesions and high mortality in cultured fish, and lethal infections in immunocompromised humans (Perdigão *et al*., 2025; Kellermand and Raquel, 2021; Noberg *et al.*, 2022); and *Flavobacterium* sp. and *Pseudomonas sp.*, which affect both aquatic organisms and humans (Lian *et al*., 2025; Perdigão *et al*., 2025; Dubbert *et al*., 2017; Letizia *et al*., 2025).

Additionally, genera such as *Halomonas*, *Shewanella*, *Paracoccus* and *Coxiella* sp. like bacteria have been documented as opportunistic pathogens in marine organisms and humans, causing infections ranging from ulcerative lesions and septicemia in fishes to bloodstream and soft tissue infections in humans (Yoo *et al*., 2025; Müller *et al*., 2023; Arias and Clark, 2019; Mohammadi *et al*., 2025). Notably, several of these bacteria carry antibiotic resistance genes (ARGs), particularly in biofilms on plastic and wood, further increasing their potential risk to human and environmental health (Magalhães *et al*., 2024).

Overall, these findings indicate that marine litter, including timber, serves as a substrate for bacterial groups. Many act as opportunistic pathogens under stress conditions, and the overlap between human and marine pathogens emphasizes the ecological and health risks associated with their persistence in aquatic environments (Magalhães *et al*., 2024; Yoo *et al*., 2025). The main bacterial groups identified in this study and their pathogenic or potentially pathogenic roles are summarized in **Table 2**.

Tab.2. Mains possible marine and human pathogens found in marine litter and sediment.

Bacteria	Mains Substrates	Disease in marine organisms	Diseases in humans	References
Pseudoalteromonas	Aluminium, Plastic, Timber and Sediment	Skin lesions, opportunistic infections in fishes and invertebrates	Skin lesions, opportunistic infections	Offret *et al.,* 2016; Dubert *et al.,* 2017
Mycobacterium	Aluminium and Timber	Weight loss and tissue necrosis	Tuberculosis, Hansen's disease, lymphadenitis, and lung and skin diseases	Austin and Austin, 2016; Petersen *et al.,* 2021
Acinetobacter	Aluminium, Plastic, Timber and Sediment	Septicemia in fishes and mollusks	Nosocomial infections, bloodstream infections	Sun *et al.*, 2023; Muleskhova *et al.,* 2025

Staphylococcus	Aluminium and Plastic	Ulcerative lesions and septicemia	Lethal to immunocompromised individuals or those with comorbidities	Noberg *et al.*, 2022; Perdigão *et al.*, 2025;
Flavobacterium	Aluminium, Plastic and Timber.	Fin rot and septicemia in fishes	Infections in immunocompromised individuals	Lian *et al.*, 2025
Pseudomonas	Aluminium and Plastic	Skin ulcerations and septicemia	Chronic infections, bloodstream, urinary tract, and soft-tissue infections	Dubert *et al.*, 2017; Perdigão *et al.*, 2025
Halomonas	Aluminum and Sediment	Opportunistic pathogens in mollusks and corals	Septicemia, bloodstream infections and others	Steven, 2009; Dubert *et al.*, 2017; Yoo *et al.*, 2025
Shewanella	Aluminium, Plastic and Timber	Ulcerative lesions and systemic infections in fishes and invertebrates	Tissue infections, otitis, septicemia and others	Müller *et al.*, 2023
Paracocus	Alumininum and Plastic	There are no reports causing disease in marine organisms	Bloodstream infections, peritonitis, and ocular infections	Arias and Clark, 2019.
Coxiella	Sediment	There are no reports causing disease in marine organisms	Q-fever	Mohammadi *et al.*, 2025

The identification of pathogenic and potentially pathogenic bacteria associated with marine litter underscores both ecological and public health concerns. Their ability to infect marine organisms and humans, coupled with antibiotic resistance, highlights the importance of monitoring microbial communities on marine litter and evaluating their role in the emergence and spread of infectious agents.

4.5 Microbiome and Pathogenic Potential of Timber

The microbiome of timber was distinct from that observed on other types of marine litter, indicating a substrate-specific selection of microbial taxa. Genera such as *Nocardioides*, members of the *Pirellulaceae* family, and *Sphingomonadaceae* were found exclusively on timber, likely due to its distinct physicochemical properties that favor the formation of stable and nutrient-rich microhabitats (Yang *et al*., 2022; Naudet *et al*., 2025). This pattern can be explained by the porous and rough surface of timber, as well as its high organic matter content, which together create favorable conditions for colonization (Naudet *et al*., 2025). In contrast, families such as *Rhodobacteraceae* and *Flavobacteraceae* were also detected on wood, but they were not restricted to this substrate, being widely distributed across other types of marine litter (including paper).

Among these exclusive taxa, the Sphingomonadaceae includes potentially pathogenic species, such as *Sphingomonas paucimobilis*, which has been associated with opportunistic infections in immunocompromised individuals and is commonly isolated from clinical environments, including medical devices and hospitals (Ryan and Adley, 2010).

The microbiome of wood exhibited high diversity, including some taxa exclusive to this substrate. Among the potential marine pathogens, *Flavobacterium* and *Mycobacterium* were predominant in estuarine beaches, whereas *Legionella* and *Mycobacterium* prevailed in oceanic beaches. In addition, *Burkholderia* was more frequent in samples from estuarine environments, while *Shewanella* showed higher occurrence in timber samples from oceanic beaches. Regarding bacteria that represent potential human pathogens in timber samples, *Flavobacterium*, *Pseudoalteromonas*, and *Mycobacterium* predominated in estuarine beaches, whereas *Legionella* and *Mycobacterium* were also predominant in oceanic beaches. *Burkholderia* was mainly detected in estuarine beaches, while *Bacillus* and *Corynebacterium* were more frequently associated with wood samples from oceanic beaches.

These microorganisms cause several diseases in marine organisms some as fishes, including weight loss, necrosis, and septicemia (Austin and Austin, 2016; Sun *et al*., 2023; Lian *et al*., 2025). In humans, they are responsible for a variety of diseases such as tuberculosis, cholera, and different infections that compromise the immune system (Petersen *et al.*, 2021; Muleskhova *et al.*, 2025; Lian *et al.*, 2025).

Microbial communities on timber vary between estuarine and oceanic beaches due to differences in environmental conditions and anthropogenic influences such as salinity, nutrient levels, organic matter, solar radiation, sewage, among others (Wu et al., 2024). Timber is as a selective environment that may harbor bacteria of clinical relevance, emphasizing the need for further investigation in the context of microbial risk assessment on marine litter.

This study has limitations inherent to microbiological analyses based on metagenomics applied to different substrates. Although metagenomics allows comprehensive characterization of bacterial communities associated with plastic, wood, aluminum, and sediment, it does not provide direct information on cell viability or metabolic activity. In addition, differences in surface properties and environmental residence time among materials may influence bacterial colonization patterns, affecting comparability across substrates. For glass, microbiological characterization was not possible due to the low bacterial concentration, which resulted in insufficient DNA yield for successful sequencing. Therefore, the results should be interpreted in light of these methodological and substrate-specific limitations.

5. Conclusions and Recommendations

Bacterial communities associated with marine litter differ significantly depending on the type of material, but they do not show substantial variation between estuarine and oceanic beaches. The physicochemical properties of the substrates indicate that the type of material, rather than the beach environment itself, plays a decisive role in shaping the microbial composition associated with marine litter.

Diverse bacteria have been found adhering to marine litter and sediments, some of which are potentially pathogenic to both marine organisms and humans, causing impacts ranging from infections in fish and mollusks to serious diseases in people, with direct consequences for public health. Direct or indirect exposure to this marine litter, through contact with contaminated water or consumption of food from affected areas, can lead to the transmission of infectious diseases.

Among the analyzed materials, timber emerged as a particularly critical substrate, supporting the richest and most diverse bacterial communities. These conditions suggest that timber may act as an under recognized reservoir and vector for the spreading of microorganisms of environmental and sanitary concern. Given its overlooked role and ecological importance, future studies should prioritize the investigation of microbial communities associated with both organic and manufactured materials, comparing their potential for biofilm formation and pathogen persistence.

In conclusion, understanding the variation in bacterial communities across different types of marine litter, rather than between estuarine and oceanic beach environments, is crucial for assessing environmental and human health risks. Implementing targeted monitoring strategies and employing advanced techniques, such as metagenomics, can identifying potential pathogenic bacteria, supporting the development of waste management policies and effective strategies to mitigate marine litter pollution in marine ecosystems, as well as the implementation of new public health strategies.

CRediT authorship contribution statement

Alain Alves Póvoa: Conceptualization, Data curation, Investigation, Methodology, Validation, Writing - original draft, Writing - review & editing. **Emily Amorim Magalhães:** Conceptualization, Data curation, Investigation, Methodology. **Katariny Pereira dos Santos:** Formal analysis, Investigation, Methodology. **André Luís Canellas:** Formal analysis, Investigation, Methodology, Data Analysis, Software. **Abilio Soares-Gomes:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing - original draft, Writing - review & editing. **Henrique Fragoso dos Santos:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing - original draft, Writing - review & editing.

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. Data availability and data will be made available on request.

Acknowledgments

We thank the reviewers and Leandro da Silva Alves for support in data analysis. This manuscript was financed by the Niterói City Hall trhouh the Programa de Desenvolvimento de Projetos Aplicados (PDPA). Abilio Soares-Gomes (ASG) is supported by CNPq Brazil (301475/2017-2).

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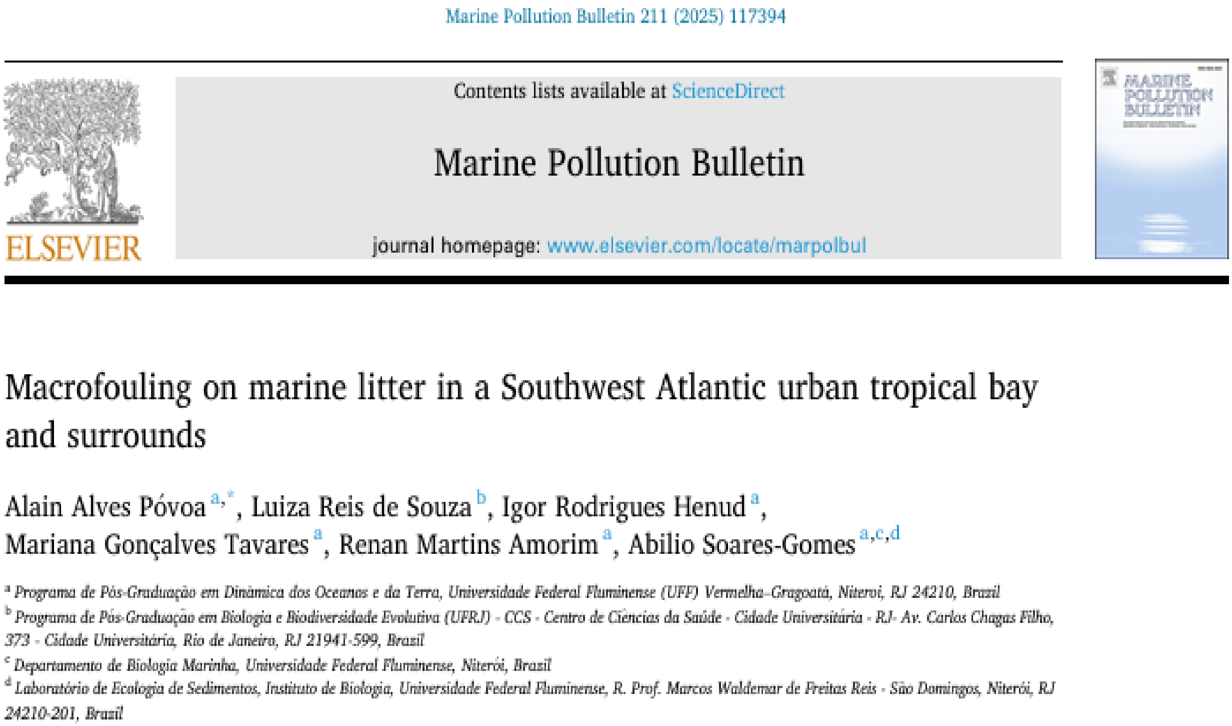
9. CHAPTER 3



Marine Pollution Bulletin 211 (2025) 117394

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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Macrofouling on marine litter in a Southwest Atlantic urban tropical bay and surrounds

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Abstract:

Rafting is the transport of marine litter by organisms, influenced by substrate characteristics such as degradation, shape, surface orientation, color, and polymer type. This study focuses on rafting in the Southwest Atlantic, characterizing biofouling on different materials across high- and low-energy beaches. Conducted in Guanabara Bay and Niteroi's oceanic beaches, sampling focused on strandlines. Litter was categorized by material, shape, degradation, surface orientation, color, and polymer, with fouling organisms identified to the lowest taxonomic level. Flechas, Icaraí, and Itaipu beaches had the highest litter concentrations due to their geographic orientation and wind exposure. Biofouling was more frequent on intact litter with cylindrical or irregular shapes, rough surfaces, and white, red, or green PET or PP plastics. Polychaetes, bryozoans, and barnacles were the most common organisms. These findings highlight substrate and environmental conditions that influence rafting in the region, underscoring the role of plastic waste as novel ecological substrate in coastal ecosystems.

Keywords: Fouled organisms, High and low energy, Plastic, *Rafting*, Sandy beaches.

1. Introduction

Sandy beaches are defined as coastal sedimentary environments of varied composition, most formed by sand and conditioned by the interaction of the wave systems reaching the coast. Moreover, beaches are influenced by factors that interfere in their morphology, such as tides and wind, and are classified as low energy or high energy (Short and Klein, 2016). Low-energy beaches are characterized by low wave heights and short-wave periods, often protected by natural barriers that diminish wave impact and reduce wind exposure, while high-energy beaches are directly exposed to strong waves and currents, which erode the sand and transport sediment (Davis Jr. and FitzGerald, 2009). High-energy and low-energy beaches are both impacted by the presence of marine litter, which accumulates due to various environmental factors (Macedo *et al.,* 2019; Póvoa *et al.,* 2022).

Marine litter is defined as "any solid material, persistent, processed, discarded or abandoned in the sea" (Cheshire and Adler, 2009). It could be classified according to their origin as land-based or sea-based sources (Munari *et al*., 2016). Land-based sources include sewage discharge, river inputs, wind transport, and improper disposal by beachgoers (Munari *et al*., 2016). Sea-based sources include fishing, oil activities, and accidental or intentional disposal by commercial or recreational vessels (Angiolillo *et al.,* 2015; Munari *et al.,* 2016).

Marine litter can be retained in coastal vegetation, particularly in sand dunes, where plants play a crucial role for its trapping (Gallitelli *et al*., 2021). Dunes, with their dense vegetation and complex root systems, act as natural barriers that intercept litter transported by wind or tides (Gallitelli *et al*., 2021; Battisti *et a*l., 2023b). The vegetation, especially grasses and shrubs that stabilize the dunes, creates physical barriers that trap various types of debris, including litter (Battisti *et al.*, 2023b). Over time, this accumulation can alter the natural landscape and negatively affects coastal ecosystems, posing threats to local biota by introducing pollutants and physical hazards (Gallitelli *et al*., 2021; Battisti *et al*., 2023a; Battisti *et al*., 2023b).

A variety of organisms exploit different types of marine litter for diverse purposes, including foraging, protection from predators, and shelter against competitors, among other ecological functions (Costa et al., 2022; Jagiello et al., 2024). According to Jagiello et al. (2024), hermit crabs, for example, use plastic and other materials as protective shells. Additionally, a plethora of macroorganisms can be found fouled to different types of marine litter, that provides a wide range of substrates for them (Rech *et al.*, 2018; Rech *et al.*, 2021; Póvoa *et al*., 2021). In various environments, seeds may also disperse by rafting on different types of plastic (Waters and Craw, 2018; Battisti *et al*., 2019; Battisti *et al.*, 2020a). Historically, many species used natural rafts, such as tree trunks and gastropod shells, for dispersal (Waters and Craw, 2018). Certain mobile organisms can become entangled in various types of marine litter (Battisti *et al*., 2019). For instance, species such as *Charadrius hiaticula* (Linnaeus, 1758) and Ocypode quadrata crabs (Fabricius, 1787) may interact with waste in diverse ways, sometimes even becoming trapped in discarded fishing materials (Battisti *et al.*, 2019; Costa *et al.*, 2022).

Species attached to marine litter could potentially be dispersed to other locations through ocean currents and winds, using different materials such as plastic, anthropogenic wood, textiles, among others, as vectors in an ecological process known as "*rafting*" (Rech *et al.*, 2016; Rech *et al*., 2018; Póvoa *et al.*, 2021). Organisms associated with different types of marine litter can be considered harmful when they invade ecosystems and cause impacts on structure and functioning of native ecosystems (Thiel and Gutow, 2005; Rech *et al.,* 2018).

Marine litter with fouled organisms (MLFO) exhibits different behaviors in the sea such as buoyancy and movement on the water surface, is susceptible to coastal currents, and has potential for attaching on soft and hard substrates (Chubarenko *et al.*, 2018). The shape and size of marine litter determine its interaction with the environment, affecting its stability and exposure to elements such as wind, waves, and tides (Uzun *et al*., 2022; Piazzolla *et a*l., 2023). The physical characteristics also influence its ability to serve as substrate for biofouling (Póvoa *et al*., 2021; De-la-Torre *et al.*, 2023). Among these characteristics, the main factors that may influence organisms adhering to marine litter are color, chemical composition, geometric shape, surface orientation, and polymer type (Fazey and Ryan, 2016; Rech *et al.*, 2021; Póvoa *et al*., 2021; De-la-Torre *et al*., 2023). Plastic found in the sea has distinct colors (Pinochet *et al*., 2020; De-la-Torre *et al*., 2021). Plastics have been largely identified in the North and South Pacific gyres, as highlighted by Hidalgo-Ruz *et al.* (2020) and Rech *et al.* (2021). In the North Pacific gyre, predominant plastics are white, transparent, and blue hues (Hidalgo-Ruz *et al.*, 2020). Conversely, in the South Pacific gyre, the most abundant plastic litter is black (Rech *et al*., 2021). Additionally, a higher presence of ascidians, bryozoans, and barnacles, among others, was observed on plastic with dark colors and shaded surfaces, which may potentially provide protection against solar radiation or confer a negative adaptation in relation to gravitational orientation (Satheesh and Wesley, 2010; Chase *et al*., 2016).

Marine litter, especially plastics, showed various chemical compositions since they are composed of different polymers (GESAMP, 2019). The low-density polymers float in seawater and may subsequently be deposited on sandy beaches (Audrezet *et al*., 2021). Recent studies have revealed a potential preference of bryozoans for certain plastic polymers, such as PET and PP (Rech *et al*., 2018; Pinochet *et al*., 2020; Póvoa *et al*., 2021). As highlighted by Pawlik (1992) and Pinochet *et al*. (2020), this preference may be associated with the duration of exploration of these organisms during the larval phase, resulting in lower energy expenditure for individual behavior.

Exposure of these materials to ultraviolet radiation, combined with high temperatures and the presence of oxygen, promotes oxidation and degradation, favoring fragmentation (Andrady, 2015; Audrezet *et al*., 2021). Fragmentation then occurs by the action of waves, currents and winds, radiation, influence of dissolved ions, photo-oxidation, hydrolysis, and processes of mineralization and microbial degradation that disintegrate the marine litter and alter its geometric shape (Rech *et al*., 2018; Audrezet *et al*., 2021). Organisms found in the marine litter can colonize both smooth and rough surfaces (Chase *et al*., 2016; Chase *et al*., 2016; Póvoa *et al*., 2022; Rech *et al*., 2021). Rough surfaces present turbulent flows that could influence the settlement of organisms such as bryozoans, hydrozoans, and barnacles, although they are also found less frequently on smooth surfaces (Chase *et al*., 2016; Mancini *et al*., 2021).

MLFO can be found on both low-energy and high-energy beaches, influenced by seasonal and temporal variations (Macedo *et al*., 2019; Póvoa *et al*., 2022). Macedo et al. (2019) found higher densities of marine litter on ocean-exposed beaches in Ilha Grande Bay (south eastern Brazil), while Póvoa *et al*. (2022) also observed greater densities of marine litter with fouled organisms in ocean-exposed beaches in the same region. Different types of litter are found in this region after the passage of Southerly cold fronts that generate storm waves coming from the South and Southwest (Macedo *et al*., 2019; Póvoa *et al*., 2022).

Until the year 2023, approximately 50 studies have been published on the topic of “rafting” in marine litter (Póvoa *et al*., 2021; De-la-Torre *et al*., 2023). This number has increased globally, especially after a tsunami in 2011 in Japan have introduced various anthropogenic materials into the oceans (Póvoa *et al*., 2021; De-la-Torre *et al*., 2023). These materials were later found on Pacific sandy beaches in the United States (Carlton *et al*., 2017; Póvoa *et al*., 2021). In the last decade, recent studies on the topic have been published on beaches in Morocco and India (Mghili *et al*., 2022, 2023; Kannan *et al*., 2023; De-la-Torre *et* *al.*, 2023; Abelouah *et al.*, 2024), and few studies in Brazil (Breves and Skinner, 2014; Mantelatto *et al.*, 2020; Póvoa *et al.*, 2022).

The objectives of this study were to qualitatively and quantitatively assess MLFO and relate them to the physicochemical characteristics of the substrate in an urban tropical bay and in oceanic areas of the Southwest Atlantic. The following hypotheses were tested: 1) The density of marine litter and MLFO differ between low-energy and high- energy beaches; 2) Characteristics such as geometric shape, color, sur face, and type of polymer influence the colonization of organisms on marine litter. This study also establishes a correlation between the species associated with marine litter and the stage of biological invasion.

Finally, this research aimed to enhance the understanding of "rafting" ecological processes along the Southwest Atlantic coast. Given the limited number of studies in this region, it aimed to provide updated insights and novel perspectives, especially in the context of an urban bay and nearby oceanic areas characterized by a high human density population and heavy pollution environment (Soares-Gomes et al., 2016).

2. Material and methods

2.1 Study area

The present study was conducted on beaches inside the Guanabara Bay and the Oceanic Region of the Niterói municipality, Rio de Janeiro, Brazil. Guanabara Bay is in the Rio de Janeiro Metropolitan Region, surrounded by seven municipalities. The population of the bay exceeded 8.5 million inhabitants, making it one of the regions with the highest population density in the country (IBGE, 2022). The bay has approximately 380 km 2 and is one of the most degraded bays in the world (Fries *et al.*, 2019). Its watershed covers about 4000 km², with approximately 45 rivers draining into its waters, exerting a strong influence on it (Kjerfvre *et al.*, 1997; Baptista Neto and Fonseca, 2011; Silva *et al.*, 2016a; Soares-Gomes *et al.*, 2016). Additionally, Guanabara Bay also receives oceanic influence up to the region of the Rio-Niterói Bridge and Paquetá Island, with currents and winds coming from the open sea (Silva *et al.*, 2016a; Soares-Gomes *et al.*, 2016).

The Oceanic Region of Niterói has approximately 51.2 km 2 and has undergone intense urbanization since the 1970s, after the construction of the Rio-Niterói Bridge (Rodrigues *et al.*, 2015; Silva *et al.*, 2022). The area harbors some conservation units, such as the Serra da Tiririca State Park, which is also a World Biosphere Reserve and the Itaipu

Marine Extractive Reserve (Timbó *et al*., 2019; Leite *et al*., 2021). Various coastal ecosystems, including sandy beaches, lagoons, rocky shores, mangroves, and sandbanks are found in the area (Leite *et al*., 2021; Silva *et al*., 2022).

The beaches of Niterói are situated in Guanabara Bay and the Oceanic Region (Silva *et al*., 2016 b; Eccard *et al*., 2017). They are categorized as either low-energy or high-energy, with generally calm seas for most of the year, although conditions can change following storm waves and swells (Silva *et al*., 2016 a; Eccard *et al*., 2017). The tides in the region are microtidal and semidiurnal (Silva *et al*., 2016a; Eccard *et al*., 2017). Prevailing waves come from the south, southeast, and southwest (Silva *et al*., 2016 a). South winds often exceed 10 m.s 1, particularly with the arrival of cold fronts, while northerly winds are also frequent (Filippo and Figueiredo-Júnior, 2012). In Guanabara Bay, currents are more intense on the right side of the bay's entrance, with surface velocities reaching 1.56 m.s 1 during the flood tide and 1.37 m. s 1 during the ebb tide (Silva *et al*., 2016 a). The beaches experience two distinct seasons: a dry season from June to August and a rainy season from December to April (Kjerfvre *et al*., 1997; Baptista Neto and Fon seca, 2011; Soares-Gomes *et al*., 2016). In Guanabara Bay, Flechas (22◦ 54′ 18″ S; 43◦ 07′ 20″ W), Icaraí (22◦ 54′ 26″ S; 46◦ 06′ 45″ W), São Francisco (22◦55′ 04″ S; 43◦05′ 41″ W) and Charitas (22◦55′ 48″ S; 43◦ 05′ 52″ W) are classified as low energy (Silva et al., 2016a). In the Oceanic Region, Camboinhas (22◦96′ 01″ S; 46◦06′ 34″ W) and Piratininga (22◦95′ 48″ S; 43◦08′ 31″ W) are classified as high-energy and Itaipu (22◦97′ 11″ S; 43◦04′ 59″ W) are classified as low energy (Eccard *et al*., 2017).

In Guanabara Bay we studied Flechas (365 m), Icaraí (1230 m), Charitas (1930 m), and Sãoo Francisco beaches (642 m), and in the Oceanic Region, Itaipu (650 m), Piratininga (2500 m), and Camboinhas (2330 m) (**Fig. 1**). The criteria for the selection of these beaches were their orientation relative to South and Southwest winds (Godoi et al., 2011), as well as the predominant maritime currents in the region, which can influence the destination of various pollutants, such as marine litter deposited on sandy beaches (Silva et al., 2016 b).

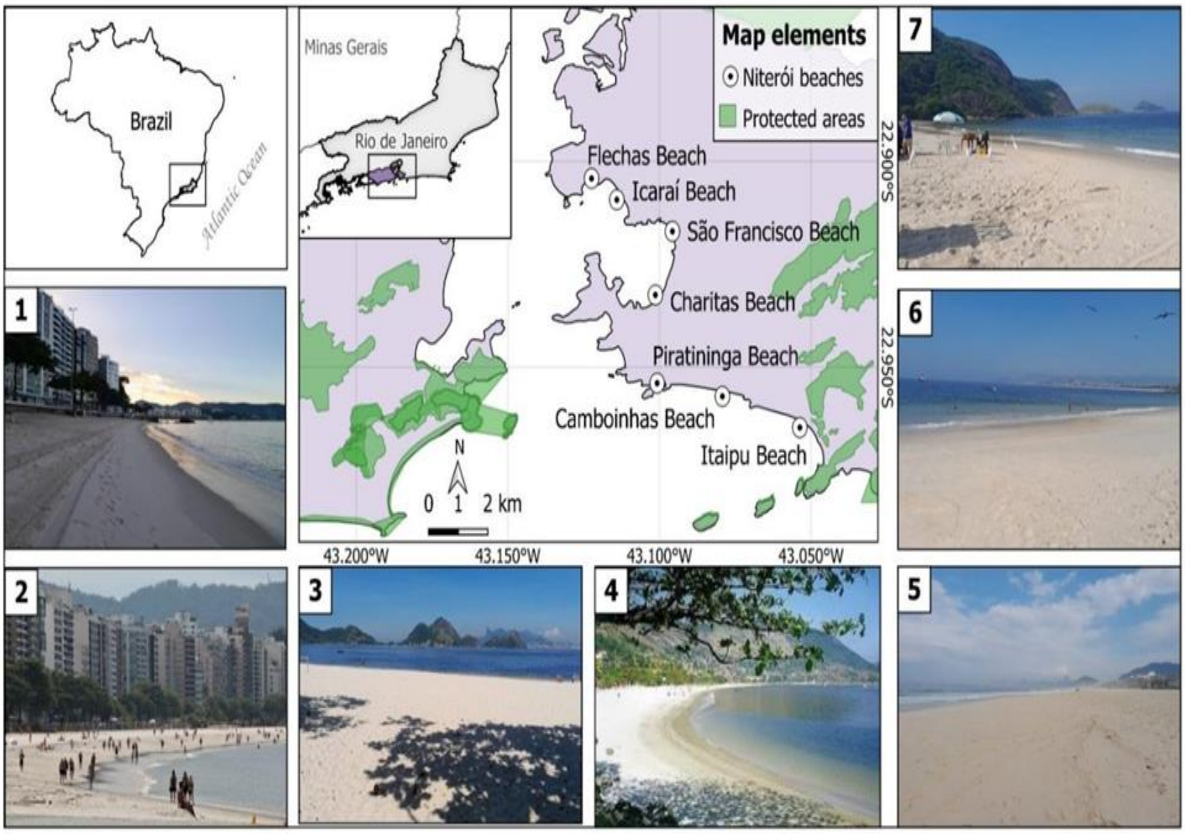

Figure 1. Geographical location and pictures of the beaches studied (1 – Flechas, 2 – Icaraí, 3 – São Francisco, 4 – Charitas, 5 – Piratininga, 6 – Camboinhas, 7 – Itaipu).

2.2 Sampling design and laboratory procedures

Sampling was done in two rainy and two dry periods at each beach between 2022 and 2023, with three replicates in each period. Marine litter was sampled along the strandline (±1 m2) during low tides, before the daily beach cleaning performed by the local municipality (**Fig. 2**). Marine litter was sampled over two consecutive days on weekdays (Tuesdays and Wednesdays), after two or three days following the occurrence of swells and the passage of cold fronts. Additionally, we clarify that we avoid Fridays, Saturdays, Sundays and Mondays as these are days when the beaches are more crowded. The first campaign took place in 2022, with samplings of the rainy season being carried out from February to April and the rainy season from June to August. The second was carried out in 2023, with the campaign done in the same months.

Fig.2. Picture showing the strandline observed in one of the beaches included in this study.

Samples with fouling were transported to the laboratory for the identification of the marine litter types and associated organisms. The MLFO was classified according to Cheshire and Adler (2009), which includes plastic, processed wood, glass, candles and ceramics, textiles, among others, with appropriate modifications due to the variety of plastic items

2.2.1 Cleaning classification of beaches

The beaches were categorized by Clean-Coast Index (CCI) (Alkalay et al., 2007). The CCI values were categorized by cleanliness level as: very clean (0–2), clean (2–5), moderate (5–10), dirty (10–20), and extremely dirty (above 20). The clean coast index was obtained from the average density of marine litter multiplied by 20 (Alkalay et al., 2007).

2.2.2 Sources of marine litter

The classification of marine litter sources was divided into three categories: domestic, fishing, and indeterminate. Domestic included items such as rubber, toys, pipes, straws, slippers, cups, packaging, bottles, cigarette butts, personal hygiene products, seals, cans, jars, bags, lids, utensils, tubes, and shoes. Fishing are litter related to fishing activities including buoys, ropes, lines, and fishing gear. Indeterminate items such as fragments and styrofoam that could not be clearly attributed to either domestic or fishing sources. For instance, polystyrene objects like fishing floats were classified as fishing-related, while fragmented polystyrene items were categorized as having an indeterminate origin. The classification approach for determining the origin of the litter followed the scheme proposed by Fernandino *et al*. (2016), with adaptations made as necessary to fit the specific context of the study.

2.3. Processing and characterization of MLFO

The MLFO were sorted according to their physicochemical characteristics: degradation, geometric shape, surface, color, and chemical composition, through visual observation. It was also categorized regarding the degradation state into intact and fragmented, and by their geometric shapes - cylindrical, irregular, flat, and cubic, among others, following Rech *et al*. (2021) and Póvoa *et al*. (2022). Additionally, these items were grouped by the orientation of their surface, and smooth or rough surfaces by visual observation.

Regarding colors, the marine litter was classified as blue, white, black, red, orange, and green, among others. The colors were classified according to Rech *et al.* (2021) that consist in comparison of the sampled items to a printed color sheet, with minor modifications to accommodate colors not present in the original classification.

Plastics with fouling were also classified according to the type of polymer by visual observation: EPS (Expanded Polystyrene), PA (Nylon), PET (Polyethylene terephthalate), PLA (Polyamid Acid), PP (Polypropylene), PS (Polystyrene), and others. The classification of polymer composition followed the categories provided in tables by Lusher et al. (2017) and Audrezet et al. (2021), with necessary adaptations (**Tab.1**).

Tab.1. Classification model based on polymer type.

Polymer type	Application
EPS	Styrofoam
PA	Fishing nets and ropes

PET	Cups, bottles and bags
PLA	Food containers, bottles, and disposable utensils
PP	Ropes, bottle caps, fishing materials, and cosmetic products
PVC	Films, tubes, containers, window boxes, and flooring
PS	Utensils, containers, disposable cups, plates, and cutlery
Others	Acrylics (textiles), polycarbonates.

2.3.1. Abundance, diversity and similarity of MLFO

The abundance of MLFO was assessed by frequency of occurrence (FO) that was calculated using the following formula: number of items sampled/number of MLFO x 100. Data were expressed in percentages, following Rech *et al.* (2021) and Abelouah *et al.* (2024).

MLFO diversity was evaluated by the Shannon–Wiener index (H′), a non-parametric metric that considers both the number of species and their relative frequencies (Shannon and Weaver, 1949). The index is calculated as ($H' = \sum(fr \times logn(fr))$, where “fr” represents the relative frequency of each litter “species and $\log_n$ (fr) is the natural logarithm of this frequency, following the approach outlined by Battisti et al. (2018). We calculate the evenness (Shannon/ Species richness (S)), Margaleff (M) and beta diversity between study periods following the methodology established by Battisti et al. (2017). Additionally, the Jaccard Index of similarity was calculated between the study periods (Jaccard, 1901). All these indexes were calculated in PAST Statistical Software v.4.

2.3.2. Identification of MLFO and classification according to conservation status

The MLFO was photographed using an Axiocam ERc5s camera attached to a Zeiss stereomicroscope. After this procedure, the litter was preserved in 70 % alcohol for a preliminary identification of the taxa. After sorting, specimens were sent to specialists for taxonomic confirmation of identification at the most precise taxonomic level. The species names were checked in WoRMS (World Register of Marine Species) for possible synonyms.

Taxa were classified as cryptogenic (with uncertain or unknown biogeographical origin), invaders (when an established species exhibits abundance or geographic spread that disrupts the survival of other species within a specific area or across a wider geographic region), detected (a single occurrence of an exotic species in a natural environment, without evidence of increased abundance or spread, and lacking information on subsequent occurrences), natives (species that occurs within its natural distribution area, in which it has established itself without any human intervention) and no data (without any or no record of terms in studies), among others, using the Brazilian Platform of Bio invasion (Carlton, 1996; Casares et al., 2024). However, when the platform did not provide the information, we searched for them in available scientific literature, as well as information on the origin and geographical distribution of the species (Appendix V).

2.4. Statistical analysis

The density of marine litter and its distribution between high-energy and low-energy beaches, as well as differences across the study years, were compared by Kruskal-Wallis test, with factors treated as fixed effects.

A permutation analysis of variance (PERMANOVA) was performed to test the differences in the density of MLFO between rainy and dry periods, as well as the classification of their distribution in the high and low dynamics of the beaches, and among the study years, with factors treated as fixed factors. The same analysis was performed to test the differences in the physicochemical characteristics of MLFO (degradation, geometric shape, color, roughness, and polymer type). All the analysis adopted a significance level of 0.05 and were performed using PAST Statistical Software v. 4.

3. Results

The results will be presented in three sections, with the first addressing the occurrence of Marine Litter and MLFO, the physico chemical characteristics in their different variables, and the species associated with their status of biological invasion.

3.1. Occurrence of marine litter found in the strandline

Over a two-year monitoring period, 22,960 (28.51 items.m^{-2}) marine litter items were sampled, averaging 7.13 items.m^{-2} (±2.96 – 3.16 items.m^{-2}). Of these, 6,412 marine litter items (3.18 items.m^{-2}; 11%) were collected from beaches of high energy, while 16,548 (25.33 items.m^{-2}; 89%) were found on beaches of low energy. During the rainy season, 10,877 marine litter items were recorded (15.24 items.m^{-2}; 49%), and 12,083 (13.26 items.m^{-2}; 51%) were found during the dry season (**Tab.2.**).

Among beaches of high energy, Camboinhas showed higher densities of marine litter during both the dry and rainy seasons - 1.20 items.m^{-2} (4%) in the rainy and 1.01 items.m^{-2} (4%) in dry season. Among beaches of low energy, Flechas showed a density of 5.94 items.m^{-2} in the rainy (23%) and 4.42 items.m^{-2} (16%) in the dry season, and Icaraí 2.35 items.m^{-2} (8%) and 2.67 items.m^{-2} (10%) in the rainy and dry season, respectively (**Tab.2.**).

According to CCI, all the beaches of low energy were categorized as extremely dirty. The beaches of high energy were categorized as dirty (Piratininga) and extremely dirty (Camboinhas) (**Tab.2.**). Marine litter showed no significant difference between the dry and rainy periods ($p > 0.05$), but it did differ significantly between high-energy and low-energy beaches ($p < 0.05$).

Tab 2. Quali-quantitative analysis of marine litter found in beaches studied of Southwest of Atlantic (items.m^{-2}).

Period/Beaches	Type of energy of beaches	First rainy season	Second rainy season	Total rainy season	First dry season	Second dry season	Total dry season	Total general	Average	CCI	Classification
Piratininga	High	0.42 (1%)	0.25 (3%)	0.67 (4%)	0.19(2%)	0.10 (0%)	0.29(1%)	0.96 (5%)	0.24	19.2	Dirty
Camboinhas	High	0.70(2%)	0.50 (2%)	1.20 (4%)	0.54(2%)	0.47 (2%)	1.01 (4%)	2.22 (6%)	0.55	44.4	Extremely dirty
Total of high energy		1.12 (3%)	0.75 (5%)	1.87 (8%)	0.70 (4%)	0.57 (2%)	1.30 (5%)	3.18 (11%)	0.74	-	-
Flechas	Low	5.24 (18%)	0.70 (5%)	5.94 (23%)	3.04 (11%)	1.38(4%)	4.42 (15%)	10.36 (21%)	2.59	207.2	Extremely dirty
Icaraí	Low	1.63 (5%)	0.72 (3%)	2.35 (8%)	1.59 (6%)	1.07(3%)	2.67 (9%)	5.02 (13%)	1.25	101.4	Extremely dirty

São Francisco	Low	1.64 (5%)	0.55 (2%)	2.19 (7%)	1.26 (4%)	0.41 (1%)	1.68 (5%)	3.87 (6%)	0.97	77.4	Extremely dirty
Charitas	Low	0.48 (1%)	0.27(1%)	0.74 (2%)	0.66 (2%)	0.19 (0%)	0.85 (2%)	1.59 (2%)	0.40	31.8	Extremely dirty
Itaipu	Low	1.62 (5%)	0.52 (2%)	2.14 (7%)	1.40 (5%)	0.95 (3%)	2.35 (8%)	4.49 (11%)	1.12	89.80	Extremely dirty
Total of low energy		10.61 (33%)	2.75 (15%)	13.36 (49%)	7.96 (27%)	4.00 (11%)	11.9 (40%)	25.33 (89%)	6.33	-	-
General total		11.74 (36%)	3.50 (20%)	15.24 (56%)	8.68 (31%)	4.57 (13%)	13.26(44%)	28.51 (100%)	7.13	-	-

Of all marine litter sampled, 99% of the items were plastics. The remaining 1% comprised other materials, distributed as follows: 0.5% wood, 0.3% metal, and 0.2% fabrics. Among plastics, the composition included caps (23.5%), packaging (20.4%), fragments (15.88%), and styrofoam (13.2%), and other types of plastic representing less than 10%. However, plastic bottles were found in 3.8% (**Fig.3**). The presence of caps and packaging indicates the domestic origin of these items, while fragments and styrofoam may suggest a domestic source for some styrofoam materials or an indeterminate origin.

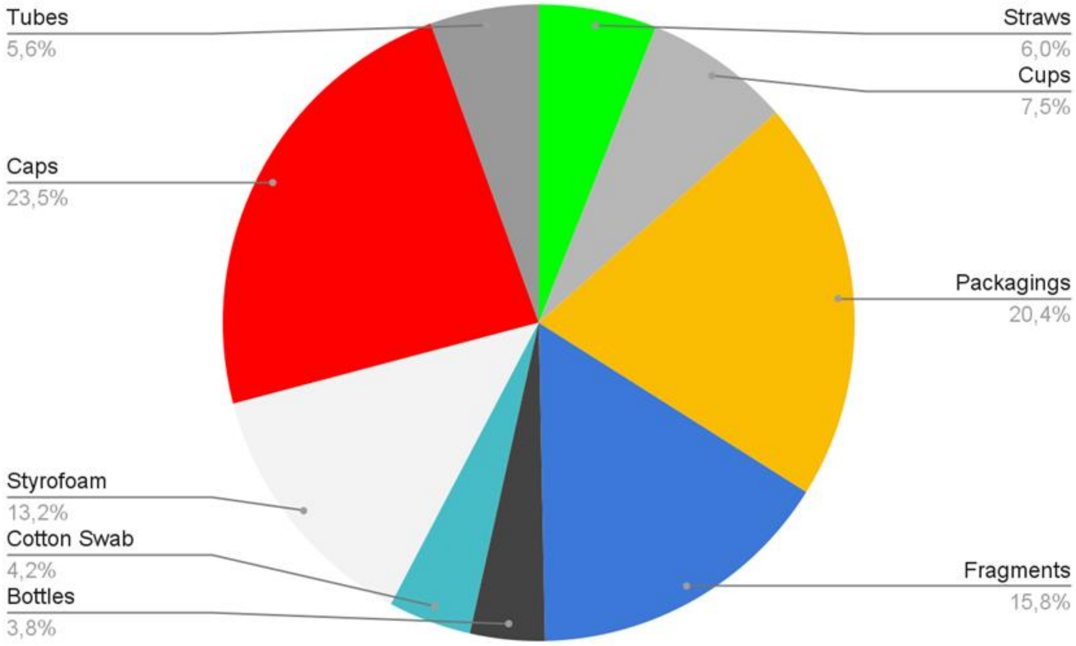

Fig.3 Predominance of plastic marine litter found in the studied beaches of Niterói, southeast Brazil.

3.2 Concentration of MLFO

Of 22,960 marine litter items found, only 525 items had fouled organisms, corresponding to 0.56 items.m^{-2}, with a media of 0.11 items.m^{-2} (± 0.07 – 0.08 itens.m^{-2}). The rainy period presented a total of 0.21 items.m^{-2} (39%) and the dry period 0.35 items.m^{-2} (61%) of MLFO (**Tab.3.**). No significant difference was detected between the studied periods ($p > 0.05$), but a significant difference was found between high-energy and low-energy beaches ($p < 0.05$).

Among the high-energy beaches, Camboinhas had the highest densities of marine litter with fouling, with 0.03 items.m^{-2} (5%) Among the low-energy beaches, Flechas and Icaraí exhibited the highest density of fouled marine litter, with respective values of 0.26 items.m^{-2} (43%) and 0.10 items.m^{-2} (15%) each (**Tab.3**).

Among the 525 items, 98% (514 items) were plastic. Occasionally, fouling was observed on 6 items of anthropogenic wood (1%) and 4 items of fabric (1%). Due to the predominance of plastic, only these items were classified according to their physicochemical features.

Tab 3. Density (items.m^{-2}) and percentage of marine litter with fouling observed across the studied beaches.

Beaches	**Energy**	**First rainy season**	**Second rainy season**	**Total rainy season**	**First dry season**	**Second dry season**	**Total**	
Piratininga	High	0.01 (1%)	0.00(0%)	0.01(1%)	0.01(1%)	0.00(0%)	0.01(1%)	0.01(1%)
Camboinhas	High	0.01(1%)	0.00(0%)	0.01(1%)	0.01(1%)	0.01(1%)	0.02(3%)	0.03(5%)
Total of high energy		0.02 (2%)	0.00(0%)	0.02 (2%)	0.02 (2%)	0.01(1%)	0.03 (4%)	0.04 (6%)
Flechas	Low	0.07 (12%)	0.02 (3%)	0.09 (16%)	0.09 (16%)	0.06 (11%)	0.15 (27%)	0.26 (43%)
Icaraí	Low	0.03 (3%)	0.00 (0%)	0.03(3%)	0.05 (9%)	0.02(3%)	0.07(12%)	0.10(15%)

São Francisco	Low	0.04 (7%)	0.00 (0%)	0.04(7%)	0.01 (1%)	0.01 (1%)	0.02(3%)	0.06(11%)
Charitas	Low	0.01 (1%)	0.00 (0%)	0.01(1%)	0.02 (3%)	0.00 (0%)	0.02(3%)	0.03 (5%)
Itaipu	Low	0.02 (3%)	0.00 (0%)	0.02(3%)	0.05(9%)	0.01 (1%)	0.06(11%)	0.12(21%)
Total of low energy		0.17(23%)	0.02(3%)	0.19(27%)	0.22(38%)	0.10(16%)	0.32(55%)	0.53(88%)
General total		0.19 (35%)	0.02(3%)	0.21 (39%)	0.24 (43%)	0.11 (18%)	0.35 (61%)	0.56(100%)

3.3. Physicochemical features of marine litter with fouling

The results of the physicochemical characteristics were expressed below in percentage, based on the total quantity, since when trying to convert them to density few variables showed a concentration above 0.01 items.m^{-2}.

3.3.1. Degradation, geometric shape e surface orientation

Of the items sampled, 69.7 % were intact and 30.3 % fragmented, with a higher prevalence ($p < 0.05$) of intact items during the dry season compared to the rainy season (**Fig. 4A**). In terms of geometric shape, 67.3 % of the items exhibited cylindrical shape, 20.7 % irregular shape (without a defined geometric shape), 10 % flat shapes, and 2.1 % cubes, with a higher prevalence of cylindrical and irregular shapes during the dry season compared to the rainy season (**Fig. 4B**). The MLFO analyzed for geometric shape showed significant differences regarding periods, sampling locations (Guanabara Bay and Oceanic Region), and study years ($p < 0.05$).

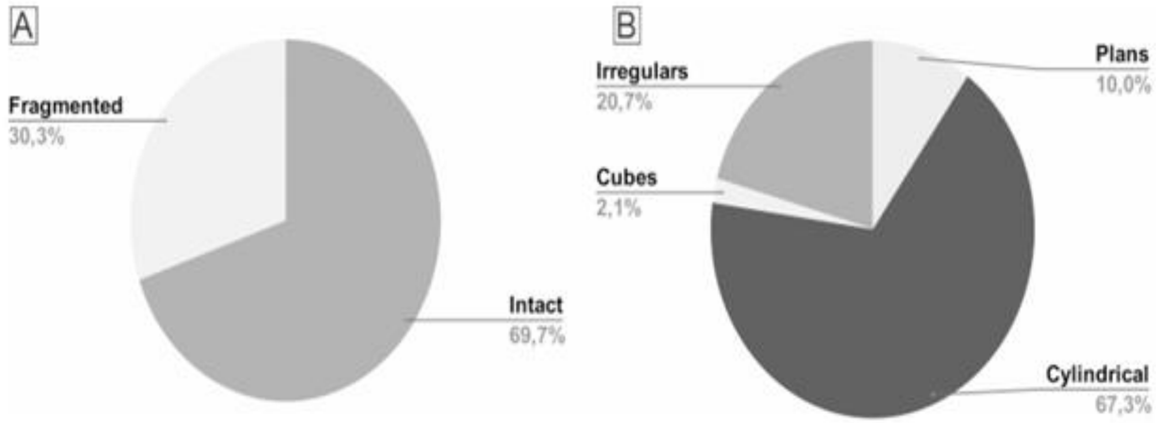

Figure 4. Stage of degradation (A) and percentage of geometric shapes (B) of marine litter with fouled organisms found in this study.

In terms of surface texture, 60 % of the fouled organisms were identified on rough surfaces (irregulations and variations in their texture), and 40 % were identified on smooth surfaces (Little to no irregularity). Rough surfaces were found at higher prevalence during the dry season compared to the rainy season (**Fig. 5**). The presence of fouled species with marine litter also differed according to surface ($p < 0.05$).

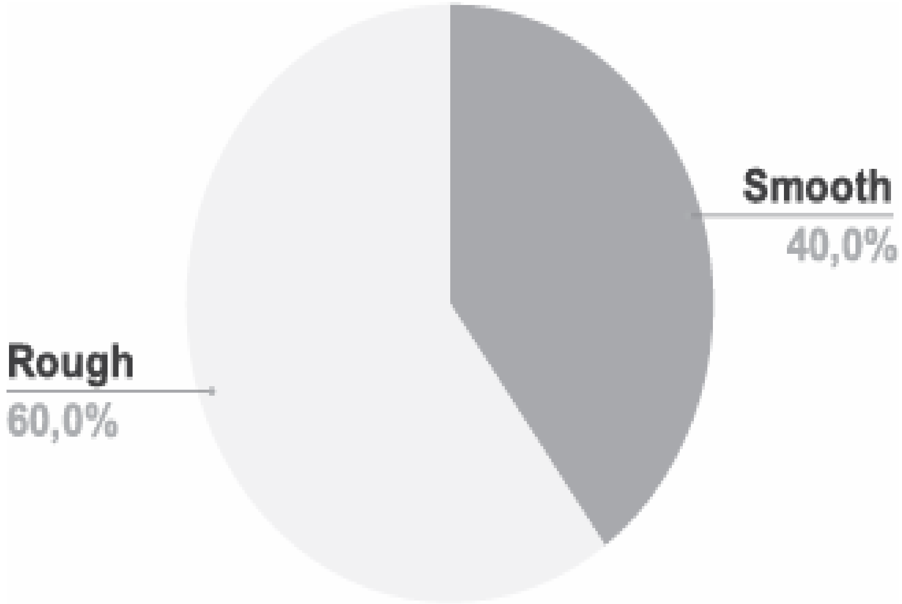

Fig.5. Surface texture of marine litter with fouled organisms found in this study.

3.3.2. Color and polymer type

The main colors of MLFO were white (21.7 %), red (16.9 %), blue (15.7 %), black (12.2 %), green (11.1 %) and transparent (10.0 %). Other colors represented <10 % (**Fig. 6A**), with a higher prevalence of white and red in both study periods. Statistical analysis showed no significant differences in the color of MLFO ($p > 0.05$). MLFO were mostly found on polypropylene (PP) polymers (57.6 %), followed by polyethylene terephthalate (PET), which represented 30.4 % of the items (**Fig. 6B**), with a higher prevalence of PET (Polyethylene terephthalate) and PP (Polypropylene) in both study periods. The MLFO was statically different according to the type of polymer ($p < 0.05$)

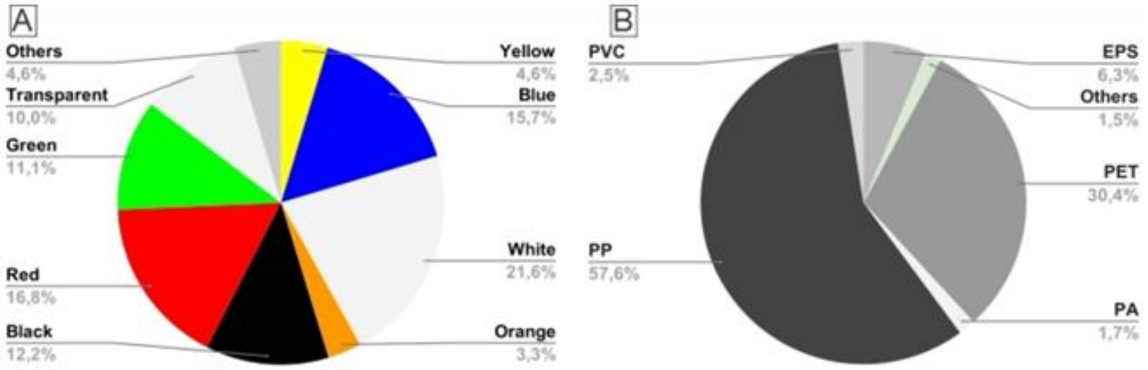

Fig.6. Main color (A) and polymer types (B) of marine litter with fouled organisms found in this study.

3.4. Main taxa adhered to marine litter

Twenty-one taxa corresponding to six phyla were found in MLFO (Annelida, Arthropoda, Bryozoan, Mollusca, Porifera, and Protoctista). Of these phyla, only Porifera and Protoctista showed sporadic occurrences. Polychaetes were found in 45.9 % of the samples, followed by barnacles (27.2 %), bryozoans (22.3 %), and mollusks (2.6 % bivalves 2.0 % gastropods) (**Fig. 7 A and Fig. 8**). The species found attached to marine litter are primarily invasive (36.4 %), native (22.7 %), cryptogenic (18.2 %), established (13.6 %) and undetermined (9.1 %) (**Fig. 7 B** and **Supplementary Material**).

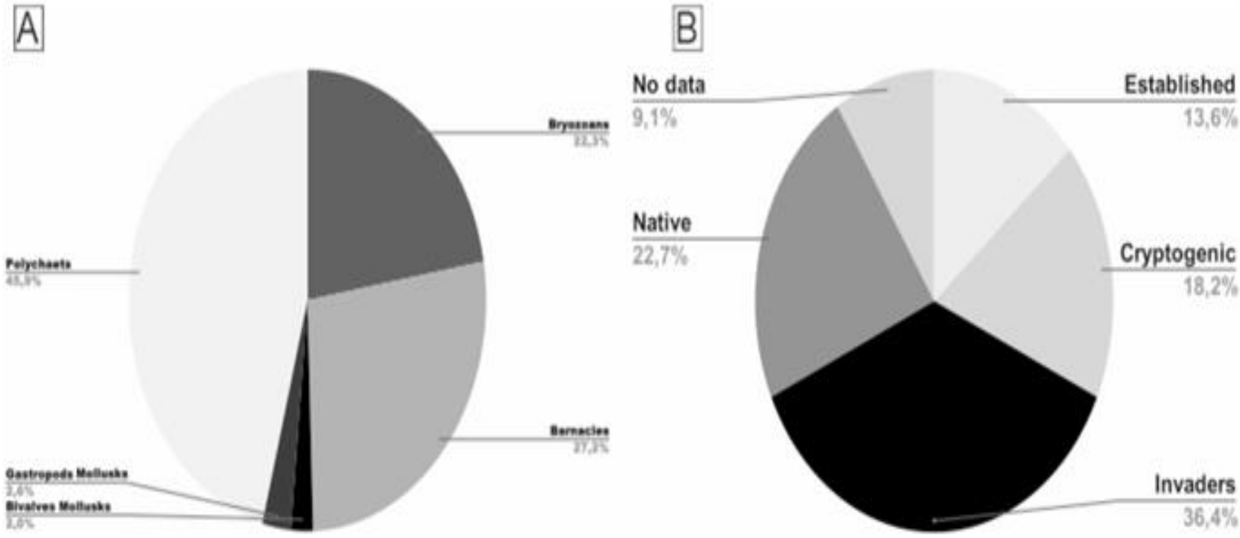

Fig.7. Main occurrence (A) and status (B) of zoological groups found on marine litter in this study.

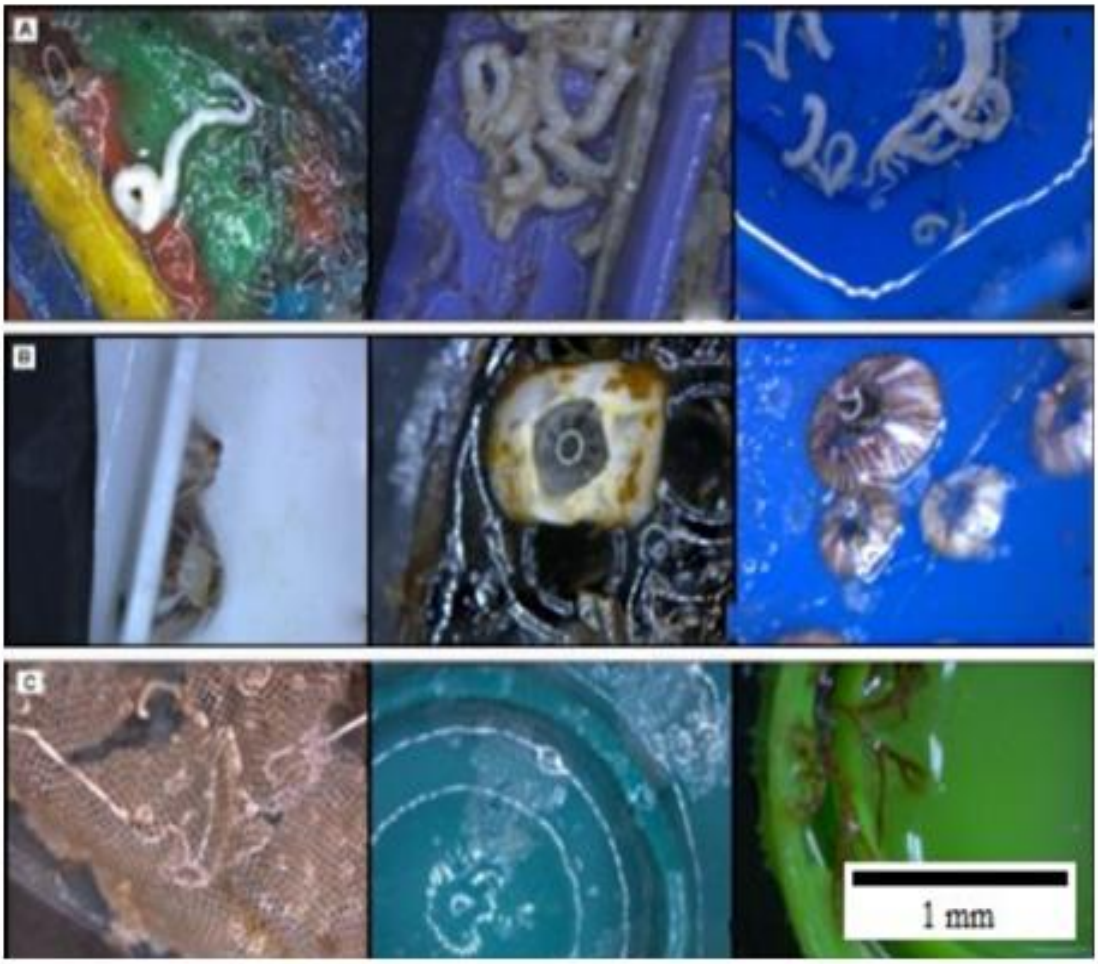

Fig.8. Polychaetes (A), barnacles (B) and bryozoans (C) found in marine litter in this study.

Some families were predominant in fouled litter, such as Serpulidae polychaetes, Membranipora and Bugulidae bryozoans, Balanidae barnacles, and Ostreidae bivalve mollusks. The balanids *Megabalanus tintinnabulum* (Linnaeus, 1758), *Megabalanus coccopoma* (Darwin, 1854), and *Megabalanus vinaceus* (Darwin, 1854) (**Table 4**).

The present study found a species diversity (H′) of 1.20, with an Evenness (E) and Margaleff (M) of 0.76, and a Jaccard index (J) of 0.81. Among low-energy beaches, São Francisco and Charitas showed the highest diversity, while Camboinhas had the highest diversity among high-energy beaches. The remaining indices displayed similar values across high- and low-energy beaches (**Fig. 9**). Statistical analysis revealed no significant differences between beach types ($p > 0.05$) or between the dry and rainy seasons ($p > 0.05$).

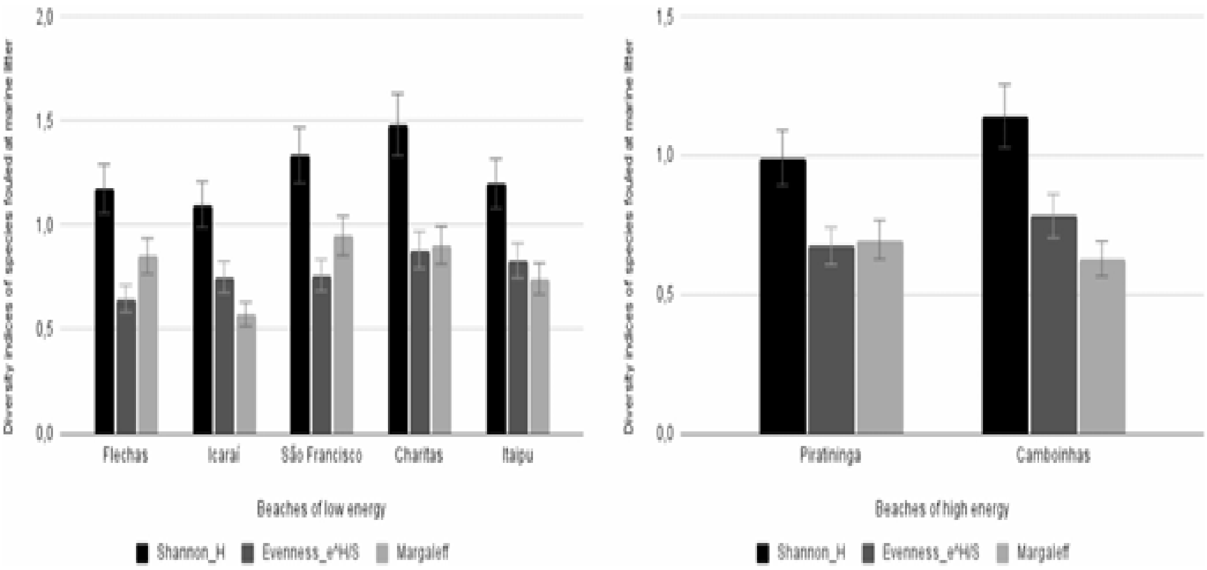

Fig.9. Biological indices for species fouled at marine litter in beaches of low and high energy.

4. Discussion

4.1. Density and origin of marine litter

Brazil is one of the countries with the highest concentrations of marine litter in coastal ecosystems such as beaches (Póvoa *et al.*, 2021; Videla and Araújo, 2021). The beaches of Guanabara Bay and the Oceanic Region in Niterói, located near urban centers, have high marine litter density due to disordered development in surrounding areas lacking essential infrastructure (Tucci, 2008). Urban areas, particularly in the coastal municipalities of Rio de Janeiro and Santos, Brazil, show high concentrations of marine litter on their beaches (Abude *et al.*, 2021; Ribeiro *et al.*,2021).

The beaches of Niteroi receive marine litter from both local (autochthonous) and external (allochthonous) sources as also reported by Castro *et al.* (2020). In 2022, the average precipitation rate was 0.125 mm, with a higher amount of waste found on the beaches. In contrast, 2023 had an average precipitation rate of 0.37 mm, with less waste deposited (INMET, 2025).The difference in precipitation can be explained by variations in the frequency of intense rainfall events and the efficiency of drainage systems, as well as potential year-to-year variations exacerbating pollution in coastal areas (Thiel *et al.*, 2021). Urban waste, including plastics, heavy metals, and chemicals, is transported to the oceans via intense rainfall and urban drainage systems, negatively impacting water quality and marine biodiversity. Studies show that this runoff is a significant pathway for pollutants such as microplastics, organic compounds, and pathogens, which, in turn, harm both marine ecosystems and human health (Graells *et al.*, 2021).

The present study demonstrates that high-energy and low-energy beaches differ significantly in the deposition of litter along the wrack line of sandy beaches, reflecting the impact of environmental processes such as currents, tides, and winds. High-energy beaches, such as those in the Oceanic Region, are more likely to receive marine litter from external (allochthonous) sources due to the transport of materials by ocean currents and winds. For example, Camboinhas beach, which is oriented toward the open ocean, experiences high litter densities. This orientation exposes it to strong wave action and makes it particularly susceptible to swells, cold fronts, and prevailing winds that deposit litter along its shore (Silva *et al.*, 2016a; Eccard *et al.*, 2017). In contrast, low- energy beaches primarily receive litter from local (autochthonous) sources, including untreated sewage, river inputs, domestic waste, and improper disposal. While the litter on these beaches is mostly local, Icaraí may occasionally receive some allochthonous litter, although this is much less frequent (Castro e*t al.*, 2020; Silva *et al.*, 2022).

Although low-energy beaches, such as Flechas and Icaraí, generally receive marine litter predominantly from local sources, their specific location and environmental conditions also allow for the accumulation of allochthonous marine litter. They receive litter from both local (autochthonous) and external (allochthonous) sources due to factors specific to their location and environmental conditions, which increase the likelihood of litter accumulation from various origins (Baptista Neto and Fonseca, 2011; Silva *et al.*, 2016a). Improper disposal of solid waste on slopes, streets, and drainage systems increases the risks of flooding and landslides by causing slope overload and drain blockages (Bernardino and Franz, 2016). Solid waste carried by rivers and drainage systems can reach the ocean, particularly affecting low-energy beaches like São Francisco and Charitas, especially after heavy rainfall that causes runoff and debris deposition (Castro *et al.*, 2020). Similar processes have also been observed at Tamandaré Beach in Pernambuco, Brazil, and on beaches in Chile (Araújo and Costa, 2007; Bravo *et al.*, 2009).

This study classifies the beaches of Niterói as extremely dirty with exception of Piratininga beach classified as dirty likely due to deficiencies in the cleaning services provided by the Niteroi Cleaning Company (CLIN). In contrast, Silva et al. (2022) found seasonal variations in Clean Coast Index (CCI) values for beaches in the Oceanic Region, categorizing them as clean, moderate, or dirty. Effective cleaning requires mechanized beach sand cleaning with 4 × 4 tractors and towed mechanical sieves, as outlined in the Municipal Solid Waste Policy of Niteroi (2012). CLIN operates from 6 AM to 3 PM and conducts night time cleaning at high-energy beaches. Morning cleaning focuses on sweeping, especially at low-energy beaches, where litter is gathered into piles for transport to garbage trucks (Luz, 2018).

The majority of marine litter on both high-energy and low-energy beaches consists primarily of plastic items. On low-energy beaches, the litter is predominantly locally sourced, while on high-energy beaches, the influence of allochthonous sources, transported by currents and winds. Recent studies indicate that plastics make up about 93 % to 97 % of marine litter on beaches (Bettim *et al*., 2021; Krelling *et al*., 2023). Research in beaches of Guanabara Bay and Oceanic Region, has shown a higher concentration of plastic items, which can be transported to the beaches through currents, winds, improper disposal by beach goers, and tidal movements (Baptista Neto and Fonseca, 2011; Timbó *et al.*, 2019; Silva *et al.*, 2022).

Plastic litter is prevalent in oceans due to its extensive use in daily life, thanks to its durability, malleability, and low cost (Cheshire and Adler, 2009; Castro *et al*., 2020). Its lightweight nature enhances transport capacity, influenced by buoyancy and winds in marine environments (Aliani and Molcard, 2003; Hidalgo-Ruz *et al*., 2018). Beachgoers often use plastics for disposal, as observed at Itaipu Beach (Santana-Neto et al., 2011; Timbó et al., 2019; Póvoa *et al*., 2022). In this study, styrofoam is categorized as plastic, although other research treats it as distinct (Cheshire and Adler, 2009). Fishing gear, primarily made from plastics, may be classified as plastic or of indeterminate origin (Azevedo-Santos *et al.*, 2021).

4.2. Concentration of MLFO

Brazil has few studies on rafting in marine litter on beaches (Póvoa *et al*., 2021). A higher incidence of marine litter associated with fouled organisms, which were linked to personal use and largely derived from allochthonous sources, such as those transported by currents and winds (Póvoa *et al.*, 2022). This distinction sets their findings apart from those of the current study.

The density of MLFO exhibits significant variation between high-energy and low-energy beaches, reflecting the influence of distinct environmental processes. Nonetheless, the presence of fouled marine litter on both beach types indicates the contribution of both local and external sources to its deposition. In beaches of Niterói, while the majority of marine litter originates from local sources, certain low-energy beaches are also affected by external inputs transported via marine currents and winds (Baptista Neto and Fonseca, 2011; Silva *et al.*, 2016 b; Silva *et al*., 2022).

The beaches of Flechas and Icaraí, although low-energy, are among the most dynamic in Guanabara Bay (Silva *et al*., 2016 a). As a result, they can receive marine litter with fouled organisms from both autochthonous and allochthonous sources. Beaches of low energy such as São Francisco and Charitas revealed that their lower hydrodynamics is insufficient to disperse marine litter over long distances. Consequently, marine litter tends to accumulate along the strandline, as demonstrated in studies by Prevenios *et al*. (2018). Furthermore, once these materials enter the study area, many become trapped and circulate within the region, making their exit challenging (Soares-Gomes *et al*., 2016). On high-energy beaches, this marine litter is primarily from external sources (Póvoa *et al*., 2022).

These findings are consistent with research by Mghili *et al*. (2023) and Abelouah *et al.* (2024) on urban beaches in Morocco, which identified that marine litter can originate from terrestrial (autochthonous) and marine (allochthonous) sources. However, Póvoa *et al.* (2022) observed a higher prevalence of marine litter with fouled organisms on beaches facing the open sea in Ilha Grande Bay, located in southern Rio de Janeiro in areas not urbanized. This differs from the present study, which found a higher density of marine litter with fouled organisms on low-energy beaches.

Marine litter can reach sandy beaches through winds too (Hidalgo- Ruz *et al.*, 2018; Timbó *et al.*, 2019). Wind direction significantly influences the presence of litter on beaches (Andrades *et al*., 2018, 2020; Castro *et al*., 2020). In the Southwest Atlantic, currents such as the South Atlantic Current, the South Equatorial Current, and the North Equatorial Current can transport materials into the South Atlantic Subtropical Gyre (Andrades *et al.*, 2018; Soares *et al*., 2023). Previous studies emphasize the critical role of ocean currents in transporting marine litter. Cyclones and tsunamis can deposit various types of litter along shorelines globally, as evidenced by the North Pacific Gyre, where a tsunami transported diverse materials to the Pacific coast (Carlton *et al*., 2017; P´ ovoa *et al*., 2021). However, in Brazil, where tsunamis are rare, the dispersion of fouled organisms associated with marine litter is more likely driven by marine currents.

On the studied beaches, the increased presence of MLFO during the dry season suggests accumulation over time, potentially due to inefficiencies in Niter´ oi's beach cleaning system. Silva *et al*. (2022) note that the rainy season enhances the municipality's beach cleaning efficiency. In contrast, this finding differs from Póvoa *et al.* (2022), who reported a greater presence of fouled organisms during the rainy season in Ilha Grande Bay. Plastic and anthropogenic wood are the most cited materials for dispersing species globally (Rech *et al.*, 2018; P´ ovoa *et al*., 2021, 2022; Mghili *et al*., 2023; Abelouah *et al*., 2024). In this study, fouled organisms were found in greater abundance on plastic. Due to its durability, buoyancy, and ease of dispersion, plastic is particularly susceptible to colonization by fouled organisms, acting as a vector for the dissemination and transport of marine macroinvertebrates over long periods (Gregory, 2009; Mghili *et al*., 2022; Abelouah *et al.*, 2024). Consequently, plastic is often found on the water's surface or deposited along the strandline of sandy beaches after storms (Póvoa *et al.*, 2022; Abelouah *et al*., 2024)

The study conducted in this region revealed that wood represented 1 % of the collected samples. Various anthropogenic wood items were noted, with associated species documented globally. These wood fragments primarily originate from either riparian areas, falling into the sea naturally or being introduced through recreational activities (Mantelatto *et al.*, 2020; Póvoa *et al*., 2022). In contrast, materials such as metal, glasses, and construction debris are generally not considered suitable substrates for species rafting due to their weight and structural properties that may sink in the water column or air reservatories (Mantelatto *et al*., 2020; P´ ovoa *et al*., 2022; Kannan *et al*., 2023; Abe louah *et al*., 2024). Interestingly, some submerged litter may resurface due to disturbances on the ocean floor or the presence of air pockets, which can facilitate dispersion (Goldstein *et al*., 2014; Andrades *et al.*, 2018; Mantelatto *et al*., 2020; De-la-Torre *et al*., 2021).

Recognizing marine litter with fouled organisms in both open ocean and coastal regions is essential, as these species can sometimes be invasive, disrupting native fauna and species distribution worldwide (Póvoa *et al.*, 2021; De-la-Torre *et al.*, 2021). The diversity of marine litter with fouled organisms can influence future studies in urban areas by affecting sample design, identifying contamination sources, and determining sampling efforts (Rees and Pond, 1995; Velander and Mocogni, 1999; De-la-Torre *et al*., 2023). Additionally, physical, chemical, and biological factors play a role in the post-recruitment processes that determine species adherence to different marine litter materials (Al Khayat *et al.*, 2021; Mghili *et al*., 2022).

4.3. Physical-chemical characteristics of marine litter with fouled organisms

The buoyancy and stability of marine litter in the marine environment can be influenced by characteristics such as polymer type, density, color, roughness, texture, and the resistance of the objects (Goldstein *et al*., 2014; Fazey and Ryan, 2016; Mghili *et al*., 2022).

4.3.1. Degradation, shape geometric and surface

The present study found the highest presence of intact litter with cylindrical and irregular geometric shapes and intact and degraded, primarily in low and high energy beaches. The presence of litter from local sources suggests that larval settlement and colonization by marine organisms may be occurring in the studied area due to the presence of many recruits observed in the species identification. Such litter, including plastics and wood fragments, often provides stable and durable surfaces for larval attachment and the development of fouled organisms such as mollusks and crustaceans (Rech *et al.*, 2018; Rech *et al.*, 2021; Mghili *et al*., 2022), which are available in the region due to the presence of vessels from around the world (Puga *et al*., 2019; Amaral *et al*., 2020).

The significant differences in the geometric shapes and the aspect intact or fragmented, between high-energy and low-energy beaches can be attributed to the mechanical processes at play in these environments. High-energy beaches are subject to intense marine litter action and strong currents, which can alter the shape of waste items, leading to a predominance of irregularly shaped and fragmented litter (Póvoa *et al*., 2022). Conversely, low-energy beaches tend to preserve original characteristics of marine litter that retain smoother and rounded shapes due to the reduced abrasion forces acting on them (Browne *et al*., 2007). In low-energy beaches, where wave and current action is reduced, these materials tend to experience less degradation and, consequently, remain along the strandline, creating a favorable environment for the colonization and growth of biological entities (Mghili *et al*., 2022). This study contradicts with Póvoa *et al.* (2022), which found a higher concentration of fragmented litter on beaches exposed to the open sea.

Fouled organisms can colonize the entire surface of an object or only parts of it, depending on the orientation and geometric shape resulting from the material's degradation stage, especially in cylindrical objects (Rech *et al*., 2018; Shabani *et al*., 2019; Póvoa *et al.*, 2022). The colonization of plastic bottles in marine environments, including brackish areas, significantly affects marine ecology by providing substrates for organisms and trapping macroinvertebrates (Gallitelli *et al.*, 2023). These bottles create artificial habitats for species such as algae, mollusks, and small crustaceans, which attach to their surfaces or seek refuge inside (Gallitelli *et al.*, 2023). The internal surfaces offer protection from predators, making them attractive for colonization (Barnes and Milner, 2005). Additionally, the narrow neck design of the bottles facilitates a trapping effect, increasing mortality rates among macro invertebrates and disrupting local community structures (Gall and Thompson, 2015). In brackish environments, this impact is particularly pronounced, affecting organisms that rely on specific habitats (Gallitelli *et al.*, 2023).

Biological interactions between different fouled organisms and marine litter are important in the species-area relationship due to the geometric shape of the waste (Ryan, 2015; Al Khayat *et al.*, 2021; Mghili *et al.*, 2022). Larger objects are more likely to be recognized as substrates and to be colonized by pelagic larvae (Thiel and Gutow, 2005; Shabani et al., 2019). Additionally, Ye and Andrady (1991) reported that marine litter with larger surface areas is colonized by macro invertebrates more rapidly. The diversity of shapes and sizes of marine litter presents challenges in standardizing studies on *rafting* (Ryan, 2015; Póvoa *et al.*, 2021).

Marine litter with fouled organisms showed a significant difference between smooth and rough surfaces on high-energy and low-energy beaches. In high-energy beaches, the intense action of waves and currents tends to destabilize materials with smooth surfaces, making it difficult for organisms to attach. In contrast, rough surfaces provide more anchorage points and microhabitats, facilitating colonization by fouled organisms, even under conditions of greater turbulence (Póvoa *et al.*, 2022; De-la-Torre *et al.*, 2023). Smooth surfaces may result in lower colonization rates because the lack of irregularities limits the attachment of organisms (Abelouah *et al.*, 2024).

Our results demonstrated the presence of fouled organisms on marine litter associated mainly with rough surfaces, corroborating findings from beaches in the Persian Gulf and Morocco (Battaglia *et al.*, 2019; Abelouah *et al.*, 2024). Substrate roughness plays a fundamental role in the initial establishment of organisms, influenced by the microscopic movements of larvae during the early stages of biofilm formation (Koehl, 2007).

The fragmentation of marine litter contributes to the formation of rough surfaces conducive to the settlement of organisms such as bryozoans and barnacles mainly in oceanic areas (Goldstein *et al.*, 2014; Rech *et al.*, 2018, 2021; Abelouah *et al.*, 2024). While rough surfaces are particularly favorable for the rafting community, sessile organisms such as polychaetes, bryozoans, and hydrozoans (Kiessling *et al.*, 2015; Rech *et al.*, 2018) can also colonize smooth surfaces. The levels of fouling by marine biota can be influenced by factors such as the shape, surface stiffness, and roughness of marine litter (Póvoa *et al*., 2022; Mghili *et al*., 2022). However, the fragmentation of various types of marine litter occurred due to prolonged exposure to wind, solar radiation, and wave action in marine environments, can enhance colonization by creating rough surfaces (Goldstein *et al.*, 2014; Rech *et al.*, 2018; Póvoa *et al*., 2022; Abelouah *et al*., 2024).

Recent studies emphasize the significant influence of substrate texture on the rafting community, highlighting its importance in the colonization of marine litter by larvae available in the water (Thiel and Gutow, 2005; Rech *et al.*, 2021; Kannan *et al.*, 2023). Experiments such as the one conducted by Pinochet *et al*. (2019) on larval settlement on plastic and construction material with bryozoan species concerning roughness and material type could be insightful. In this study, we also observed the highest density of fouled organisms on internal surfaces of marine litter, which are submerged below the strandline. This suggests that these organisms may colonize internal surfaces to seek protection from solar radiation, desiccation, mechanical damage, winds, and rainfall, as also observed by Rech *et al.* (2021) in the South Pacific.

4.3.2 Colors

The current study observed a higher abundance of fouled organisms associated with white, red, and blue shades on marine litter, with no statistically significant difference noted in coloring ($p > 0.05$). The absence of a significant difference in the color of marine litter with fouled organisms can be attributed to several factors related to the environmental conditions and biological processes involved. Firstly, the color of waste materials may not significantly influence the colonization by encrusting organisms, as these organisms often rely more on surface texture and chemical cues for attachment rather than color (Carve *et al.*, 2019)

A range of physical, chemical, and biological factors may influence this color variation. The color blue may have been one of the most abundant due to the durability of the pigment, as well as its resistance to heat and sunlight as reported by Trindade *et al.* (2023). Additionally, light colors such as white, red, and transparent are commonly observed due to oxidative processes. These oxidative processes alter the chemical composition of the litter, leading to discoloration and the formation of new hues. This can affect not only the appearance of the debris but also its interactions with the environment and the organisms that establish themselves on it (Faruk Çullu *et al*., 2021).

The study suggests that this potential selectivity could be linked to various adaptive strategies, including camouflage, habitat selection, sexual attraction, thermoregulation, and defense against parasites and predators (Gilby *et al*., 2012). For instance, in areas where the landscape is predominantly bright, white litter may offer effective camouflage. Additionally, the color of marine litter could affect heat absorption and dissipation (Gilby *et al*., 2012). Another consideration is that the presence of red-colored litter may be associated with toxicity protection in certain organisms, deterring predators due to perceived harmfulness (Cortesi and Cheney, 2010; Gilby *et al*., 2012).

Some species exhibit a potential preference for colonizing substrates of darker tones, such as red and blue, as supported by prior research (Su *et al*., 2007; Satheesh and Wesley, 2010; Chase *et al*., 2016)). Notably, examples like the bryozoan Amphiblestrum osburni (Powell, 1968) found on a blue plastic cup highlight this preference (Brandler and Carlton, 2023). Another study in the South Pacific noted a higher presence of fouled organisms on black-colored marine litter, possibly due to exposure to sunlight and the organisms' affinity for rocky shores (Rech *et al.*, 2021).

4.3.3. Polymer type

The most prevalent types of polymers in this study were PET and PP, which are also the most abundant polymers in other places of the world such as Chile, Peru and Spain, for example (De-la-Torre *et al.*, 2021; Rech *et al.*, 2021; Subías-Baratau *et al*., 2022). The significant difference in the embedding of MLFO may be subject to the resistance to fragmentation varies among polymers. More robust materials, such as high- density polyethylene (HDPE), tend to be less prone to degradation in high-energy environments, where intense wave action may cause less structural damage (Lebreton *et al.*, 2017). In contrast, more fragile polymers, such as polystyrene (PS), are more susceptible to breaking under intense movement, resulting in a greater quantity of fragments on high-energy beaches (Geyer *et al*., 2017).

Additionally, the rate of chemical and biological degradation of the polymers also plays an important role. Polymers that contain additives promoting biodegradation may fragment more rapidly in high-energy environments, where exposure to UV light and the activity of decomposing organisms are more pronounced (Sharma and Chatterjee, 2017). This accelerated degradation can lead to a higher proportion of fragmented waste compared to that found on low-energy beaches, where conditions are more stable, and degradation occurs more slowly.

These polymers are widely produced and commercially available worldwide (PlasticsEurope, 2021). The polymers most found in the oceans are the same ones used in bottles, disposable packaging, food containers, shampoo bottles, bottle caps, and disposable facemasks (UNEP, 2018; Belli *et al*., 2024). Fouled organisms have been observed to colonize various plastic polymers, including PET, PP, and EPS (De-la- Torre *et al.*, 2021; Abelouah *et al.*, 2024).

While some studies suggest significant variations in species abundance and diversity among different types of plastics such as PP, PE, and PET (Gündo˘ gdu *et al.,* 2017). Research by De Tender *et al.* (2015) indicates that the structural and chemical properties of various polymer types can influence bacterial communities. However, De-la-Torre et al. (2021) propose that fouled biota does not exhibit a specific preference for a particular polymer type. The reasons for associations with certain polymers remain unclear but may be related to the biofilm formed on each type of polymer (Morohoshi *et al.*, 2018).

Rech *et al.* (2021) reported a low diversity of plastic polymers on Chilean beaches, which did not suffice to explain a potential preference regarding polymer type. Similarly, the study by De-la-Torre *et al*. (2021) in the coastal region of Peru did not find a high density of PET residues, unlike the findings in the present study. PET is associated with the presence of bottles and some textiles, while PA originates from fishing nets (De-la-Torre *et al.,* 2021). Recent studies underscore the importance of confirming the composition of plastic litter through FTIR spectroscopy, as well as analyzing the surface microstructure and hydrophilicity of items. However, there is currently limited research addressing the preference of fouled organisms for different types of plastic polymers (De-la-Torre *et al*., 2021; Mghili *et al*., 2023). The lack of financial resources in Brazil leads to limitations in the identification of marine litter with fouled organisms (De-la-Torre *et al.*, 2023).

4.4 Abundance, diversity, similarity and identification of marine litter with fouled organisms

Various species associated with marine litter, including bryozoans, mollusks, polychaetes, and others have been documented in studies conducted worldwide, particularly on plastic items (Póvoa *et al*., 2021; De-la-Torre *et al*., 2023; Kannan *et al.,* 2023; Abelouah *et al.*, 2024). The findings of the present study partially align with those of Póvoa et al.

(2022). However, the comparisons have some limitations, as they are influenced by the heterogeneity of methodologies in previous studies for assessing the presence of marine litter with fouled organisms, as demonstrated by De-la-Torre *et al*. (2023) and Mghili *et al*. (2023).

A wide range of species are found in association with marine litter globally (Barnes and Fraser, 2003; Goldstein *et al*., 2014; Carlton *et al.*, 2017; Póvoa *et al.*, 2021; Mghili *et al*., 2023; Abelouah *et al.*, 2024). The taxa found in this study, such as *Hydroides elegans* (Haswell, 1883), *Hydroides* sp., barnacles of the Balanidae family, *Jellyella tuberculata* (Bosc, 1802) and *Saccostrea cuculatta* (Born, 1778), have already been found in other locations around the world, such as the Persian Gulf, the Pacific and the Indian Ocean (Rech *et al.*, 2018; Shabani *et al*., 2019; Cesarini *et al.*, 2022; Kannan *et al*., 2023). For instance, the green mussel *Perna viridis* (Linnaeus, 1758) has been observed on litter not only in Brazil but also in Colombia and India (Rangel-Buitrago *et al*., 2020; Kannan *et al.*, 2023; Soares *et al.*, 2023). The mussel *Perna perna* (Linnaeus, 1758) has been observed in Brazil in plastics (Neves et al., 2024). The gastropod *Crepidula* sp., the mussel *Perna viridis* (Linnaeus, 1758) and the sponge Haliclona sp. were found for the first time associated with marine litter in Southwest Atlantic, although they are already reported in other parts of the world (Elvin *et al*., 2018).

Records of various organisms in different locations worldwide evidence the dispersal of species via marine litter. For instance, the alga Pyropia sp. has been found in British Columbia, while the gastropod *Littorina saxatilis* (Olivi, 1792) has become a global issue (Lindstrom, 2018; Póvoa *et al*., 2021). Additionally, tropical corals such as *Favia fragum* (Esper, 1793) and *Astrangia poculata* (Ellis and Solander, 1786) have reached the Netherlands, likely originating from the southwest United States, possibly transported by the Gulf Stream (Hoeksema *et al*., 2012; Hoeksema and Hermanto, 2018). Similarly, native Japanese species such as *Magallana gigas* (Thunberg, 1793) and *Schizoporella japonica* (Ortmann, 1890) have been discovered fouled in marine litter on North American and Canadian beaches, suggesting potential trans oceanic dispersion (Simkanin et al., 2019). Some of these rafting in vertebrates, like *Isognomon bicolor* (Adams, 1845) and *Perna viridis* (Linnaeus, 1758) bivalves, and the bryozoan *Membraniporopsis tubigera* (Osburn, 1940), are known to have environmental impacts such as ecosystem alteration, changes in community structure, decline of native species and pathogen transmission through resistance genes found on plastic (Soares *et al*., 2023; Magalhães *et al*., 2024).

The results indicate moderate diversity and an even distribution of species across the studied beaches, with no significant differences between high- and low-energy beaches or between dry and rainy seasons. This suggests strong ecological connectivity, enabling species dispersion through currents or larval movement (Defeo *et al.*, 2003; Risoli *et al.*, 2023). Local factors like resource availability and substrate suitability appear to have a greater influence on species distribution than beach energy (Cordeiro *et al.*, 2024).

The community is predominantly composed of polychaetes, barnacles, and bryozoans. Barnacles are considered obligate rafts with a strong cosmopolitan distribution (Rech *et al*., 2018; Abelouah *et al*., 2024). These organisms, known for their cosmopolitan distribution and ability to raft on marine litter, are commonly associated in Brazil (Skinner *et al*., 2016; Rech *et al*., 2018; Póvoa *et al*., 2022; Abelouah *et al*., 2024). Bryozoa are frequently associated with plastic and exhibit high species richness (Mghili *et al*., 2022).

The number of taxa found in the study area (21) was higher than that found in other locations worldwide, such as the Ilha Grande Bay beaches and like those found at Moroccan beaches and Persian Gulf and lower than that found in the Catalan Sea in Spain (**Tab. 4**).

Tab.4. The number of taxa found in marine litter around the world.

Reference	Study area	Number of taxons
Mantelatto *et al.,* 2020	Ilha Grande bay	2
Ibabe *et al.,* 2020	Spanish beaches	3
Węsławski e Kotwicki, 2018	Canadian beaches	4
De-la-Torre *et al.,* 2021	Peruvian beaches	5
Cesarini *et al.,* 2022	Italian beaches	9
Póvoa *et al.,* 2022	Ilha Grande bay beaches	11
Mghili *et al.,* 2022	Morrocan beaches	13
Al-Khayat *et al.,* 2021	West coast of Qatar	18
Shabani *et al.,* 2019	Persian Gulf	21
Abelouah *et al.,* 2024	Morrocan beaches	21
Subías-Baratau *et al.,* 2022	Catalan sea	26

The identification of organisms associated with marine litter poses challenges, often due to damaged essential structures hindering accurate identification. Loss or damage of vital taxonomic structures, such as opercula in serpulids or zooids in Bryozoa, limits precise taxonomic identification (Póvoa *et al*., 2021; Hove *et al*., 2009; Vieira *et al*., 2015; Pitombo, 2004). Additionally, the lack of accessibility for various researchers and insufficient interest from taxonomic specialists further complicates the identification process (Póvoa *et al.*, 2021).

Efforts toward taxonomic identification need enhancement, as emphasized in recent studies (Póvoa *et al*., 2021; Mghili *et al*., 2022; De- la-Torre *et al.*, 2023; Kannan *et al*., 2023; Abelouah *et al*., 2024). Genetic sequencing through DNA or RNA analysis, such as barcoding, has been suggested but faces challenges due to resource limitations in emerging countries and the absence of barcode sequence libraries (De-la-Torre *et al.*, 2023; Mghili *et al.*, 2023; Abelouah *et al.*, 2024).

Sessile organisms predominantly colonize marine litter from the larval stage, a trend consistent with previous findings (Póvoa *et al*., 2021; De-la-Torre *et al*., 2023; Mghili *et al*., 2022; Abelouah *et al*., 2024). This prevalence of sessile species can be attributed to the potential migration of mobile taxa, influenced by decreased habitat suit ability or displacement post-deposition (Shabani *et al*., 2019; Al Khayat *et al*., 2021; Mghili *et al*., 2022). However, according to De-la-Torre *et al*. (2023) marine litter can also act as vectors for mobile species.

Success in colonization depends on characteristics such as suspension feeding or autotrophy, rapid expansion through asexual reproduction, short life cycles, and tolerance to environmental variations (Murray *et al*., 2012; Kiessling *et al.*, 2015). However, survival post- dispersal faces challenges due to abiotic and biotic factors, including temperature, salinity, competition, and predation (Hoeksema *et al*., 2012; Carlton *et al.,* 2017; Simkanin *et al*., 2019).

Observations on beaches indicate recent recruitment of various organisms on marine litter items, particularly barnacles, polychaetes, and oysters, suggesting recent colonization. The presence of juvenile individuals indicates the early settlement phase, highlighting ongoing recruitment processes and larvae in the water column seek substrates for colonization, and marine litter serves as a substrate for the settlement of diverse fouled organisms (Petracco *et al.*, 2023).

4.4.1. Classification of organisms according to the stage of biological invasion population

Most species associated with marine litter are originally from the Pacific or Indo-Pacific regions and have a global distribution around the world (Supplementary Material 1). Most species associated with marine litter are invasive or cryptogenic, indicating uncertain biogeographical origins. This aligns with findings by Póvoa *et al*. (2022), Kannan *et al*.

(2023) and Abelouah *et al*. (2024) in different regions, contrasting with studies in Chilean and Moroccan beaches (Rech *et al*., 2018; Mghili *et al*., 2022). Plastic pollution on beaches may contribute significantly to the introduction of invasive species, posing ecological concerns (Cesarini *et al*., 2022; Mghili *et al.*, 2022; Abelouah *et al*., 2024). *Rafting* marine litter can introduce organisms to new environments, affecting native fauna through competition for resources, thus termed invasive species (Thiel and Gutow, 2005; Thiel and Haye, 2006; Gall and Thompson, 2015). Examples include the vermetid *Petaloconchus varians* (d'Orbigny, 1839) and sun corals *Tubastraea tagusensis* (Wells, 1982) and *Tubastrea coccinea* (Ehrenberg, 1834) reported in Brazilian coastal regions (Breves and Skinner, 2014; Faria and Kitahara, 2020; Mantelatto *et al*., 2020).

The presence of invasive and cryptogenic species suggests transoceanic dispersal facilitated by different types of marine litter acting as vectors (Póvoa *et al.*, 2022; Kannan *et al*., 2023). Species like bryozoans *Jellyella tuberculata* (Bosc, 1802) and *Jellyella eburnea* (Hincks, 1891) and barnacle *Amphibalanus amphitrite* (Darwin, 1854), are commonly associated with marine litter globally (Goldstein *et al*., 2014; Kiessling *et al*., 2015; Carlton and Fowler, 2018; McCuller and Carlton, 2018; Rech *et al.*, 2021; Mghili *et al.*, 2023; Abelouah *et al*., 2024).

In the studied region, the introduction of species likely occurred through fouling, as the area receives species from around the world due to the presence of the Port of Rio de Janeiro, which brings various impacts (Santos *et al.*, 2023; Madon *et al*., 2023). The presence of invasive species associated with marine litter suggests that the colonization of this debris is occurring within the region itself. Given the role of urban coastal areas as potential hotspots for invasive species, monitoring efforts should prioritize these regions, especially in port and marina areas (Mghili *et al*., 2022; Kannan *et al*., 2023; Abelouah *et al*., 2024). Reports indicate the presence of various species attached to marine litter in a hotspot located in the Cagarras Islands, an area close to the research site. However, the authors did not observe the occurrence of invasive species associated with marine litter (Neves *et al*., 2024).

The Covid-19 pandemic introduced new types of polymers in beaches, which can act as substrates for invasive species, raising public health concerns, as well as the presence of bacteria and antibiotic resistance genes in plastic (Ribeiro *et al*., 2021; De-la-Torre *et al.*, 2021; Mghili *et al.*, 2022; Magalhães *et al*., 2024). Cleanup campaigns, environmental education, and active monitoring of vessels are recommended to control the entry and spread of invasive species through marine litter (Bouzekry *et al*., 2022; Mghili *et al*., 2023; Andrés *et al*., 2021).

Beach clean-ups can serve as effective conservation actions, as marine litter threatens various ecosystem components. However, these efforts should adhere to specific criteria and careful planning to prevent unintentional harm, especially in fragile sandy beach or dune ecosystems, where unplanned clean-ups may lead to excessive trampling or sand removal. Essential steps include context analysis, input and planning, activity execution, and monitoring (Battisti *et al*., 2020b). Continuous monitoring is vital for effective risk management and conservation of marine ecosystems (Mghili *et al*., 2023).

5. Conclusions and recommendations

The high concentration of marine litter, particularly plastic, on the beaches of Niteroi reflects the challenges of urban development and inadequate waste management. Both high-energy and low-energy beaches are impacted by local and external litter sources, necessitating effective cleaning strategies. Addressing these issues is crucial for protecting marine biodiversity and fostering sustainable coastal ecosystems. Urgent action is needed to mitigate pollution and enhance community awareness regarding waste disposal.

The research revealed a notable accumulation of fouled marine litter in beaches of low energy, particularly in comparison to neighboring sites. To enhance our understanding of marine litter dispersion, we suggest future investigations incorporate modeling techniques that consider oceanographic variables such as modeling of sea currents, wind patterns, and continental drainage.

Based on our analyses, fouled marine litter is primarily found on intact or degraded items that are cylindrical or irregular in shape, with rough surfaces, in various shades, and composed mainly of PET and PP polymers. We recommend dedicated experiments to explore larval settlement dynamics, specifically examining how factors like roughness and material composition influence the establishment of marine organism larvae on different types of litter. This research will enhance our understanding of colonization patterns and inform effective management practices. Additionally, further studies using FTIR (Fourier Transform Infrared Spectropy) are necessary to investigate species selectivity regarding color and to confirm larval settlement on various plastic polymers. Recent observations on beaches indicate the recruitment of organisms such as barnacles, polychaetes, and oysters, suggesting ongoing colonization. In terms of practical measures, we propose implementing signage in port and marina areas to monitor various marine litter items and evaluate waste management strategies. Additionally, we recommend comprehensive assessments and analyses of bacterial biofilms, including potential pathogens and resistance genes, associated with different types of marine litter found on beaches. Such initiatives can contribute to both environmental conservation efforts and public health protection. Thus, project-oriented approaches to beach cleaning not only improve the health of coastal ecosystems but also foster a culture of environmental stewardship.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2024.117394.

CRediT authorship contribution statement: Alain Alves Póvoa: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. Luiza Reis de Souza: Writing – review & editing, Investigation, Conceptualization. Igor Rodrigues Henud: Writing – review & editing, Investigation. Mariana Gonçalves Tavares: Writing – review & editing, Investigation. Renan Martins Amorim: Writing – review & editing, Software. Abilio Soares-Gomes: Writing – review & editing, Writing – original draft, Supervision.

Financing: CAPES (Coordenação de Aperfeiçoamento Pessoal de Nível Superior).

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Reports a relationship with that includes: Has patent pending to. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank Dra Ana Brasil and Msc. Andrielle Rodrigues by identifying polychaets, Dr. Fábio Pitombo and Dr. Rodrigo Soares Pessanha D’almeida by identifying barnacles, Dr. Ana Carolina Almeida by identifying bryozoans, Dr. Igor Mihayra and Dra Vanessa Simão by identifying bivalve mollusks and Graduating Carlos Martins Sigmaringa by identifying gastropod mollusks. Dr. Humberto Fortunato by identifying sponges. Authors would like to thank various referees for all the suggestions and reviews of this manuscript. We appreciated the help of the graduate students who often assisted in the field. We also appreciate the support provided by the UFF (Federal Fluminense University).

Data availability

No data was used for the research described in the article.

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10. CONSIDERAÇÕES FINAIS

O presente estudo apresentou como objetivo geral realizar uma revisão cientométrica de estudos sobre resíduos sólidos ao longo de praias arenosas do Atlântico demonstrando o estado atual do conhecimento do tema complementado pela aplicação de estudos de caso utilizando o município de Niterói como modelo, localizado na região Sudeste do Atlântico, como área para investigar a relação entre resíduos sólidos e a biota associada. A pesquisa foi estruturada em três capítulos interligados, cujas hipóteses foram confirmadas ou parcialmente confirmadas, nas quais oferecem um panorama abrangente sobre a presença, a composição e os impactos ecológicos dos resíduos sólidos em praias arenosas.

No Capítulo 1, a hipótese de que não há uma compilação sistematizada de informações sobre resíduos sólidos em praias arenosas ao longo do Atlântico foi confirmada. A análise cientométrica revelou uma concentração de estudos na América do Sul e na Europa, com lacunas evidentes em outras regiões, como África e América do Norte. Este panorama evidenciou a necessidade de padronização metodológica e ampliação das pesquisas em áreas subamostradas, reforçando deste modo a importância do mapeamento global integrado por meio do gerenciamento costeiro e interligando as relações das mudanças climáticas com os resíduos sólidos.

O Capítulo 2 avaliou a presença da microbiota associada aos resíduos sólidos, comparando diferentes tipos de materiais e o sedimento de praias. As hipóteses foram parcialmente confirmadas, demonstrando que a comunidade microbiana difere significativamente em função das propriedades físico-químicas do tipo de substrato, mas que estas variações da comunidade microbiana não diferem entre praias estuarinas e oceânicas. Este achado reforça o papel do tipo de substrato como fator determinante para a estruturação da comunidade microbiana, uma vez que estes substratos artificiais atuam como vetores de patógenos.

O Capítulo 3 avaliou a presença de macro-organismos incrustantes sobre resíduos sólidos e as características físico-químicas associadas, bem como suas relações com os resíduos como vetores de invasão biológica marinha. As hipóteses também foram parcialmente confirmadas: a quantidade de resíduos diferiu entre os períodos secos e chuvosos, mas não entre praias de alta e baixa energia. Por outro lado, os resíduos com organismos incrustantes apresentaram diferenças entre praias de alta e baixa energia, mas não entre os períodos sazonais.

Neste terceiro capítulo também foi avaliado as características físico-químicas dos resíduos com incrustações biológicas, as quais foram observadas diferenças significativas em relação ao estágio de degradação, ao formato geométrico, a orientação da superfície e ao tipo de polímero, mas a cor não apresentou influência significativa. Este achado sugere que a cor do tipo de substrato não é um fator preponderante para a colonização dos organismos incrustantes, enquanto as demais características físicas e estruturais desempenham funções importantes. Ainda, destacou-se a maior predominância de espécies invasoras ou criptogênicas associadas aos resíduos, apontando para riscos ecológicos relevantes relacionados ao transporte das espécies por meio dos resíduos sólidos, uma vez que estas espécies utilizam os resíduos como vetores.

Esses três capítulos, integrados delineiam um quadro multidimensional sobre a problemática dos resíduos sólidos nas praias arenosas do Atlântico o que demonstra a escassez de dados consolidados em escala regional e global quanto os processos ecológicos que envolvem a colonização dos organsimos em diferentes tipos de substratos artificiais, feitos pelo homem. A ausência de uma base de dados de estudos científicos integrados, evidenciada no Capítulo 1 limita a capacidade de comparação entre diferentes regiões e compromete a formulação de políticas públicas eficazes. Os Capítulos 2 e 3 demonstram que os resíduos sólidos não devem ser vistos apenas como poluentes estéticos, mas também como agentes na estruturação de comunidades biológicas, no qual desempenham funções relevantes como como vetores de diversas espécies, dentre as quais diversos organismos patogênicos que podem compremeter a saúde de outros organismos e dos seres humanos ocasionando impactos sociais, econômicos e estéticos.

Diante desse cenário, é necessário reformular as estratégias de gerenciamento costeiro com a incoroporação de uma perspectiva ecológica que reconheça os resíduos sólidos como elementos da paisagem. A influência das propriedades físico-químicas dos materiais na composição das comunidades aderidas, bem como a presença de espécies invasoras ou criptogênicas colonizando os diferentes tipos de resíduos reforçam o risco de impactos significativos que demandam uma atenção imediata do Poder Público.

Diante das evidências levantadas neste presente estudo, uma vez que diversas frentes de pesquisa precisam ser ampliadas para avançar na compreensão do tema para perspectivas futuras. Nesse sentido, é necessário a criação de uma base de dados integrada, padronizada e georreferenciada, na qual é essencial para permitir a comparação entre diversas regiões e subsidiar ações orientadas às políticas públicas eficazes. Além disso, futuras investigações devem explorar a funcionalidade das comunidades microbianas associadas aos resíduos por meio das tecnologias “ômicas” como metagenômica, metabolômica e análises de resistência a antibióticos com o objetivo de compreender os riscos ecológicos e sanitários decorrentes dessas interações.

Além disso, seria fundamental ampliar investigações experimentais sobre a colonização de organismos em resíduos sólidos, no qual deve considerar as propriedades físico-químicas dos polímeros e os diferentes regimes hidrodinâmicos que influenciam a colonização e a dispersão dessas comunidades. Essas pesquisas devem combinar coletas experimentais e amostras de resíduos flutuantes, integrando análises microbiológicas e macrobiológicas, no qual devem incluir a aplicação de métricas ecológicas como riqueza, diversidade e composição funcional, considerando um enfoque especialmente na identificação de espécies que podem ser consideradas como exóticas, invasoras ou criptogênicas para a melhor compreensão deste processo. A identificação das espécies incrustantes é outro ponto que precisa ser melhorado, pois pode ser realizado por meio de análises genéticas considerando o gene COI para a identificação das espécies, o que possivelmente pode confirmar a mudança de nome de algumas espécies através de uma biblioteca digital utilizada em estudos genéticos como o GenBank (Banco de Dados Genéticos).

No âmbito prático, é urgente incorporar os resíduos sólidos como elementos ativos da dinâmica ecológica costeira nas estratégias de gestão e planejamento. Ferramentas de modelagem espacial podem ser utilizadas para prever rotas de transporte e áreas doadoaras e receptoras, bem como áreas de acúmulo de resíduos, no qual auxiliam em processos de tomada de decisões pelo Poder Público. Além disso, ações de educação ambiental que abordam os resíduos como vetores biológicos são essenciais para sensibilizar a sociedade e fomentar o engajamento em programas de ciência cidadã e monitoramento participativo. Assim, integrar ciência, política e sociedade pode ser considerada como uma estratégia indispensável para mitigar os impactos dos resíduos sólidos e assegurar a conservação e resiliência das praias arenosas diante das crescentes pressões antrópicas.

Por fim, a abordagem integrada entre ciência, gestão e engajamento social evidenciada neste estudo representa um caminho promissor para enfrentar os desafios impostos pelos resíduos sólidos nas praias arenosas. A conjugação de Políticas Públicas eficazes fundamentadas em evidências científicas e estratégias de educação ambiental e participação comunitária configura como uma resposta eficaz para promover a conservação das praias arenosas. Reconhecer os resíduos sólidos como vetores ecológicos não é apenas uma alternativa, mas uma necessidade para preservar a resiliência ecológica das praias. Assim, o presente estudo contribui para a reformulação das estratégias de gerenciamento costeiro, ressaltando a urgência de ações interdisciplinares e colaborativas voltadas à proteção e sustentabilidade das praias arenosas do Atlântico.

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APÊNDICE I – MATERIAL SUPLEMENTAR DO CAPÍTULO 1.

Number	Reference	Title	Year	Platform	Country	Theme	Periodic
1	10.1016/0025-326X(82)90038-8	Drift plastic—An expanding niche for a marine invertebrate?	1982	Scopus	USA	Rafting	Marine Pollution Bulletin
2	https://doi.org/10.1016/0025-326X(93)90574-4	Marine debris along the Caribbean coast of Panama	1993	Pubmed	Panamá	Monitoring	Marine Pollution Bulletin
3	https://doi.org/10.1016/0025-326X(93)90575-5	Marine debris contamination of beaches in St. Lucia and Dominica	1993	Pubmed	Santa Lucia and Dominica	Monitoring	Marine Pollution Bulletin
4	0025-326X/02/$	Quantification and classification of marine litter on the municipal beach of Ensenada, Baja California, Mexico	2003	Pubmed	Mexico	Quali-quantitative analysis	Marine Pollution Bulletin
5	https://doi.org/10.1016/j.ocecoaman.2004.01.002	The influence of the environmental status of Casa Caiada and Rio Doce beaches (NE-Brazil) on beaches users	2003	Pubmed	Brazil	Environmental perception	Ocean and Coastal Management
6	https://doi.org/10.1016/j.ocecoaman.2005.08.006	Influence of socio-economic characteristics of	2005	Pubmed	Brazil	Environmental perception	Ocean and Coastal

		beach users on litter generation					Management
7	https://doi.org/10.1016/j.marpolbul.2007.05.004	Marine debris review for Latin America and the Wider Caribbean Region: From the 1970s until now, and where do we go from here?	2007	Scopus	-	Review	Marine Pollution Bulletin
8	https://doi.org/10.2112/1551-5036(2007)23[421:QACOML]2.0.CO;2	1 March 2007Quantification and Classification of Marine Litter on Beaches along Armação dos Búzios, Rio de Janeiro, Brazil	2007	Pubmed	Brazil	Quali-quantitative analysis	Journal of Coastal Research
9	https://doi.org/10.1108/14777830710717677	An analysis of the riverine contribution to the solid wastes contamination of an isolated beach at the Brazilian Northeast	2007	Pubmed	Brazil	The riverine contribution	Management of Environmental Quality
10	10.1016/j.marpolbul.2009.05.004	Here, there and everywhere. Small plastic fragments and pellets on beaches of Fernando de Noronha	2009	Pubmed	Brazil	Quali-quantitative analysis	Marine Pollution Bulletin

		(Equatorial Western Atlantic)					
11	10.1177/0734242X08088705	Plastic litter on an urban beach — a case study in Brazil	2009	Pubmed	Brazil	Quali-quantitative analysis	Waste Management and Research
12	https://doi.org/10.1007/s10661-008-0175-z	Marine debris contamination along undeveloped tropical beaches from northeast Brazil	2009	Pubmed	Brazil	Monitoring	Environmental Monitoring and Assessment
13	https://doi.org/10.1016/j.marpolbul.2010.03.021	Trends and drivers of marine debris on the Atlantic coast of the United States 1997–2007	2010	Pubmed	USA	Monitoring	Marine Pollution Bulletin
14	https://doi.org/10.2112/JCOASTRES-D-09-00072.1	Marine Debris in the Island of Santa Catarina, South Brazil: Spatial Patterns, Composition, and Biological Aspects	2010	Pubmed	Brazil	Monitoring	Journal of Coastal Research
15	https://doi.org/10.1007/s10661-009-1113-4	On the importance of size of plastic fragments and pellets on the strandline: a snapshot of a Brazilian beach	2010	Pubmed	Brazil	Quali-quantitative analysis	Environmental Monitoring and Assessment

16	https://www.redalyc.org/articulo.oa?id=388340132002	Trends in Marine Debris in the U.S. Caribbean and the Gulf of Mexico 1996-2003	2011	Pubmed	Mexico	Monitoring	Journal of Integrated Coastal Zone
17	http://www.redalyc.org/articulo.oa?id=388340132005	Marine debris on Rio Grande do Sul north coast, Brazil: spatial and temporal patterns	2011	Pubmed	Brazil	Monitoring	Journal of Integrated Coastal Zone
18	http://www.redalyc.org/articulo.oa?id=388340132004	Seasonal, spatial and compositional variation of beach debris along of the eastern margin of Guanabara Bay (Rio de Janeiro) in the period of 1999-2008	2011	Pubmed	Brazil	Monitoring	Journal of Integrated Coastal Zone
19	http://www.redalyc.org/articulo.oa?id=388340132006	Assessing Public Perceptions on Marine Debris Contamination according to Beach Users' Profile: A Case Study in an Urban Beach of Northeast Brazi	2011	Pubmed	Brazil	Environmental perception	Journal of Integrated Coastal Zone
20	http://www.redalyc.org/articulo.oa?id=388340133005	Socio-economic profile of beach users and awareness	2011	Pubmed	Brazil	Environmental perception	Journal of Integrated

		on marine pollution by litter: Porto da Barra beach, BA, Brazil					Coastal Zone
21	http://www.redalyc.org/articulo.oa?id=388340132006	Assessing Public Perceptions on Marine Debris Contamination according to Beach Users' Profile: A Case Study in an Urban Beach of Northeast Brazi	2011	Pubmed	Brazil	Environmental perception	Journal of Integrated Coastal Zone
22	http://www.aprh.pt/rgci/pdf/rgci-395_Frias.pdf	Local marine litter survey - A case study in Alcobaça municipality, Portugal*	2013	Pubmed	Portugal	Monitoring	Journal of Integrated Coastal Zone
23	10.1016/j.marenvres.2013.08.013	A multi-criteria evaluation system for marine litter pollution based on statistical analyses of OSPAR beach litter monitoring time series	2013	Scopus	Sweden	Monitoring	Marine Environmental Research
24	http://www.redalyc.org/articulo.oa?id=388340142010	Environmental perception of the inhabitants of São Vicente city of solid	2013	Pubmed	Brazil	Environmental perception	Journal of Integrated Coastal Zone

		waste in Gonzaguinha Beach, São Paulo, Brazil					
25	http://dx.doi.org/10.12957/geouerj.2014.9884	Acúmulo da Deposição de Lixo em Ambientes Costeiros: O caso da praia oceânica de Piratininga	2014	Pubmed	Brazil	Quali-quantitative analysis	Revista GEOUERJ
26	https://doi.org/10.1016/j.marpolbul.2014.01.032	Influence of proximity to an urban center in the pattern of contamination by marine debris	2014	Pubmed	Brazil	Quali-quantitative analysis	Marine Pollution Bulletin
27	https://doi:10.15560/10.3.684	First records of the non-native bivalve Isognomon bicolor (C. B. Adams, 1845) rafting to the Uruguayan coast	2014	Pubmed	Uruguay	Rafting	CheckList
28	10.1016/j.marpolbul.2015.10.056	Beach debris in the Azores (NE Atlantic): Faial Island as a first case study	2015	Scopus	Portugal	Quali-quantitative analysis	Marine Pollution Bulletin
29	10.1016/j.marenvres.2015.03.005	Comparative analysis of time series of marine litter	2015	Scopus	Sweden	Quali-quantitative analysis	Marine Environmental Research

		surveyed on beaches and the seafloor in the southeastern North Sea					
30	https://doi.org/10.1016/j.marpolbul.2014.12.036	Spatial–temporal analysis of marine debris on beaches of Niterói, RJ, Brazil: Itaipu and Itacoatiara	2015	Pubmed	Brazil	Monitoring	Marine Pollution Bulletin
31	10.1016/j.marpolbul.2016.06.039	Debris size and buoyancy influence the dispersal distance of stranded litter	2016	Scopus	South Africa	Monitoring	Marine Pollution Bulletin
32	10.1016/j.marpolbul.2016.03.039	Beach debris on Aruba, Southern Caribbean: Attribution to local land-based and distal marine-based sources	2016	Scopus	Aruba	Monitoring	Marine Pollution Bulletin
33	https://doi.org/10.1016/j.envpol.2016.08.041	Plastics and microplastics on recreational beaches in Punta del Este (Uruguay): Unseen critical residents?	2016	Pubmed	Uruguay	Environmental percpeptiom	Environmental Pollution
34	https://doi.org/10.1007/s10661-016-5544-4	Mapping marine debris across coastal	2016	Pubmed	Belize	Monitoring for techonoloy	Environmental monitoring and

		communities in Belize: developing a baseline for understanding the distribution of litter on beaches using geographic information systems					assessment,
35	https://doi.org/10.1016/j.marpolbul.2016.10.061	The influence of the intensity of use, rainfall and location in the amount of marine debris in four beaches in Niteroi, Brazil: Sossego, Camboinhas, Charitas and Flechas	2016	Pubmed	Brazil	Monitoring	Marine Pollution Bulletin
36	https://doi.org/10.1016/j.marpolbul.2017.02.061	Litter assessment on 99 Cuban beaches: A baseline to identify sources of pollution and impacts for tourism and recreation	2017	Pubmed	Cuba	Use of tourism	Marine Pollution Bulletin
37	https://doi.org/10.1016/j.ocecoaman.2017.01.021	Magnitudes, sources, and management of beach litter along the Atlantico department coastline, Caribbean coast of Colombia	2017	Pubmed	Colombia	Management	Ocean and Coastal Management

38	10.1016/j.marpolbul.2017.04.030	Marine debris in beaches of the Southwestern Atlantic: An assessment of their abundance and mass at different spatial scales in northern coastal Argentina	2017	Scopus	Argentina	Quali-quantitative analysis	Marine Pollution Bulletin
39	10.1016/j.scitotenv.2016.11.137	Marine anthropogenic litter on British beaches: A 10-year nationwide assessment using citizen science data	2017	Scopus	United Kingdom	Monitoring	Science of the Total Environment
40	10.1016/j.marpolbul.2017.06.045	OSPAR standard method and software for statistical analysis of beach litter data	2017	Scopus	Germany	Monitoring	Marine Pollution Bulletin
41	10.1016/j.marpolbul.2017.05.043	Geophysical features influence the accumulation of beach debris on Caribbean islands	2017	Scopus	A lot of countries	Geology of plastic	Marine Pollution Bulletin
42	https://doi.org/10.1016/j.marpol.2017.08.021	Differences in perception and reaction of tourist groups to beach	2017	Pubmed	Brazil	Use of tourism	Marine Policy

		marine debris that can influence a loss of tourism revenue in coastal areas					
43	10.1016/j.marpolbul.2018.05.038	Spatio-temporal variability of beached macro-litter on remote islands of the North Atlantic	2018	Scopus	Portugal	Monitoring	Marine Pollution Bulletin
44	10.1016/j.envpol.2018.01.096	Plastic pollution in islands of the Atlantic Ocean	2018	Scopus	Brazil	Review	Environmental Pollution
45	10.1016/j.marpolbul.2018.04.066	Marine litter in south Bay of Biscay: Local differences in beach littering are associated with citizen perception and awareness	2018	Scopus	Spain	Environmental perception	Marine Pollution Bulletin
46	10.1016/j.marpolbul.2018.04.037	Leave no traces – Beached marine litter shelters both invasive and native species	2018	Scopus	Sweden	Rafting	Marine Pollution Bulletin
47	https://doi.org/10.1016/j.marpolbul.2018.01.017	Beach litter and woody-debris colonizers on the Atlantico department Caribbean coastline,	2018	Pubmed	Colombia	Rafting	Marine Pollution Bulletin

		Colombia					
48	https://doi.org/10.1016/j.marpolbul.2018.09.040	Abundance and distribution of beach litter along the Atlantico Department, Caribbean coast of Colombia	2018	Pubmed	Colombia	Quali-quantitative analysis	Marine Pollution Bulletin
49	https://doi.org/10.1016/j.marpolbul.2018.10.009	Litter impacts on beach/dune systems along the Atlantico Department, the Caribbean Coastline of Colombia	2018	Pubmed	Colombia	Management	Marine Pollution Bulletin
50	https://doi.org/10.1016/j.marpolbul.2017.08.060	Quantification of marine macro-debris abundance around Vancouver Island, Canada, based on archived aerial photographs processed by projective transformation	2018	Pubmed	Canada	Quali-quantitative analysis for technology	Marine Pollution Bulletin
51	https://doi.org/10.1016/j.marpolbul.2018.04.061	Troubles in the paradise: Litter and its scenic impact on the North Santa Catarina island	2018	Pubmed	Brazil	Monitoring	Marine Pollution Bulletin

		beaches, Brazi					
52	https://doi.org/10.1016/j.marpolbul.2018.10.003	Marine debris in Trindade Island, a remote island of the South Atlantic	2018	Scopus	Brazil	Quali-quantitative analysis	Marine Pollution Bulletin
53	https://doi.org/10.1007/s11852-018-0615-z	A case study on the influence of beach kiosks on marine litter accumulating in Camboinhas beach, Southeast Brazil	2018	Scopus	Brazil	Relation witk kiosks	Journal of Coastal Conservation
54	https://doi.org/10.1016/j.marpolbul.2018.03.026	Marine debris on beaches of Arraial do Cabo, RJ, Brazil: An important coastal tourist destination	2018	Pubmed	Brazil	Use of tourism	Marine Pollution Bulletin
55	https://doi.org/10.3389/fmars.2018.00233	Anthropogenic Litter on Beaches With Different Levels of Development and Use: A Snapshot of a Coast in Pernambuco (Brazil)	2018	Pubmed	Brazil	Quali-quantitative analysis for technology	Frontiers in Marine Science
56	10.1016/j.marpolbul.2019.110544	Cost-effective monitoring of large micro- and meso-litter in tidal and flood accumulation	2019	Scopus	Norwegian	Monitoring	Marine Pollution Bulletin

		zones at south-western Baltic Sea beaches					
57	10.1016/j.csr.2019.04.016	Beach litter forecasting on the south-eastern coast of the Bay of Biscay: A bayesian networks approach	2019	Scopus	Spain	Monitoring	Continental Shelf
58	10.1016/j.marpolbul.2019.03.036	Spatial trends and drivers of marine debris accumulation on shorelines in South Eleuthera, The Bahamas using citizen science	2019	Scopus	Bahamas	Monitoring	Marine Pollution Bulletin
59	10.1016/j.marpolbul.2019.02.034	Marine litter and public involvement in beach cleaning: Disentangling perception and awareness among adults and children, Bay of Biscay, Spain	2019	Scopus	Spain	Environmental perception	Marine Pollution Bulletin
60	10.1016/j.marpolbul.2018.12.023	Accumulation and distribution of marine debris on barrier islands across the northern Gulf of	2019	Scopus	Mexico	Monitoring	Marine Pollution Bulletin

		Mexico					
61	https://doi.org/10.1016/j.ocecoaman.2019.104835	Litter impacts on cleanliness and environmental status of Atlantico department beaches, Colombian Caribbean coast	2019	Pubmed	Colombia	Management	Ocean and Coastal Management
62	https://doi.org/10.1016/j.marpolbul.2018.12.023	Accumulation and distribution of marine debris on barrier islands across the northern Gulf of Mexico	2019	Pubmed	Mexico	Monitoring	Marine Pollution Bulletin
63	https://doi.org/10.1016/j.rsma.2019.100771	Marine debris and pollution indexes on the beaches of Santa Catarina State, Brazil	2019	Pubmed	Brazil	Monitoring	Regional Studies in Marine Science
64	http://www.aprh.pt/rgci/pdf/rgci-n75_Silva.pdf | DOI:10.5894/rgci-n75	Diagnosis of the environmental perception of the users of Itaipu and Itacoatiara beaches regarding the presence of marine debris	2019	Pubmed	Brazil	Environmental percpetion	Journal of Integrated Coastal Zone
65	10.1016/j.scitotenv.2020.141474	Beach-dune morphodynamics	2020	Scopus	Portugal	Quali-quantitative	Science of the Total

		and marine macro-litter abundance: An integrated approach with Unmanned Aerial System				analysis for technology	Environment
66	10.3390/jmse8120966	Spatio-Temporal Variability of Anthropogenic and Natural Wrack Accumulations along the Driftline: Marine Litter Overcomes Wrack in the Northern Sandy Beaches of Portugal	2020	Scopus	Portugal	Monitoring	Journal of Marine Science and Engineering
67	10.1016/j.scitotenv.2020.139632	Mapping marine litter on coastal dunes with unmanned aerial systems: A showcase on the Atlantic Coast	2020	Scopus	Portugal	Monitoring for technology	Science of the Total Environment
68	10.1016/j.seares.2020.101929	The Bay of Biscay as a trapping zone for exogenous plastics of different sizes	2020	Scopus	Spain	Quali-quantitative analysis	Journal of Sea Research
69	10.1016/j.marpolbul.2020.111323	Marine litter arrived: Distribution and potential sources on an unpopulated atoll	2020	Scopus	Colombia	Monitoring	Marine Pollution Bulletin

		in the Seaflower Biosphere Reserve, Caribbean Sea					
70	10.1016/j.envpol.2020.114494	Beaches of the Azores archipelago as transitory repositories for small plastic fragments floating in the North-East Atlantic	2020	Scopus	Portugal	Quali-quantitative analysis	Environmental Pollution
71	10.1016/j.ocecoaman.2020.105118	Beach cleaning costs	2020	Scopus	Spain	Relation with cust	Ocean and Coastal Management
72	10.1016/j.rsma.2020.101050	Beach litter composition and distribution on the Atlantic coast of Cádiz (SW Spain)	2020	Scopus	Spain	Monitoring	Regional Studies in Marine Science
73	10.5614/j.eng.technol.sci.2020.52.1.8	Developing a Plastic Waste Management Program: From River Basins to Urban Beaches (Case Study)	2020	Scopus	Brazil	Riverine contributtion	Journal of Engineering and Technological Sciences
74	https://doi.org/10.1016/j.marpolbul.2020.111558	The impact of tourism on marine litter pollution on Santa Marta beaches, Colombian	2020	Pubmed	Colombia	Use of tourism	Marine Pollution Bulletin

		Caribbean					
75	https://doi.org/10.1016/j.marpolbul.2020.110909	The impact of anthropogenic litter on Colombia's central Caribbean beaches	2020	Pubmed	Colombia	Monitoring	Marine Pollution Bulletin
76	https://doi.org/10.1177/1178622120920268	Distribution of Plastic Debris in the Pacific and Caribbean Beaches of Panama	2020	Pubmed	Panama	Monitoring	Air, Soil and Water Research
77	https://doi.org/10.1016/j.envpol.2020.115495	Plastic litter pollution along sandy beaches in the Caribbean and Pacific coast of Colombia	2020	Pubmed	Colombia	Monitoring	Environmental Pollution
78	https://doi.org/10.1016/j.marpolbul.2020.111631	Socio-economic impacts of marine litter for remote oceanic islands: The case of the Azores	2020	Pubmed	Portugal	Environmental perception	Marine Pollution Bulletin
79	https://link.springer.com/article/10.1007/s11270-020-04517-x	A Comprehensive First Baseline for Marine Litter Characterization in the Madeira Archipelago (NE Atlantic)	2020	Pubmed	Portugal	Quali-quantitative analysis	Water, Air, & Soil Pollution

80	https://doi.org/10.1016/j.scitotenv.2020.139633	Density and composition of surface and buried plastic debris in beaches of Senegal	2020	Pubmed	Senegal	Quali-quantitative ananlysis	Science of the Total Environment
81	https://doi.org/10.1016/j.marpolbul.2019.110842	Anthropogenic litter on Brazilian beaches: Baseline, trends and recommendations for future approaches	2020	Scopus	Brazil	Review	Marine Pollution Bulletin
82	https://doi.org/10.1016/j.marpolbul.2020.111659	Marine litter and wood debris as habitat and vector for the range expansion of invasive corals (Tubastraea spp.)	2020	Scopus	Brazil	Rafting	Marine Pollution Bulletin
83	https://doi.org/10.1016/j.marpolbul.2020.111015	Initial beach litter survey in a conservation unit (Santa Isabel Biological Reserve, Sergipe) from northeast Brazil	2020	Pubmed	Brazil	Monitoring	Marine Pollution Bulletin
84	https://doi.org/10.1016/j.wasman.2020.04.026	Marine debris on a tropical coastline: Abundance, predominant sources and fate in a region	2020	Pubmed	Brazil	Quali-quantitative ananlysis	Waste Management

		with multiple activities (Fortaleza, Ceará, northeastern Brazil)					
85	10.1016/j.marpolbul.2021.112901	Methods for determining the geographical origin and age of beach litter: Challenges and opportunities	2021	Scopus	Norwegian	Monitoring	Marine Pollution Bulletin
86	10.1016/j.envpol.2021.117729	Message in a bottle: Assessing the sources and origins of beach litter to tackle marine pollution	2021	Scopus	South Africa	Rafting	Environmental Pollution
87	10.1016/j.scitotenv.2021.148009	Potential sources of marine plastic from survey beaches in the Arctic and Northeast Atlantic	2021	Scopus	Norwegian	Quali-quantitative analysis	Science of the Total Environment
88	10.1016/j.marpolbul.2021.112548	Arenas Blancas (El Hierro island), a new hotspot of plastic debris in the Canary Islands (Spain)	2021	Scopus	Spain	Monitoring	Marine Pollution Bulletin
89	10.1016/j.marpolbul.2021.112490	Spatial and size distribution of macro-litter on	2021	Scopus	Portugal	Quali-quantitative analysis for	Marine Pollution Bulletin

		coastal dunes from drone images: A case study on the Atlantic coast				technology	
90	https://doi.org/10.1016/j.envpol.2021.118168	The role of hydrodynamic fluctuations and wind intensity on the distribution of plastic debris on the sandy beaches of Paraná River, Argentina	2021	Pubmed	Argentina	Monitoring	Environmental Pollution
91	https://doi.org/10.3390/w13233455	Qualitative and Quantitative Beach Cleanliness Assessment to Support Marine Litter Management in Tropical Destinations	2021	Pubmed	Colombia	Quali-quantitative analysis	Water
92	https://doi.org/10.1016/j.marpolbul.2020.111837	Plastic pollution on the Colombian central Caribbean beaches	2021	Pubmed	Colombia	Monitoring	Marine Pollution Bulletin
93	https://doi.org/10.1016/j.ecss.2021.107195	Woody debris on beach environments: Magnitudes, collateral effects,	2021	Pubmed	Colombia	Monitoring	Marine Pollution Bulletin

		and management					
94	https://doi.org/10.1016/j.marpolbul.2021.112916	A baseline analysis of marine debris on southern islands of Belize	2021	Pubmed	Belize	Monitoring	Marine Pollution Bulletin
95	https://doi.org/10.3390/jmse9040412	Marine Litter on the Coast of the Algarve: Main Sources and Distribution Using a Modeling Approach	2021	Pubmed	Portugal	Monitoring for technology	Journal of Marine Science and Engineering
96	https://doi.org/10.1016/j.ocecoaman.2021.105940	Marine litter in the central Atlantic coast of Morocco	2021	Pubmed	Morocco	Monitoring	Ocean and Coastal Management
97	https://doi.org/10.1016/j.ocecoaman.2020.105400	Marine debris on the Brazilian coast: which advances in the last decade? A literature review	2021	Scopus	Brazil	Review	Ocean and Coastal Management
98	https://doi.org/10.1016/j.envpol.2021.116927	Spatio-temporal characterization of litter at a touristic sandy beach in South Brazil	2021	Pubmed	Brazil	Monitoring	Environmental Pollution
99	https://doi.org/10.1016/j.marpolbul.2021.112859	Daily environmental variation influences temporal patterns of marine debris	2021	Pubmed	Brazil	Monitoring	Marine Pollution Bulletin

		deposition along an estuarine outlet in southern Brazil					
100	https://doi.org/10.1016/j.marpolbul.2021.112743	Spatiotemporal variability of solid waste on sandy beaches with different access restrictions	2021	Pubmed	Brazil	Monitoring	Marine Pollution Bulletin
101	https://doi.org/10.1016/j.marpolbul.2021.111978	Marine litter on a highly urbanized beach at Southeast Brazil: A contribution to the development of litter monitoring programs	2021	Pubmed	Brazil	Monitoring	Marine Pollution Bulletin
102	10.1016/j.marenvres.2021.105345	Marine debris from the past - Contamination of the Brazilian shore by a WWII wreck	2021	Pubmed	Brazil	Rafting	Marine Pollution Bulletin
103	10.1016/j.marpolbul.2021.112021	Marine debris in the Fernando de Noronha Archipelago, a remote oceanic marine protected area in tropical SW Atlantic	2021	Scopus	Brazil	Monitoring	Marine Pollution Bulletin

104	https://doi.org/10.1016/j.marpolbul.2021.112532	Records of marine litter contamination in tropical beaches (Sergipe, Brazil) with different uses	2021	Pubmed	Brazil	Uses of litter	Marine Pollution Bulletin
105	https://doi.org/10.1016/j.rsma.2021.101865	Cleaning efficiency in a Southwestern Atlantic sandy beach	2021	Scopus	Brazil	Cleanning efficiency	Regional Studies in Marine Science
106	https://doi.org/10.1016/j.marpolbul.2022.114031	Plastic debris forms: Rock analogues emerging from marine pollution	2022	Scopus	Brazil	Quali-quantitative analysis	Marine Pollution Bulletin
107	10.1016/j.scitotenv.2021.152650	Occurrence and distribution of micro(meso)plastic-sorbed heavy metals and metalloids in sediments, Gulf of Guinea coast (SE Atlantic)	2022	Scopus	Guiana	Environmental perception	Science of the Total Environment
108	10.1016/j.ocecoaman.2022.106040	Public awareness of beach litter and alien invasions: Implications for early detection and management	2022	Scopus	Spain	Monitoring	Ocean and Coastal Management
109	10.1016/j.scitotenv.2021.152308	Heterogeneous weathering of polypropylene in the	2022	Scopus	A lot of countries of Europe	Monitoring for technology	Science of the Total Environment

		marine environment					
110	10.1016/j.marpolbul.2021.113307	Is coastal erosion a source of marine litter pollution? Evidence of coastal dunes being a reservoir of plastics	2022	Scopus	Portugal	Geology of plastic	Marine Pollution Bulletin
111	10.1016/j.marpolbul.2021.113187	Field observations in pebble beach habitats link plastiglomerate to pyroplastic via pebble clasts	2022	Scopus	Portugal	Monitoring	Marine Pollution Bulletin
112	https://doi.org/10.1016/j.envpol.2022.118919	The status of marine debris/litter and plastic pollution in the Caribbean Large Marine Ecosystem (CLME): 1980–2020	2022	Pubmed	A lot of countries of Caribe	Monitoring	Environmental Pollution
113	https://doi.org/10.5281/zenodo.6706296	Basura plástica y microplásticos: contaminantes emergentes presentes en sedimentos de una playa urbana del oriente venezolano	2022	Pubmed	Venezuela	Monitoring	Ciencia e Ingenieria
114	https://doi.org/10.1016/j.scitotenv.2021.151878	Where does marine litter hide? The Providencia and	2022	Pubmed	Colombia	Deposition with tides	Science of the Total Environment

		Santa Catalina Island problem, SEAFLOWER Reserve (Colombia)					
115	https://doi.org/10.25268/bimc.invemar.2022.51.1.996	Basura en el paraíso: desechos marinos en las playas de la isla de San Andrés, Reserva de Biosfera Seaflower, Caribe colombiano	2022	Pubmed	Colombia	Environmental perception	Boletín de Investiganciones Marinas y Costeras
116	https://doi.org/10.1016/j.marpolbul.2022.113392	Marine litter on sandy beaches with different human uses and waste management along the Gulf of Nicoya, Costa Rica	2022	Pubmed	Costa Rica	Monitoring	Marine Pollution Bulletin
117	https://doi.org/10.1016/j.marpolbul.2022.114048	Spatiotemporal variations in marine litter along the Gulf of Guinea coastline, Araromi seaside, Nigeria	2022	Pubmed	Nigeria	Monitoring	Marine Pollution Bulletin
118	https://doi.org/10.1016/j.marpolbul.2022.113347	Macroorganisms fouled in marine anthropogenic litter (rafting) arround a tropical bay in the	2022	Scopus	Brazil	Rafting	Marine Pollution Bulletin

		Southwest Atlantic					
119	https://doi.org/10.1016/j.marpolbul.2021.113161	Evaluation of microplastic and marine debris on the beaches of Niterói Oceanic Region, Rio De Janeiro, Brazil	2022	Pubmed	Brazil	Riverine contributtion	Marine Pollution Bulletin
120	https://doi.org/10.2112/JCOASTRES-D-22A-00005.1	Indexing Anthropogenic Litter as a Contamination Gradient from Rivers to Beaches in Southeast Brazil	2022	Pubmed	Brazil	Monitoring	Journal of Coastal Research
121	https://doi.org/10.1016/j.marpolbul.2022.114124	Anthropogenic litter on the macrotidal sandy beaches of the Amazon region	2022	Scopus	Brazil	Relation with COVID-19	Marine Pollution Bulletin
122	doi: 10.12957/jheotb.2022.69511	Environmental Perception of Beachgoers of Itaipu, Niterói, RJ, about the Antrhopogenic litter after Awareness Activities	2022	Pubmed	Brazil	Environmental perception	d and Environmen
123	https://doi.org/10.1016/j.marpolbul.2023.114915	Beach litter in three South American countries: A baseline for restarting	2023	Pubmed	Brazil and Colombia	Monitoring	Marine Pollution Bulletin

		monitoring and cleaning after COVID-19 closure					
124	https://doi.org/10.1016/j.marenvres.2022.105827	Relationships between marine litter and type of coastal area, in Northeast Atlantic sandy beaches	2023	Pubmed	Portugal	Monitoring	Marine Environmental Research
125	https://doi.org/10.1016/j.rsma.2023.102991	Monitoring marine litter on Funchal beaches (Madeira Island): Insights for litter management	2023	Pubmed	Portugal	Environmental perception	Regional Studies in Marine Science
126	https://doi.org/10.1016/j.marpol.2023.105742	Public perceptions of marine litter and impacts on coastal ecosystem services in Galicia (Spain)	2023	Pubmed	Spain	Environmental perception	Marine Policy

APÊNDICE II – CAPÍTULO 2: GRÁFICOS DE BACTÉRIAS POTENCIALMENTE PATOGÊNCIAS EM ORGANISMOS MARINHOS E SERES HUMANOS EM PRAIAS ESTUARINAS E OCEÂNICAS.

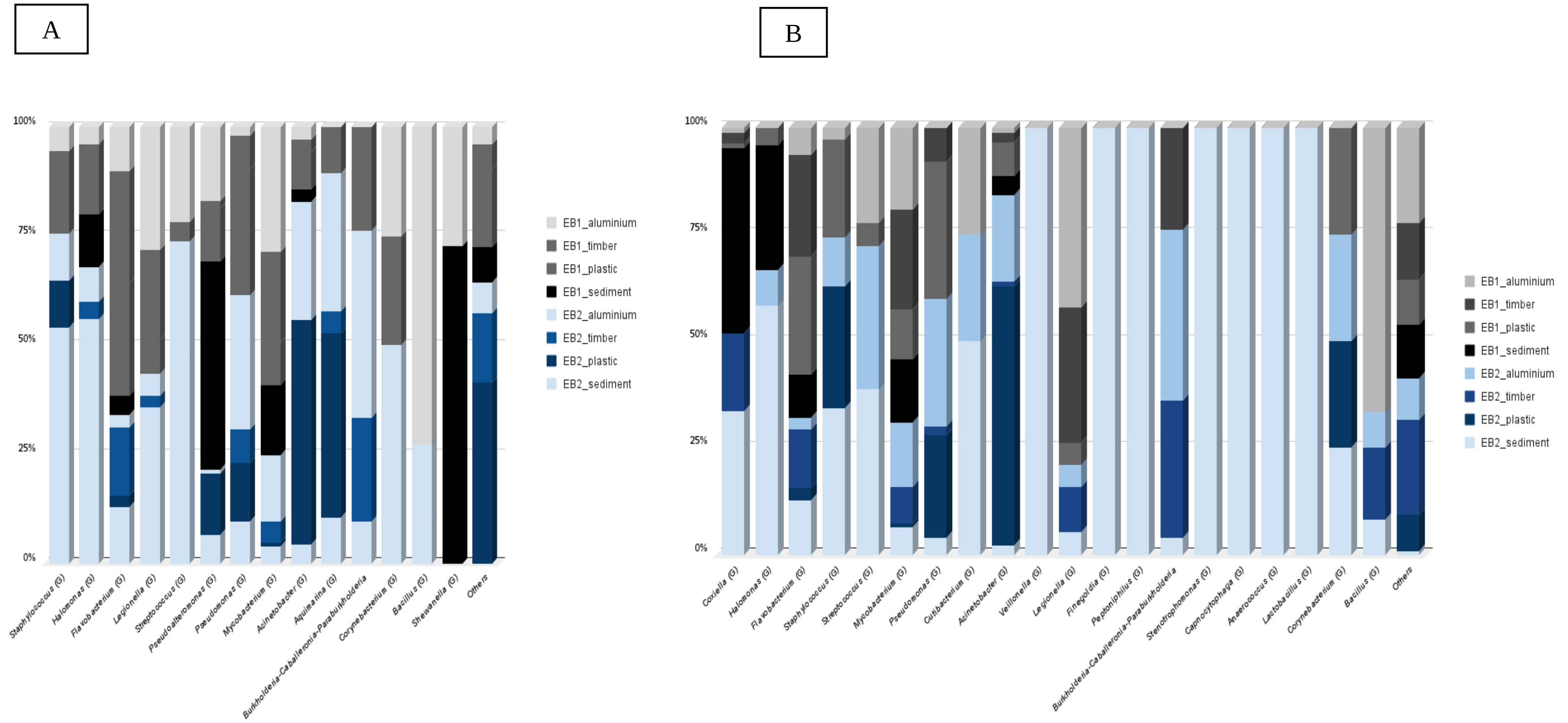

Figure 1 - BGPM (A) and BGPH (B) in Estuarine Beaches.

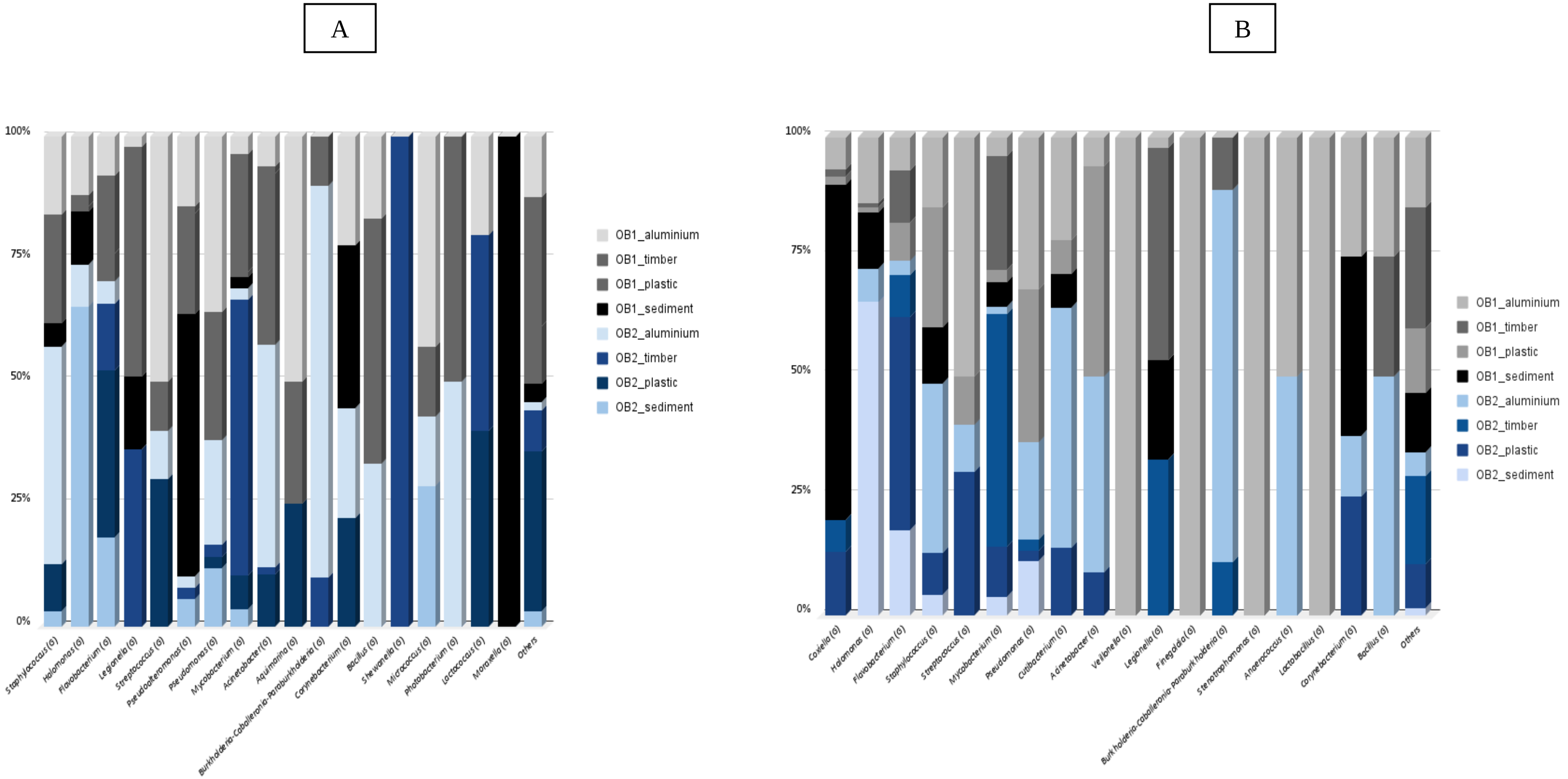

Figure 2. BGMP (A) and BGPH (B) in Oceanic Beaches.

APÊNDICE III – CAPÍTULO 3: MODELO DE PLANILHA PARA A CATEGORIZAÇÃO DOS RESÍDUOS SÓLIDOS

Tipos de Resíduos	Boia	Borrachas	Brinquedos	Chinelos	Canos	Copos	Cordas	Embalagens	Fragmentos	Garrafas	Guardanapos	Higiene Pessoal	Hastes	Isopor	Latas	Linhas	Lacres	Petrechos	Sacos	Tampas	Tênis	Tubos	Sapatos	Outros
Plástico																								
Guimbas																								
Lixo Orgânico																								
Madeira Antropogênica																								
Metal																								
Papel																								
Tecido																								
Vela																								
Vidros e Cerâmicas																								
Outros																								

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APÊNDICE IV – CAPÍTULO 3: MODELO DE PLANILHA PARA A CATEGORIZAÇÃO DOS RESÍDUOS SÓLIDOS COM ORGANISMOS INCRUSTANTES

Características		Plástico	Algas	Briozoários	Cirripédios	Esponjas	Hidrozários	Moluscos	Poliquetas	Outros
Degradação	Intactos									
	Fragmentos									
Formato Geométrico	Planos									
	Cilíndricos									
	Cubos									
	Esferas									
	Irregulares									
	Outros									
Cores	Amarelo									
	Azul									
	Branco									
	Laranja									
	Preto									
	Transparente									
	Verde									
	Vermelho									
	Outros									
Superfície	Lisa									
	Rugosa									
Composição Química	EPS									
	PA									
	PET									
	PLA									
	PP									
	PVC									
	PS									

	Outros										

APÊNDICE V – CAPÍTULO 3: LISTA DE ESPÉCIES ASSOCIADAS AOS RESÍDUOS SÓLIDOS

Table 3 - Taxonomic classification of the fouled organisms collected, type of litter and beaches where they were found, and population status.

Phylum	Class	Order	Family	Gender and Species	Status Populacional	Local found the species at marine litter	Reference for status populacional	Type of marine litter	Previously described in marine litter in the state of Rio de Janeiro
Arthropoda	Hexanauplia	Sessilia	Balanidae	*Amphibalanus amphritrite* (Darwin, 1854)	Established	Guanabara Bay and Oceanic Region	Brazilian Bioinvasion Platform	Plastic	Yes (Póvoa et al., 2022)
Arthropoda	Hexanauplia	Sessilia	Balanidae	*Amphibalanus eburneus* (Gold, 1841)	Cryptogenic	Guanabara Bay and Oceanic Region	Brazilian Bioinvasion Platform	Plastic	Yes (Póvoa et al., 2022)
Arthropoda	Hexanauplia	Sessilia	Balanidae	*Amphibalanus reticulatus* (Utinomi, 1967)	Established	Oceanic Region	Brazilian Bioinvasion Platform	Plastic	Yes (Póvoa et al., 2022)
Arthropoda	Hexanauplia	Sessilia	Balanidae	*Balanus trigonus* (Darwin, 1854)	Established	Guanabara Bay	Brazilian Bioinvasion Platform	Plastic	No
Arthropoda	Hexanauplia	Sessilia	Balanidae	*Megabalanus coccopoma* (Darwin, 1854)	Invader	Guanabara Bay	Brazilian Bioinvasion Platform	Plastic	No
Arthropoda	Hexanauplia	Sessilia	Balanidae	*Megabalanus tintinnabulum* (Linnaeus, 1758)	Cryptogenic	Guanabara Bay and Oceanic Region	Brazilian Bioinvasion Platform	Plastic	No
Arthropoda	Hexanauplia	Sessilia	Balanidae	*Megabalanus vinaceus* (Darwin, 1854)	Invader	Guanabara Bay	Oricchio et al., 2019	Plastic	No
Arthropoda	Hexanauplia	Sessilia	Balanidae	*Megabalauns vesiculosus* (Darwin, 1854)	Native	Oceanic Region	Abreu et al., 2016	Plastic	No
Annelida	Polychaeta	Sabellida	Serpulidae	*Hydroides elegans* (Haswell, 1883)	Invader	Guanabara Bay and Oceanic Region	Brazilian Bioinvasion Platform	Plastic	Yes (Póvoa et al., 2022)

Annelida	Polychaeta	Sabellida	Serpulidae	*Hydroides* sp.	Invader	Guanabara Bay and Oceanic Region	Brazilian Bioinvasion Platform	Plastic	Yes (Póvoa et al., 2022)
Bryozoa	Gymnolaemata	Cheilostomatida	Electridae	*Arbopecula tenella* (Hincks, 1880)	Cryptogenic	Oceanic Region	Miranda et al., 2018	Plastic	Bryozoans from the same family were found in another study, but not identified to species level (Póvoa et al., 2022)
Bryozoa	Gymnolaemata	Cheilostomatida	Bugulidae	*Bugula* sp.	Invader	Guanabara Bay	Miranda et al., 2018	Plastic	No
Bryozoa	Gymnolaemata	Cheilostomatida	Membranipora	*Jellyella tuberculata* (Bosc, 1802)	Invader	Guanabara Bay and Oceanic Region	Mancini et al., 2021	Plastic	Bryozoans from the same family were found in another study, but not identified to species level (Póvoa et al., 2022)
Mollusca	Bivalvia	Mytillida	Mytilidae	*Perna perna* (Linnaeus, 1758)	Native	Guanabara Bay amd Oceanic Region	Pierre et al., 2016	Plastic	No
Mollusca	Bivalvia	Mytillida	Mytilidae	*Perna viridis* (Linnaeus, 1758)	Invader	Guanabara Bay	Messano et al., 2019	Plastic	No
Mollusca	Bivalvia	Ostreida	Ostreidae	*Saccostrea cucullata* (Born, 1778)	Invader	Guanabara Bay	Amaral et al., 2020	Plastic	Yes (Póvoa et al., 2022)
Mollusca	Bivalvia	Ostreida	Ostreidae	*Ostrea puelchana* (d'Orbigny, 1842)	Native	Oceanic Region	Rosenberg, 2009.	Plastic	Yes (Póvoa et al., 2022)
Mollusca	Gastropoda	Littorinimorpha	Calyptraeidae	*Crepidula* sp.	Cryptogenic	Guanabara Bay	Brazilian Bioinvasion Platform	Plastic	No
Mollusca	Gastropoda	Conferir	Muricidae	*Stramonita brasiliensis* (Claremont and D.Reid, 2011).	Native	Guanabara Bay	Brazilian Bioinvasion Platform	Plastic	No
Protoctista	Chlorophyta	Ulvophyceae	Ulvaceae	*Ulva lactuca* (Linnaeus, 1753)	Cryptogenic	Guanabara Bay	Hughey et al., 2019; Guiry and Guiry, 2021.	Plastic	Yes (Póvoa et al., 2022)

Porifera	Demospongiae	Haplosclerida	Chalinidae	*Haliclona* sp.	Invader	Guanabara Bay	Elvin et al., 2018	Plastic	No

APÊNDICE VI – MATERIAL SUPLEMENTAR DO CAPÍTULO 3.

Supplentary Material 1. Origin and geographical distribution of species fouled in marine litter.

Filo	Class	Order	Family	Gender and Species	Origin	Geographical Distribution	References of Origin and Geographical Distribution
Artrhopoda	Hexanauplia	Sessilia	Balanidae	*Amphibalanus amphritrite* (Darwin, 1854)	Indo-Pacific	Atlantic, Artic, Antartic, Mediterranean, Indic and Pacific	Henry and McLaughlin 1975; Cranfield, 1998; Carlton et al., 2011
Artrhopoda	Hexanauplia	Sessilia	Balanidae	*Amphibalanus eburneus*	Atlantic	Atlantic, Artic, Antartic, Mediterranean, Indic and Pacific	Fofonoff et al., 2018; Jabarimanesh et al., 2019.
Artrhopoda	Hexanauplia	Sessilia	Balanidae	*Amphibalanus reticulatus* (Utinomi, 1967)	Pacific	Atlantic, Mediterranean, Indic and Pacific	Carlton et al., 2011
Artrhopoda	Hexanauplia	Sessilia	Balanidae	*Balanus trigonus* (Darwin, 1854)	Indo-Pacific	Atlantic, Artic, Antartic, Mediterranean, Indic and Pacific	Cranfield, 1998; Carlton et al., 2011
Artrhopoda	Hexanauplia	Sessilia	Balanidae	*Megabalanus coccopoma* (Darwin, 1854)	Pacific	Atlantic, Mediterranean, Indic and Pacific	Cohen et al., 2014; Abreu et al., 2016
Artrhopoda	Hexanauplia	Sessilia	Balanidae	*Megabalanus tintinnabulum* (Linnaeus, 1758)	Uncertain	Atlantic, Artic, Antartic, Mediterranean, Indic and Pacific	Carlton et al., 2011
Artrhopoda	Hexanauplia	Sessilia	Balanidae	*Megabalanus vinaceus* (Darwin, 1854)	No data	No data	No data
Artrhopoda	Hexanauplia	Sessilia	Balanidae	*Megabalauns vesiculosus* (Darwin, 1854)	Atlantic	South Atlantic	Abreu et al., 2016
Annelida	Polychaeta	Sabellida	Serpulidae	*Hydroides elegans* (Haswell, 1883)	Pacific	Atlantic, Mediterranean, Indic and Pacific	Sun et al., 2015; Schawn et al., 2015; Bastida-Zavala et al., 2017
Annelida	Polychaeta	Sabellida	Serpulidae	*Hydroides* sp.	Pacific	Atlantic, Mediterranean, Indic and Pacific	Sun et al., 2015; Schawn et al., 2015; Bastida-Zavala et al., 2017
Bryozoa	Gymnolaemata	Cheilostomatida	Electridae	*Arbopecula tenella* (Hincks, 1880)	Uncertain	Atlantic, Mediterranean and Pacific	Miranda et al., 2018

Bryozoa	Gymnolaemata	Cheilostomatida	Bugulidae	*Bugula* sp.	Pacific	Atlantic, Artic, Antartic, Mediterranean, Indic and Pacific	Vieira et al., 2008; Miranda et al., 2018
Bryozoa	Gymnolaemata	Cheilostomatida	Membranipora	*Jellyella tuberculata* (Bosc, 1802)	Uncertain	Atlantic, Artic, Antartic, Mediterranean, Indic and Pacific	Vieira et al., 2008
Mollusca	Bivalvia	Mytillida	Mytilidae	*Perna perna* (Linnaeus, 1758)	Uncertain	Atlantic and Indic	Pierri et al., 2016
Mollusca	Bivalvia	Mytillida	Mytilidae	*Perna viridis* (Linnaeus, 1758)	Indo - Pacific	Atlantic, Indic and Pacific	Sidall, 1980; Messano et al., 2019
Mollusca	Bivalvia	Ostreida	Ostreidae	*Saccostrea cuccullata* (Born, 1778)	Indo-Pacific	Atlantic, Indic and Pacific	Lan e Morton, 2006; Amaral et al. 2020
Mollusca	Bivalvia	Ostreida	Ostreidae	*Ostrea puelchana* (d'Orbigny, 1842)	Atlantic	South Atlantic	Rosenberg, 2009.
Mollusca	Gastropoda	Littorinimorpha	Calyptraeidae	*Crepidula* sp.	Atlantic	South Atlantic and Caribe	Simone et al., 2002; Simone et al., 2006
Mollusca	Gastropoda	Conferir	Muricidae	*Stramonita brasiliensis* (Claremont and D.Reid, 2011)	No data	Southwest Atlantic	Claremont et al., 2011.
Protoctista	Clorophyta	Ulvophyceae	Ulvaceae	*Ulva lactuca* (Linnaeus, 1753)	Indo-Pacific	Atlantic, Artic, Antartic, Mediterranean, Indic and Pacific	Hughey et al., 2019; Guiry and Guiry, 2021.
Porifera	Demospongiae	Haplosclerida	Chalinidae	*Haliclona* sp.	Indo-Pacific	Atlantic and Pacific	Elvin et al., 2018

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