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VARIABILIDADE ESPAÇO-TEMPORAL DE CURTO PRAZO DE MICROPLÁSTICOS NO SEDIMENTO DAS PRAIAS DE FERNANDO DE NORONHA

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Dissertação apresentada ao Programa de Pós-Graduação em Oceanografia da Universidade Federal de Pernambuco, como requisito parcial para a obtenção do título de mestre em Oceanografia.

Área de concentração: Oceanografia Abiótica.

Orientadora: Profa. Dra. Monica Ferreira da Costa.

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RESUMO

A poluição por microplásticos tem sido foco de diversos estudos devido à sua ampla distribuição no ambiente marinho e aos impactos causados no ecossistema. O arquipélago de Fernando de Noronha encontra-se vulnerável a este tipo de poluição, e a presença dessas partículas já havia sido anteriormente registrada no local através de coletas pontuais. O presente estudo se propôs a realizar coletas diárias de sedimento em diferentes praias do arquipélago com o intuito de avaliar a distribuição, características e variabilidade de curto prazo de microplásticos (1 – 5 mm), utilizando três diferentes unidades de concentração. As concentrações obtidas em cada praia variaram entre 0.6 ± 2.5 partículas/m² e 1059.3 ± 1385.6 partículas/m², com uma grande variabilidade espacial e temporal de pequena escala e diferenças significativas entre os dois lados da ilha e entre a maré de sizígia e de quadratura. Observou-se que este tipo de poluição é recorrente no arquipélago e que as correntes superficiais são as principais responsáveis pela chegada de resíduos na região. A distribuição dos microplásticos ao longo das praias está associada a combinação de uma série de fatores oceanográficos e meteorológicos, que devem ser levados em consideração no planejamento de futuras campanhas de amostragem. Uma comparação mais ampla com diferentes estudos ao redor do mundo se tornou possível com o uso de diferentes unidades de concentrações, porém a variedade de metodologias e de frações de tamanho utilizados nos trabalhos representou uma importante limitação. Recomenda-se então, o uso de métodos que tornem os resultados comparáveis para que variações espaciais e temporais de maior escala dos microplásticos possam ser compreendidas.

Palavras-chave: microplásticos; praias arenosas; Fernando de Noronha; ilhas oceânicas.

ABSTRACT

Microplastic pollution has been the focus of several studies due to its wide distribution in the marine environment and its impact on the ecosystem. Fernando de Noronha Archipelago is highly vulnerable to this type of pollution, which has been previously reported with snapshot samplings on the site. The present study performed daily samplings of sediment in different sandy beaches of the archipelago, aiming to assess the distribution, characteristics and short-term variability of microplastics (1 – 5 mm), expressing concentrations in three different units. The concentrations ranged from 0.6 ± 2.5 particles/m² to 1059.3 ± 1385.6 particles/m², and showed a large spatial and temporal small-scale variability, with significant differences between leeward and windward sides of the island and between spring tide and neap tide. The results indicate that microplastic contamination is recurrent in Fernando de Noronha and the intense arrival of debris on the archipelago is mainly due to surface currents. The distribution of microplastics is associated with various oceanographic, meteorological and morphologic processes, which should be taken into account on the sampling design of future studies. A wider comparison with results obtained in beaches worldwide was possible using different units of concentration, however, a variety of techniques and size fractions used on previous studies represented important limitations on the comparisons. Therefore, methods with comparable results are recommended for a better understanding of large-scale spatial and temporal variability of microplastics.

Keywords: microplastics; beach sediment; Fernando de Noronha; oceanic islands.

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1 INTRODUÇÃO

O plástico é amplamente utilizado na sociedade desde a década de 1950, quando começou a ser produzido em larga escala (Ryan, 2015). Este material, composto por polímeros sintéticos, apresenta alta durabilidade e resistência à degradação, o que o torna bastante versátil, mas também persistente na natureza. Estima-se que todo o plástico produzido no planeta até 2015 equivalha a cerca de 8,3 bilhões de toneladas, entre as quais aproximadamente 60% encontram-se acumuladas em aterros sanitários ou em outros locais do meio ambiente (Geyer et al., 2017). Quando descartados de forma inapropriada, estes resíduos entram facilmente no ambiente marinho e existem mais de 260 000 toneladas de plástico flutuando nos oceanos (Eriksen et al., 2014). Por ter uma baixa densidade, este material pode ser transportado por longas distâncias, chegando inclusive em áreas remotas e inabitadas por seres humanos (Barnes, 2005; Lavers and Bond, 2017). Atualmente, o plástico encontra-se espalhado por toda a superfície do planeta e está presente no sedimento e na coluna d'água desde a superfície até as águas profundas. Portanto, os microplásticos constituem uma das principais formas de poluição marinha (Auta et al., 2017; Barnes et al., 2009).

Os resíduos plásticos nos oceanos podem ter fontes marinhas, como a pesca, a navegação e as plataformas de petróleo; ou terrestres, entrando no mar de forma indireta através dos rios e dos efluentes domésticos e industriais (Cole et al., 2011). Este material muitas vezes se apresenta no meio ambiente em partículas menores que 5 mm, chamadas de microplásticos. Estas partículas se subdividem em duas categorias: (i) primários, que resultam diretamente de processos industriais, como os *pellets* e os abrasivos encontrados em cosméticos e esfoliantes faciais; e (ii) secundários, que resultam da fragmentação de resíduos maiores (Auta et al., 2017). Esta fragmentação pode se dar através de diversos processos, facilitados principalmente pela ação da luz, de organismos vivos, de altas temperaturas ou das ondas (Andrady, 2011; Efimova et al., 2018).

Devido ao seu tamanho reduzido, os microplásticos encontram-se disponíveis para organismos de todos os níveis tróficos (Pinheiro et al., 2020). Além disso, estas partículas contêm uma série de aditivos químicos e têm o potencial de adsorver contaminantes presentes na água como poluentes orgânicos persistentes (POPs) e metais (Heskett et al., 2012; Rochman, 2015). A ingestão dos microplásticos pode causar diversos danos físicos e químicos, como bloqueio do trato digestório, disfunções fisiológicas e alterações hormonais nos organismos (Cole et al, 2011). Existem registros da interação destas partículas com diversos grupos de vertebrados e invertebrados marinhos, incluindo espécies comercialmente importantes, podendo ter implicações na saúde humana (Auta et al., 2017; Cole et al., 2011; Ivar Do Sul and Costa, 2014). Estas partículas também podem atuar como vetores de dispersão de espécies invasoras, colocando em risco as espécies nativas e a integridade dos ecossistemas (Barnes, 2002).

Uma vez no ambiente marinho, os microplásticos estão sujeitos à ação direta das correntes, das ondas e do vento, tornando as ilhas oceânicas bastante suscetíveis ao acúmulo destas partículas (Monteiro et al., 2018). Estes ambientes podem modificar a hidrodinâmica das correntes oceânicas e causar turbulência vertical levando formação de vórtices e eventos de ressurgência, através do fenômeno conhecido como Efeito Ilha (Lira et al., 2014; Tchamabi et al., 2017). A interação entre as correntes e a topografia local favorece a retenção de microplásticos pelágicos ao redor das ilhas, enquanto fatores como ondas e marés são responsáveis pela suspensão e deposição destas partículas nas praias, determinando o seu padrão de distribuição ou mesmo uma ausência de padrão reconhecível em razão do intenso dinamismo dos fatores supracitados (Baztan et al., 2014; Browne et al., 2010; Lima et al., 2016). Os ambientes insulares são vulneráveis a esse tipo de poluição, tendo em vista que abrigam uma série de espécies endêmicas, muitas vezes ameaçadas de extinção (Lima et al., 2016; Monteiro et al., 2018).

O Brasil possui um conjunto de ilhas oceânicas de grande importância ecológica, geológica, econômica e estratégica (Mohr et al., 2009). Em 2018, foram implementadas grandes áreas marinhas protegidas (AMP) ao redor de algumas destas ilhas, cobrindo aproximadamente 920.000 km² (Soares and Lucas, 2018). Apesar de ser um avanço importante para a conservação marinha no país, o posicionamento destas AMP e os níveis de restrição em cada uma delas não protegem de forma eficaz alguns dos ecossistemas mais vulneráveis destes ambientes (Giglio et al., 2018). É necessário que a implementação de AMP ocorra em locais prioritários de acordo com evidências científicas como limiares de perturbação, capacidade de suporte, demandas da comunidade, entre outras, ressaltando a importância das pesquisas nestes locais (Svancara et al., 2005). Além disso, as medidas de proteção da fauna e da flora locais devem estar associadas com o monitoramento a longo prazo e estudos de impactos nos ecossistemas.

Resíduos plásticos já foram registrados nas ilhas de Fernando de Noronha, Trindade, Abrolhos, São Pedro e São Paulo e Atol das Rocas (Ivar do Sul et al., 2013, 2014, 2017; Soares et al., 2011), enfatizando assim a vulnerabilidade desses ambientes à poluição por plástico. A ilha de Trindade apresenta níveis relativamente altos de poluição (Ivar do Sul et al., 2014, 2017), o que pode estar relacionado à sua proximidade ao centro do Giro Subtropical do Atlântico Sul, onde grandes concentrações de resíduos são encontradas (Cózar et al., 2014). O Arquipélago de São Pedro e São Paulo, embora bastante isolado, agrega partículas de microplásticos ao seu redor em concentrações comparáveis às de larvas de peixes (Lima et al., 2016). No Atol das Rocas e em Fernando de Noronha, resíduos sólidos de diversos tipos foram registrados, incluindo itens de origem estrangeira (Soares et al., 2011, Grillo e Mello et al., 2021). Portanto, nenhuma das ilhas oceânicas brasileiras encontra-se livre da presença do plástico.

Fernando de Noronha é a única dessas ilhas que oferece infraestrutura para moradores e turistas e é foco de diversas estratégias de conservação ambiental. Desde 1986, a ilha pertence a uma Área de Proteção Ambiental e parte dela está inserida no Parque Nacional Marinho de Fernando de Noronha, criado em 1988 (Mohr et al., 2009). Em 2019, entrou em vigor o Decreto Distrital 002/2018, que proíbe a entrada, o uso e a comercialização de diversos tipos de plásticos descartáveis na ilha. A medida, conhecida como Plástico Zero, representa uma importante estratégia legislativa para redução da poluição por plásticos e proteção ambiental. Entretanto, por se tratar de um ambiente insular, a região ainda encontra-se vulnerável à chegada de resíduos sólidos trazidos pelas correntes superficiais e pelo vento (Grillo and Mello, 2021; Ivar do Sul et al., 2017, 2009).

A presença de microplásticos foi registrada na ilha, tanto no sedimento como na água (Ivar do Sul et al., 2017, 2014, 2009; Monteiro et al., 2020). Observou-se que as praias mais expostas às correntes e ao vento apresentaram uma densidade de partículas maior do que aquelas menos expostas e que a maioria destas partículas tem fonte oceânica. A presença de *pellets* também foi registrada, apesar de não haver nenhuma indústria de plástico na ilha (Ivar do Sul et al., 2009). Estes estudos demonstram que existe uma influência direta dos mecanismos meteo-oceanográficos de larga escala no transporte de resíduos plásticos na região. Entretanto, a variação temporal da distribuição de microplásticos nas praias e a influência de fatores como ondas e marés nos processos de deposição e retirada destes resíduos ainda são pouco compreendidos.

Estudos de monitoramento realizados em diferentes locais sugerem que existe uma considerável variabilidade de curto prazo na distribuição do lixo marinho nas praias, muitas vezes regulada por condições hidrodinâmicas (Browne et al., 2015). Entender esta variabilidade, bem como sua importância relativa com relação a outros fatores é essencial para interpretar padrões e tendências de longo prazo que poderão ser afetados por mudanças climáticas. Além disso, estas informações na ilha de Fernando de Noronha tem implicações metodológicas e poderão auxiliar no planejamento de futuras campanhas de amostragem e aprimorar estudos de modelagem no local e em outras ilhas oceânicas brasileiras, onde os microplásticos também já foram registrados (Ivar do Sul et al., 2017, 2014).

Todavia, inserir os níveis locais de poluição dentro de um contexto global e que tem recebido cada vez mais atenção da comunidade acadêmica torna-se desafiador diante da variedade de metodologias de coleta, extração e identificação de microplásticos utilizadas ao redor do mundo (Yu et al., 2020). O uso de diferentes unidades para expressar a concentração dessas partículas é uma das limitações que dificultam a comparação dos resultados entre estudos, pois muitas vezes estas unidades não podem ser convertidas entre si. Apesar da disponibilidade de trabalhos que investigam as concentrações de microplásticos no sedimento de praias arenosas, aqueles que podem ser comparados numericamente restringem-se a uma reduzida parcela que adota unidades em comum.

Diante disso, o presente estudo se propõe a avaliar, pela primeira vez, a variabilidade de curto prazo da concentração de microplásticos em diferentes praias do arquipélago de Fernando de Noronha, utilizando três diferentes unidades de concentração para expressar a densidade:

- Microplásticos/m² de sedimento;
- Microplásticos/m³ de sedimento;
- Microplásticos/kg de sedimento (peso seco).

Assim, esse trabalho poderá contribuir não só com a construção de uma estratégia de monitoramento mais adequada dos níveis de poluição por microplásticos nas ilhas oceânicas brasileiras, como também permitirá uma comparação mais ampla com outros estudos já existentes na literatura.

Este trabalho deu origem a um artigo publicado na revista Marine Pollution Bulletin, apresentado em sua estrutura original no capítulo 4 desta dissertação.

2 OBJETIVOS

Seguem os objetivos desta pesquisa.

2.1 OBJETIVO GERAL

Avaliar a variação espacial e temporal de curto prazo da densidade de microplásticos no sedimento de praias arenosas da ilha de Fernando de Noronha.

2.2 OBJETIVOS ESPECÍFICOS

Foram estabelecidos como objetivos específicos:

a) Avaliar os níveis gerais de poluição por microplásticos (1 - 5 mm) no arquipélago, inserindo-o em um contexto global;

b) Caracterizar as partículas identificadas de acordo com tipo, tamanho e cor;

c) Avaliar a variação espacial dessas partículas, comparando praias mais e menos abrigadas;

d) Avaliar a variação temporal de curto prazo de microplásticos e a influência de parâmetros meteo-oceanográficos na deposição destes resíduos.

3 DETALHAMENTO DA METODOLOGIA

3.1 REVISÃO BIBLIOGRÁFICA

Uma revisão bibliográfica foi realizada com o objetivo de encontrar trabalhos sobre a concentração de microplásticos no sedimento de praias arenosas, publicados até outubro de 2020. Durante a busca, foram utilizadas combinações das seguintes palavras-chave: “microplastics”, “sandy beaches” e “beach sediment”. Trabalhos realizados em praias que não tinham o sedimento arenoso ou em áreas submersas não foram incluídos neste estudo. Os artigos encontrados foram classificados de acordo com as classes de tamanho das partículas analisadas e as unidades de concentração de microplásticos. Quando a coleta era feita em diferentes regiões da praia ou diferentes profundidades de sedimento, o valor obtido na linha da maré alta mais recente e/ou na superfície do sedimento foi utilizado. Quando estes fatores não eram especificados no estudo, utilizou-se uma média geral da praia.

3.2 COLETA DE SEDIMENTO

As coletas de sedimento foram realizadas ao longo de 13 dias entre 23 de outubro de 2019 e 5 de novembro de 2019. Amostras diárias foram coletadas em duas praias a sotavento da ilha (Cacimba do Padre e Boldró) e duas praias a barlavento (Leão e Sueste) (Figura 1, Cap.4). Três réplicas foram coletadas por vez, totalizando 39 amostras (13 dias X 3 réplicas) por praia, exceto na praia do Leão que totalizou 36 amostras (12 dias X 3 réplicas). Além disso, nos dias de maior amplitude da maré de sizígia e menor amplitude da maré de quadratura, duas outras praias foram amostradas: Conceição e Atalaia, a sotavento e barlavento da ilha, respectivamente. Seis amostras foram coletadas em cada uma (2 dias X 3 réplicas).

No presente estudo, a metodologia adotada por Ivar do Sul et al. (2017) foi utilizada. Durante a maré baixa diurna, um quadrante de 30x30 cm foi posicionado sob a linha da maré alta mais recente e uma fina camada superficial de areia foi coletada com uma espátula de metal. A amostra foi transferida para um béquer para medir o volume e em seguida foi armazenada em um recipiente de alumínio. As réplicas foram coletadas de forma espaçada, buscando cobrir aproximadamente toda a extensão da praia. Os pontos de coletada não foram marcados na areia, portanto a posição variava entre os dias. Assim, a variação temporal dos microplásticos não foi afetada pelas coletas.

3.3 IDENTIFICAÇÃO E CARACTERIZAÇÃO DE MICROPLÁSTICOS

Em laboratório, as amostras foram colocadas na estufa a 60°C por 48h. As amostras secas foram pesadas e peneiradas com uma peneira de 1 mm. A fração retida na peneira foi analisada em microscópio Carl Zeiss Stemi 2000-C e as partículas de microplásticos foram identificadas individualmente. Quando não era possível distinguir uma partícula de plástico apenas visualmente, uma agulha quente foi colocada sobre a partícula para observar se derretia.

Todos os microplásticos foram fotografados e medidos com software ZEN 3.1 (blue edition) da Carl Zeiss Vision. Estas partículas foram classificadas de acordo com tamanho (1 – 1.99, 2 – 2.99, 3 – 3.99, 4 – 4.99), tipo (fragmentos, isopor, *pellets* e fibras) e cor. As partículas maiores que 5 mm foram registradas, mas não foram incluídas nos testes estatísticos, tendo em vista que não são consideradas microplásticos. Devido a incertezas na identificação e contagem de fibras solitárias e ao grande risco de contaminação, somente tufos de fibras foram contados. Para possibilitar uma comparação mais ampla com outros estudos, a concentração de microplásticos foi expressa em três diferentes unidades: partículas/m², partículas/m³ e partículas/kg de peso seco de sedimento.

3.4 PARÂMETROS FÍSICOS

Em cada dia de coleta foram registrados os dados vento e ondas de cada praia. Os dados estavam disponíveis online e forma gratuita (https://www.surfguru.com.br/). A altura, o período e a direção das ondas foram obtidas a partir do modelo WAVEWATCH III do National Weather Service / National Oceanic and Atmospheric Administration (NWS/NOAA), e os dados de velocidade e direção do vento foram obtidos a partir do Global Forecast System (GFS) do National Centers for Environmental Prediction (NCEP/NOAA). A amplitude da maré foi fornecida pela Marinha do Brasil (https://www.marinha.mil.br/chm/tabuas-de-mare) e dados de precipitação foram fornecidos pelo Agência Pernambucana de Águas e Clima (APAC).

3.5 ANÁLISE GRANULOMÉTRICA

Nos dois dias em que as seis praias foram amostradas, uma alíquota de 50 mL de sedimento foi coletada ao lado de cada quadrante. Uma análise granulométrica foi feita através do peneiramento a seco e o sedimento foi classificado de acordo com Folk e Ward (1957). O software Sysgran 3.0 foi utilizado.

3.6 ANÁLISE ESTATÍSTICA

A quantidade de microplásticos identificados foi expressa em contagem total, valores máximo e mínimo por praia, e as concentrações foram expressas em média ± dp, nas três diferentes unidades adotadas neste estudo. O teste de Shapiro-Wilk foi realizado e indicou que os dados brutos de concentração de microplásticos não eram normais. Os dados foram divididos em dois grupos: barlavento e sotavento e o teste não-paramétrico de Wilcoxon-Mann-Whitney U test (α=0.05) foi realizado para testar se existia diferença significativa entre os dois grupos. Em seguida, o mesmo teste foi aplicado para os dados divididos em maré de sizígia e maré de quadratura. O teste foi realizado duas vezes de forma independente. Os dados de ondas e vento foram plotados num gráfico radial, indicando a direção (ângulo), intensidade (cores) e concentração de microplásticos (distância do centro) (Figura 5, Cap.4). Todas as análises estatísticas foram feitas no software R 4.0.3 (R Core Team, 2020).

4 DISTRIBUTION, CHARACTERISTICS AND SHORT-TERM VARIABILITY OF MICROPLASTICS IN BEACH SEDIMENT OF FERNANDO DE NORONHA ARCHIPELAGO, BRAZIL

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1. INTRODUCTION

Microplastic particles (< 5 mm, MP) have become a widespread contaminant in the ocean, raising serious concern about their implications in the marine environment (Yu et al., 2020). Resulting from the breakdown of larger plastic pieces (secondary microplastics) or manufactured to be at microscopic size (primary microplastics), these particles can be bioavailable for organisms in all trophic levels, and have the capacity to sorb toxic chemicals from the surrounding water such as persistent organic pollutants (POPs) and heavy metals (Auta et al., 2017). When ingested, they can severely affect the health of the organisms, causing physical and chemical harm (i.e. gastrointestinal tract damage, disruption of key physiological processes and behavioural disorders), potentially disrupting natural ecosystems (Khalid et al., 2021). Furthermore, microplastic particles provide substrate for the colonization of diverse microbial communities, also known as plastisphere (Zettler et al., 2013), where pathogenic bacteria and harmful algal bloom species have been found (Kirstein et al., 2016; Masó et al., 2003) and they also increase the opportunities for invasion of exotic species (Khalid et al., 2021).

In the marine environment, microplastics are subject to long-distance transport by currents and wind, making oceanic islands susceptible to the accumulation of these particles (Monteiro et al., 2018). Islands can modify the dynamics of ocean circulation around them and generate vertical turbulence, leading to the formation of eddies and upwelling events, by the island mass effect (Doty and Oguri, 1956; Lira et al., 2014; Tchamabi et al., 2017). Small-scale oceanographic mechanisms such as the interaction between ocean currents and local topography facilitates retention of pelagic plastic debris around the islands (Lima et al., 2016), which are likely to be washed ashore on beaches and return to the ocean by tides and waves (Baztan et al., 2014; Isobe et al., 2014). Island environments are highly vulnerable to this type of contamination, as they are biodiversity hotspots, with high levels of endemism (Kier et al., 2009; Monteiro et al., 2018).

The Brazilian Archipelago of Fernando de Noronha is an area of high environmental and economic importance and is a key site for the protection of biodiversity and endangered species in the South Atlantic Ocean (UNESCO, 2020). In 2019, a range of single use plastic were banned on the archipelago, as a legislative strategy for environmental protection and mitigation of plastic pollution (Official website of Fernando de Noronha, 2020). Despite government policies and the low population, Fernando de Noronha is still vulnerable to the arrival of plastic debris by surface currents and wind (Ivar do Sul et al., 2017). The presence of microplastics have been reported in the beach sediment and surface seawater around the archipelago and the majority of the particles found were from long-distance marine-based sources (Ivar do Sul et al., 2017, 2014, 2009). However, only snapshot samplings were previously performed and the temporal variability of microplastic distribution in the beach sediment of the archipelago remains unexplored.

Beach sediment is considered a significant reservoir of plastic items and has been suggested as the best compartment to understand the dynamics of the distribution of plastic waste over time (Castro et al., 2020). This distribution is influenced by various oceanographic and meteorological processes, such as tides, waves and wind (Castro et al., 2020; Turra et al., 2014). Despite the large number of studies investigating microplastic distribution in beaches around the world, many of them do not consider these processes in their results. Investigating the short-term variability of microplastics and how they interact with physical parameters and environmental characteristics is important to better understand long-term patterns and trends, and may help in the sampling design of future works, as well as improve modelling studies.

However, inconsistencies in sampling and extraction techniques, size fractions and concentration units limit meaningful comparisons between studies, making it difficult to understand the broader spatial distribution of these particles and to identify patterns in time and space (Yu et al., 2020). Besides the recent efforts to standardize data collection, in order to be comparable (Besley et al., 2017), a vast literature already exists in different concentration units that cannot be interconverted. In order to overcome this limitation, the present study has adopted three different dimensions to measure microplastic concentration: area (m^2), volume (m^3) and dry weight (kg) of beach sediment. The main objective is to investigate the distribution, characteristics and short-term variability of large microplastic particles (1 – 5 mm) on beach sediment of Fernando de Noronha Island.

2. METHODS

2.1. Study area

Fernando de Noronha is a volcanic archipelago located on the western Tropical Atlantic Ocean, 345 km away from the Brazilian coast (3°52'S, 32°25'W) (Figure 1). It is comprised by 21 islands and islets and covers 26 km^2 (Almeida 2006). The main island, also called Fernando de Noronha is the only inhabited one and hosts a population of 3101 people (IBGE 2020).

The archipelago has a humid tropical climate, with two well-marked seasons: dry, from August to January, and rainy, from February to July (Calliari et al., 2016). Wind pattern on the island is highly influenced the meridional displacement of the Intertropical Convergence Zone (Assunção et al., 2020). Southeast trade winds are prevalent, with greater intensity from July to September (Calliari et al., 2016). Wave climate is dominated by wind waves, observed throughout the whole year, and higher energy swells, which are more frequent during summer and can reach up to 5 m on the northwest coast of the island. In winter, prevailing waves are from southeast with an average height of 1.6 m (Calliari et al., 2016). The archipelago has a semidiurnal micro-meso tide, with a spring tide range of 2.5 m and neap tide range of 1.3 m (Calliari et al., 2016).

The South Equatorial Current (SEC) is the main surface current around the archipelago, and flows westward as part of the South Atlantic Subtropical Gyre (Lumpkin and Garzoli, 2005; Peterson and Stramma, 1991; Tchamabi et al., 2018). It has a low seasonal variability and intensifies in winter (Tchamabi et al., 2018). The leeward (northwest) and windward (southeast) sides of the island have very different oceanographic characteristics, with the latter showing more intense hydrodynamics as it faces the prevailing wind and surface currents.

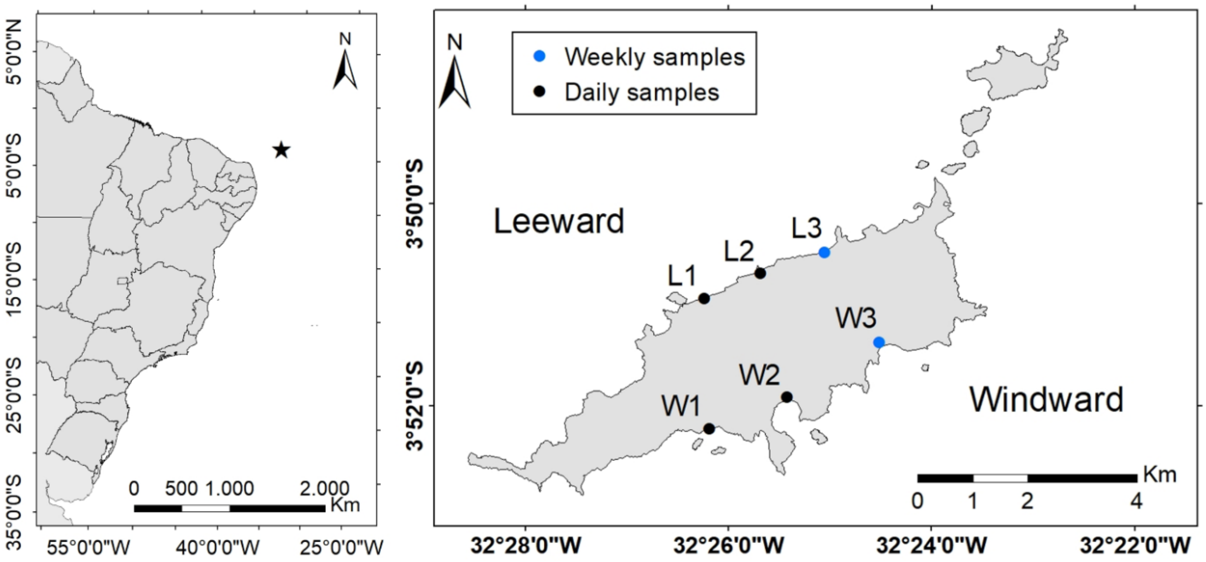
Fernando de Noronha is part of a large Marine Protected Area, which holds high ecological, economic and geological value (Mohr et al., 2009). It contains a great marine and terrestrial biodiversity, with several endemic and threatened species (Serafini et al., 2010). The archipelago has the only insular mangrove of the South Atlantic Ocean (Mohr et al., 2009) and represents an important reproduction, feeding and resting area for sea turtles (Colman et al., 2015), cetaceans (Silva-Jr et al. 2005), fish (Garla et al., 2006) and seabirds (Mancini et al., 2016).

2.2. Sediment sampling

Field work was carried out during the dry season, for 13 days between 23rd October 2019 and 5th November 2019. Daily sediment samples were taken from two beaches on the leeward side of the island (Cacimba do Padre and Boldró, hereafter L1 and L2, respectively) and two beaches on the windward side (Leão and Sueste, hereafter W1 and W2, respectively) (Figure 1). Three replicates were collected each time, totalizing 39 samples (13 days x 3 replicates) per beach, except for W1, which totalized 36 (12 days x 3 replicates). In addition, when tidal range was highest and lowest (6th and 13th days, respectively), two more beaches were sampled: Conceição (hereafter L3) and Atalaia (hereafter W3), on the leeward and windward sides, respectively. Six samples were taken in each of them (2 days X 3 replicates).

In the present work, the methodology used by Ivar do Sul et al. (2017) was applied. During the low tide, a 30x30 cm quadrat was placed on the most recent strandline of the beach and a thin surface layer of sand was taken with a stainless steel flat spatula. The sample was placed into a beaker to measure its volume and then stored in an aluminium container. All field material was brushed between samples to remove the remaining sand. Quadrats were placed apart from each other covering approximately the whole beach length.

Figure 1. Location of Fernando de Noronha Archipelago (black star) in the Western Tropical Atlantic (left) and surveyed beaches on the main island (right). Black and blue dots represent the beaches where daily and weekly samples were taken, respectively.



Fonte: A Autora (2021).

2.3. Microplastic identification and characterization

In the laboratory, samples were oven dried at 60°C overnight. The dry samples were weighted and sieved through a stainless steel sieve with 1 mm mesh. The retained fraction was analysed under a Carl Zeiss Stemi 2000-C stereomicroscope and microplastic particles were individually identified. When particles seemed doubtful, a hot needle was used to confirm whether they were plastic or not. All microplastics were photographed and measured with ZEN 3.1 (blue edition) software from Carl Zeiss Vision. They were then classified according to size (1 – 1.99, 2 – 2.99, 3 – 3.99 and 4 – 4.99 mm), type (fragments, expanded polystyrene (XPS), pellets and fibres) and colour. Plastic particles larger than 5 mm were registered but not included in the statistics, as they are not considered microplastics. Due to uncertainties in identification and count of single fibres and to the high risk of contamination, only clusters of fibres were counted. To allow a wider comparison with other studies, the concentration of microplastics was expressed in three different units: particles/m², particles/m³ and particles/kg of sediment.

2.4. Physical parameters

For each day and beach, wind and wave data available online (https://www.surfguru.com.br/) were obtained. Wave height, period and direction were obtained by the WAVEWATCH III model from the National Weather Service / National Oceanic and Atmospheric Administration (NWS/NOAA), and wind speed and direction were obtained by the Global Forecast System (GFS) from the National Centers for Environmental Prediction (NCEP/NOAA). Tidal range was provided by the Brazilian Navy (https://www.marinha.mil.br/chm/tabuas-de-mare) and precipitation data was provided by the Water and Climate State Agency (APAC – Agência Pernambucana de Águas e Clima).

2.5. Grain size characterization

On the two days when all the six beaches were surveyed, 50 mL of sediment was collected next to each quadrat for grain size characterization. The dry sieving method was applied and the sediment was classified according to Folk and Ward (1957). Grain size analysis was conducted using Sysgran 3.0 software (Table 1).

2.6. Statystical analysis

The amount of microplastics identified were summarized as total count, minimum and maximum values per beach and concentrations were summarized in mean ± sd in each dimension (Table 2). The Shapiro-Wilk test was performed and indicated that microplastic concentration data was not normal. The data was then divided into two groups: leeward side and windward side, and the non-parametric Wilcoxon-Mann-Whitney U test (α=0.05) was applied to test statistical differences between them. Subsequently, the same test was applied for spring tide and neap tide. Both tests were performed independently. All statistical analyses were conducted using R Software Version 4.0.3 (R Core Team, 2020).

Table 1. Characteristics of the surveyed beaches in Fernando de Noronha Archipelago.

	Beach	Orientation	Length (m)	Sediment characteristic		
				Main Grain size	Sorting	Skewness
Leeward	L1	Northwest	450	Medium sand	Moderate	Near symmetrical
	L2	Northwest	650	Medium sand	Moderate	Positive
	L3	Northwest	700	Medium sand	Moderate	Near symmetrical
Windward	W1	South	450	Medium sand	Moderate	Near symmetrical
	W2	South	500	Fine sand	Moderate	Negative
	W3	Southeast	100	Medium sand	Moderate	Near symmetrical

Fonte: A Autora (2021).

3. RESULTS

3.1. Total abundance

A review of 71 studies of microplastic abundance on sandy beaches revealed that 54% of them expressed concentration in particles/m² and the same percentage expressed it in particles/kg (16 studies adopted two different units and three studies adopted three units). Six percent of the studies expressed concentration in particles/m³ and 18% in g/kg, g/m² or g/L. When size range is restricted to 1 – 5 mm (16 studies), most of them (69%) adopted particles/m². Therefore, this will be the main unit used in the present study to express microplastic concentration throughout the text (Table 2).

Overall, 165 quadrats were collected in Fernando de Noronha Archipelago and all the surveyed beaches were contaminated. Plastic items larger than 5 mm accounted for 398 particles from which 97.7% were found on the windward side and

2.3% (9 pieces) were found on the leeward side. A total of 947 particles were identified as microplastics (1 – 5 mm) and a high variability was found among quadrats. In general, the replicates presented a large difference between them, therefore, high values of standard deviation were obtained (Table 2). A significant difference was observed between the leeward and the windward side of the island (Wilcoxon-Mann-Whitney U test $p<0.001$), with windward beaches being markedly more contaminated.

On the windward side, microplastics were present in 56.8% of the samples. W3 presented by far the highest average concentration (1059.3 ± 1385.6 particles/m²) with a single sample containing 3711.1 particles/m², the most contaminated quadrat collected in this study. W2 had on average 98.6 ± 167.9 particles/m², with a maximum concentration of 688.9 particles/m². A difference of up to 55-fold was observed among replicates of W2 on the same day, and there was a decreasing trend in microplastic concentration from the west to the east side of the beach. On W1, average and maximum concentration were 6.2 ± 9.0 particles/m² and 33.3 particles/m², respectively. All beaches presented at least one sample with no microplastic particles (Table 2).

On the leeward side, only 8.3% of the samples had the presence of microplastics. L3 had the highest average concentration (5.6 ±13.6 particles/m²) with a maximum of 33.3 particles/m². In L1 and L2, the average concentration was 0.6 ± 2.5 particles/m² and 1.1 ± 3.4 particles/m², respectively. Both of them had a maximum concentration of 11.1 particles/m² (one microplastics per quadrat) (Table 2).

Table 2. Amount and types of microplastics found on sediment samples from the beaches of Fernando de Noronha Archipelago, with concentrations expressed in terms of area, volume and mass of sediment. *Only clusters of fibres were counted.

	Beach	N	Total Particles	Range	Fragments	Foam	Fibres*	Pellets	Particles/m² (±Stdev)	Particles/m³ (±Stdev)	Particles/kg (±Stdev)
Leeward	L1	39	2	0-1	0	1	1	0	0.6 (±2.5)	325.7 (±1419.3)	0.3 (±1.1)
	L2	39	4	0-1	0	3	1	0	1.1 (±3.4)	751.6 (±2297.8)	0.6 (±1.7)
	L3	6	3	0-3	2	0	0	1	5.6 (±13.6)	3703.7 (±9072.2)	2.6 (±6.4)
Windward	W1	36	20	0-3	13	1	4	2	6.2 (±9.0)	2987.0 (±4382.0)	2.2 (±3.4)
	W2	39	346	0-62	341	1	2	2	98.6 (±167.9)	50949.0 (±85974.9)	45.7 (±74.6)
	W3	6	572	0-334	556	7	0	9	1059.3 (±1385.6)	469774.6 (±539847.2)	318.5 (±360.9)
Total		165	947		912	13	8	14			

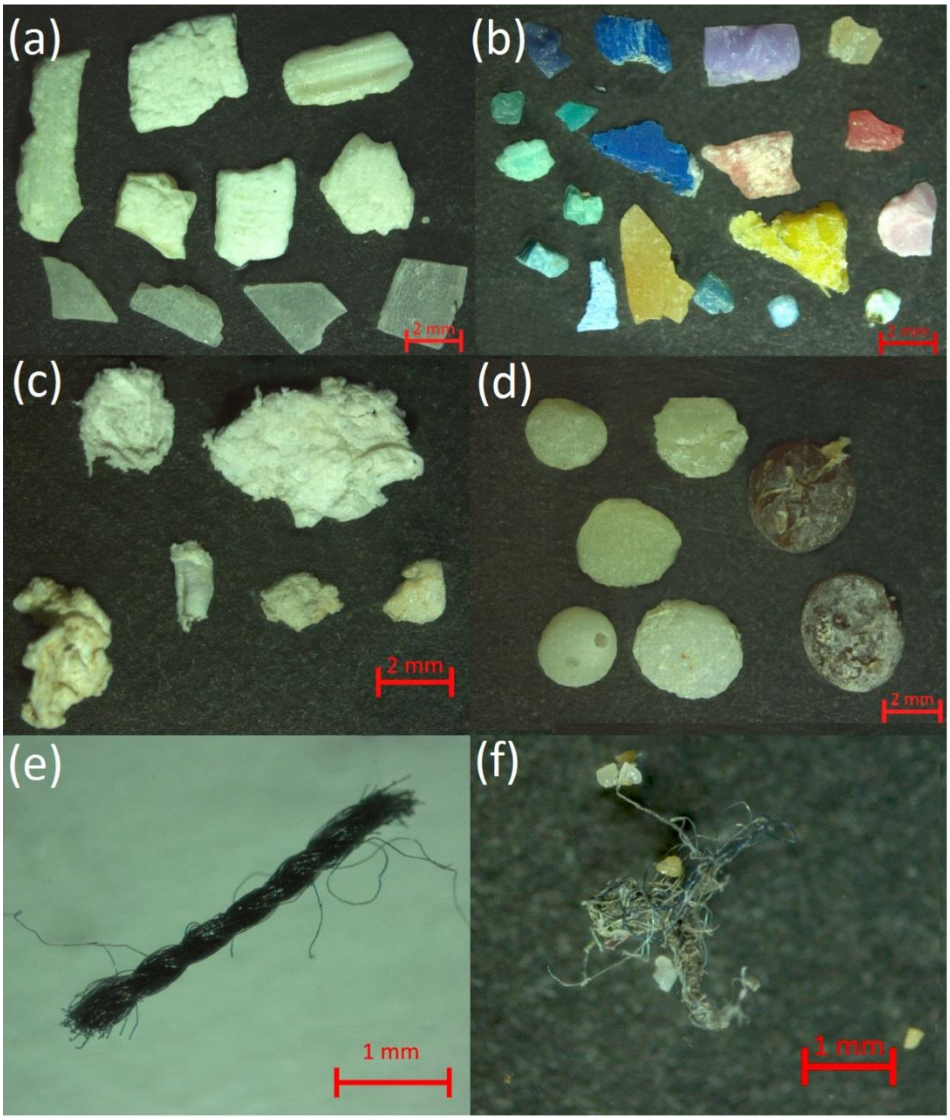
Fonte: A autora (2021)

3.2. Microplastic characteristics

Sampled microplastics comprised heterogeneous particles with diverse shapes, colours and sizes. Four different types were identified: fragments (96.3%), pellets (1.5%), XPS (1.4%) and fibres (0.8%) (Figure 2). On the leeward beaches, where microplastics were much less abundant, XPS was the most abundant type (44.4%). Out of the 14 pellets observed in this study, only one was found on the leeward side (Table 2). Signs of deterioration and weathering such as bleached colours, scratches and rounded edges were frequently observed on the microplastic particles (Figure 2).

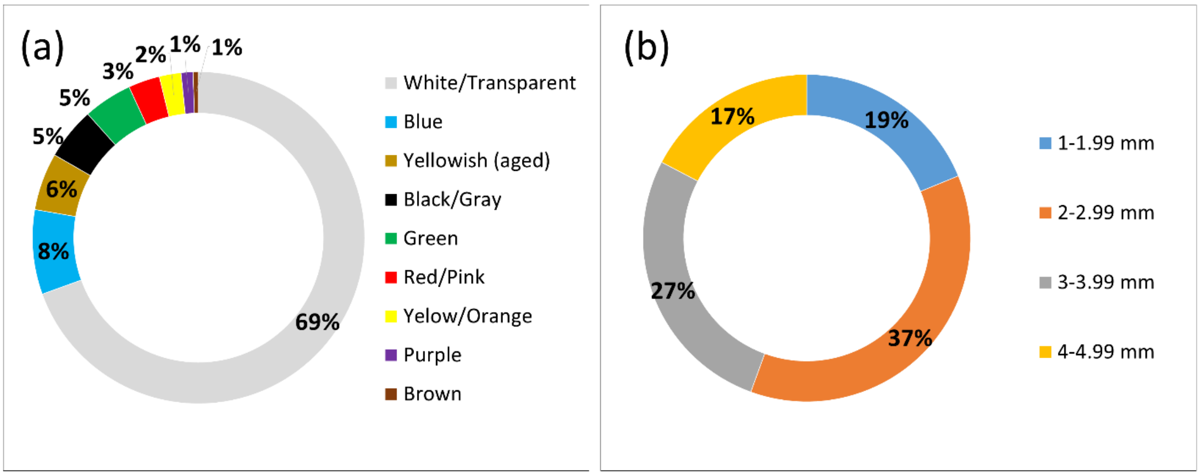
White and transparent particles were dominant (69.5%), followed by blue (8.2%), yellowish (aged, 5.6%), and black/gray (5.1%) particles. Other colours accounted for 11.6% (Figure 3a). The average size of microplastics was 2.9 ± 1.0 mm, and majority of particles ranged from 2.00 to 2.99 mm (36.7%) and from 3.00 to 3.99 mm (27.1%) (Figure 3b).

Figure 2. Examples of white and transparent plastic fragments (a), coloured plastic fragments (b), expanded polystyrene particles (c), virgin plastic pellets (d) and clusters of fibres (e and f) found on the beach sediment of Fernando de Noronha Archipelago.



Fonte: A Autora (2021).

Figure 3. Colours (a) and size classes (b) of microplastics identified in beach sediment samples from Fernando de Noronha Archipelago.



Fonte: A Autora (2021).

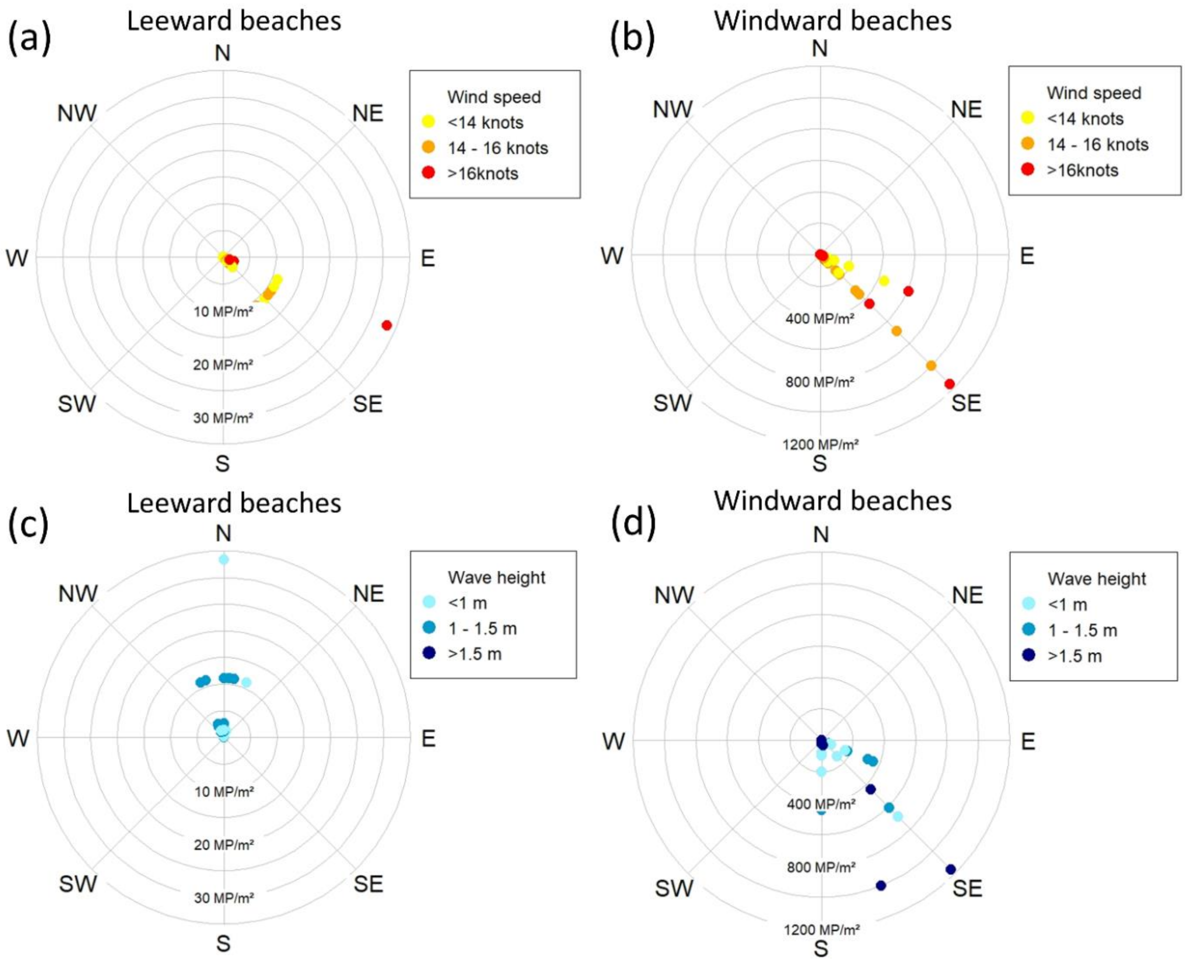
3.3. Temporal variability

On the leeward beaches, wind speed ranged from 12 to 18 knots and predominant wind direction was SE and ESE. For the waves, predominant direction was N and NNO and wave height ranged from 0.5 to 1.5 m. On the windward side, SE-ESE winds predominated with speed ranging from 12 to 19 knots. Wave heights ranged from 0.5 to 2.4 m and predominant direction was S and SE.

A large variability of microplastic concentration was observed between sampling days. The accumulation of these particles along the strandline showed a significant difference between neap tide and spring tide (Wilcoxon-Mann-Whitney U test $p<0.01$). The highest contamination levels were observed in spring tide, with an average concentration of 114.1 particles/m^2. During neap tide, average concentration was 18.6 particles/m^2 for all samples.

The azimuth wind plots showed that the highest microplastic concentrations on both sides of the island seem to be associated with wind speeds higher than 16 knots (Figure 4a and 4b). The azimuth wave plot for the windward side indicated that maximum microplastic concentrations were observed when wave height was above 1.5 m from SE and SSE (Figure 4c). On the leeward side, no clear trend was observed between microplastic concentration and wave height (figure 4d), but 91.7% of the samples had no microplastics.

Figure 4. Wind (a and b) and wave (c and d) azimuth plots for the leeward and windward beaches in Fernando de Noronha Archipelago. Distance from centre indicates microplastic concentrations in particles/m².



Fonte: A Autora (2021).

4. DISCUSSION

4.1. Total abundance

The present study provides evidence that microplastic contamination is recurrent on sandy beaches of Fernando de Noronha archipelago. For the first time, short-term variability of microplastics was assessed on the island and their concentrations were expressed in three different units. This new approach has provided a more complete assessment of the contamination status of Fernando de

Noronha and allowed a wider comparison with previous studies carried out around the world.

However, different particle size ranges and methods for sampling, extraction and identification of microplastics were important limitations for comparison with other studies. As an example, some works expressed concentrations in terms of microplastic mass (g/m^2, g/kg or g/L) instead of count (Baztan et al., 2014; Edo et al., 2019; Ivar do Sul et al., 2009). In these cases, it was not possible to numerically compare the results with the present work. Nevertheless, a qualitative comparison was still possible and similar patterns such as high variability and predominance of fragments could be observed.

Furthermore, the microplastics smaller than 1 mm (small microplastic particles, SMP) were beyond the scope of the present study, as it only focused on the 1 – 5 mm fraction (large microplastic particles, LMP). The smaller fraction may be generally more abundant and frequent than the larger one, as reported by Monteiro et al. (2020), who obtained concentrations between 85.1 ± 9.7 and 181.4 ± 64.2 SMP/m^2 for the leeward beaches of Fernando de Noronha, while Ivar do Sul et al. (2017) obtained concentrations ranging from 0 to 4.94 LMP/m^2 on the same beaches. Rapp et al. (2020) and Haave et al. (2019) have also observed very different patterns of distribution of SMP and LMP. For this reason, numerical comparisons of microplastic concentrations were restricted to studies with the same size range as the present one (Figure 5, Table S1). None of them expressed concentration in $microplastics/m^3$.

Fernando de Noronha archipelago is, in general, less contaminated than beaches in densely populated coastal areas such as Turkey (Yabanlı et al., 2019), Iran (Nabizadeh et al., 2019), India (Maharana et al., 2020) and South Korea (Eo et al., 2018). Compared to the Caribbean islands, most of the surveyed beaches in Fernando de Noronha have similar microplastic concentrations, except for W2 and W3, which are more contaminated (Schmuck et al., 2017). Only Turks and Caicos in the Caribbean had a microplastic concentration higher than W2 and W3.

In relation to the Canary Islands, most of the beaches in Fernando de Noronha presented lower levels of contamination, but once again with the exception of W2 and W3 (González-Hernández et al., 2020; Herrera et al., 2018; Rapp et al., 2020). However, the leeward beaches of Gran Canaria Island, which were selected by Rapp et al. (2020) as control, had a concentration on the same order of magnitude as W2, and in Tenerife and La Graciosa islands, average concentrations were higher than in W3 (González-Hernández et al. 2020; Herrera et al. 2018).

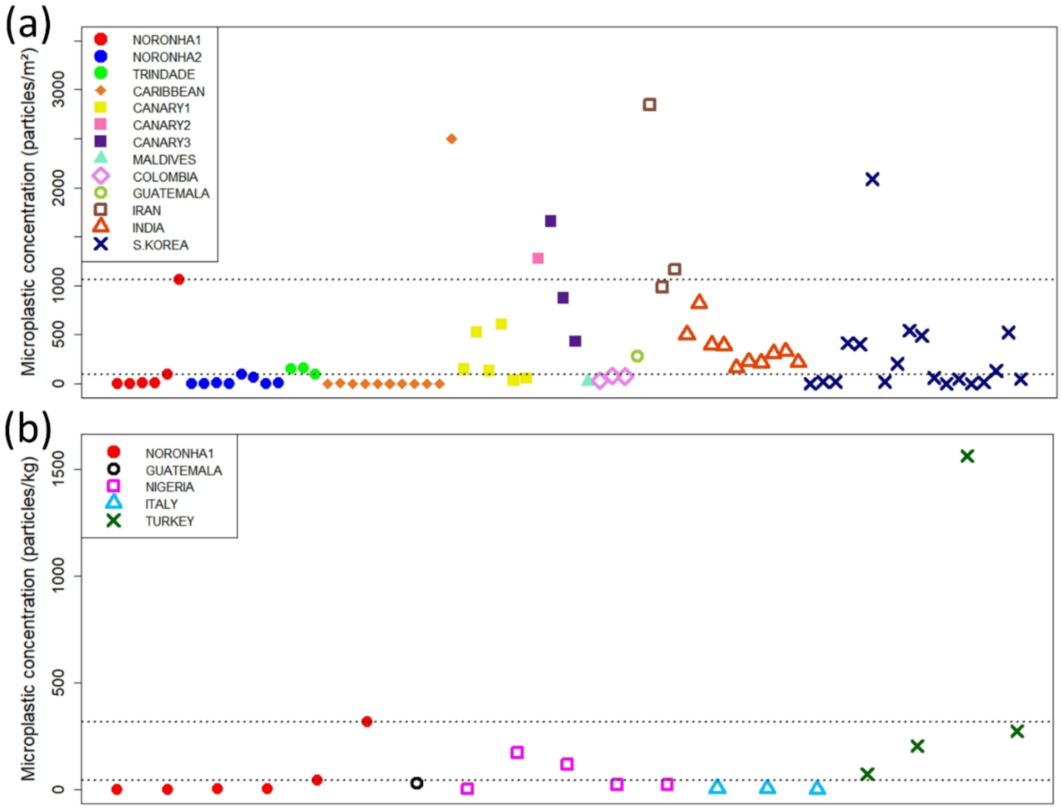
The largest amounts of floating plastic debris in the open ocean are observed in the oceanic subtropical gyres (Cózar et al., 2014), and the estimates for the North Atlantic are higher than for the South Atlantic (Eriksen et al., 2014). As the Canary Islands are close to the North Atlantic subtropical gyre, they may be receiving more plastic particles coming from the sea than Fernando de Noronha, which is not as close to the centre of the South Atlantic gyre. Furthermore, some of the beaches in the Canary Islands are intensely used by tourists and residents and sewage discharge could be contributing to the local generation of microplastics (Rapp et al., 2020).

On the Maldives, a small and remote coral island located in a sparsely populated area had an average concentration on the same order of magnitude as W2 (Imhof et al., 2017). Even though the island is scarcely inhabited and has a strongly limited on-island waste disposal, it may be receiving plastic debris from nearby islands or from coastal areas by long distance transport. It highlights the importance of drifting plastic debris for the accumulation of microplastics in remote locations, which also occurs in Fernando de Noronha (Ivar do Sul et al., 2017).

On the coast of Guatemala, Mazariegos-Ortíz et al. (2020) reported an average concentration of 279 particles/m^2 or 30 particles/kg. Considering the first unit, W2 was less contaminated by one order of magnitude. However, if we consider the concentration in particles/kg, both beaches had similar results (Figure 5). W3 in turn, had a concentration one order of magnitude higher for both units. It demonstrates how comparability between studies can be affected depending on the unit and levels of contamination and reinforces the need for standard units and methods.

On a snapshot sampling carried out seven years earlier in Fernando Noronha, no microplastics were found on L1 and L2. On L3, only one particle was found, resulting in a similar concentration as the one obtained in the present study (Ivar do Sul et al., 2017). On the windward side however, W2 and W3 reached concentrations one and two orders of magnitude higher than previously observed, respectively. On W1 concentrations were similar in both studies. There is an exponential increase in plastic consumption and waste production worldwide (Geyer et al., 2017b), which could be reflected in our results. However, further studies and long term monitoring are needed to confirm this trend in Fernando de Noronha. Furthermore, in the previous study, samples were collected in the rainy season, while in the present one, samples were collected in the dry season. As the oceanographic and meteorological parameters such as wind, waves and current vary among seasons (Calliari et al., 2016), microplastic concentration may also vary. Nevertheless, snapshot sampling may deliver biased results and does not reliably quantify the abundance of plastic debris on beaches, as suggested by Imhof et al. (2017). Future studies should explore the variabilities of microplastic distribution in different scales of time and space (i.e. days, weeks, months, seasons and years), further investigating processes of deposition and resuspension.

Figure 5. Concentration of large microplastics particles (1 – 5 mm) in different beaches around the world expressed in particles/m² (top) and particles/kg (bottom). Dotted horizontal lines represent concentrations of W2 (lower line) and W3 (upper line). NORONHA1 = Fernando de Noronha Archipelago, Brazil (present study); NORONHA2 (Ivar do Sul et al., 2017); TRINDADE (Ivar do Sul et al., 2017); CARIBBEAN (Schmuck et al., 2017); CANARY1 (Rapp et al., 2020); CANARY2 (González-Hernández et al., 2020); CANARY3 (Herrera et al., 2018)*; MALDIVES (Imhof et al., 2017); COLOMBIA (Garcés-Ordóñez et al., 2020); GUATEMALA (Mazariegos-Ortíz et al., 2020); IRAN (Nabizadeh et al., 2019); INDIA (Maharana et al., 2020); S.KOREA (Eo et al., 2018); NIGERIA (Fred-Ahmadu et al., 2020); ITALY (Piehl et al., 2019); TURKEY (Yabanlı et al., 2019). * Values estimated from mean weight of particles; samples includes tar and microplastics.



Fonte: A Autora (2021).

4.2. Spatial distribution

The significantly higher contamination rates found on the windward beaches of Fernando de Noronha suggest that large amounts of debris are being transported to the island by the wind and surface currents. This is a well known pattern that has been described in previous works in the archipelago and elsewhere (Baztan et al., 2014; Ivar do Sul et al., 2017, 2009; Rapp et al., 2020). The leeward beaches, which are less exposed to currents and wind, presented low levels of contamination, indicating that local sources of microplastics are less important.

A similar pattern was observed by Grillo and Mello (2021) for the macro-litter on the island. The total weight of debris was significantly higher on the windward coast and items such as hospital waste and packages with foreign language labels at early decomposition states, which probably came from far away, were found exclusively on this side of the island. Some of the items frequently observed are made of polymers that are less dense than seawater (e.g. polyethylene and polypropylene), therefore they float in the ocean and can be easily transported by currents and wind (Andrady, 2011). On the leeward side, which is more sheltered, locally generated debris such as cigarette butts and disposable plastics were more abundant (Grillo and Mello, 2021). However, these items had probably not been on the marine environment for long enough to degrade into microplastics.

W2 and W3 had especially high microplastic concentrations when compared to the other surveyed beaches. This may be related to a series of unique characteristics in each of them. W2 is a semi-enclosed bay, with shallow water and gentle slope. It represents the most sheltered coastal environment of the archipelago (Barcellos et al., 2017), as the presence of small headlands and islets in front of it restrain wave action and facilitate microplastic accumulation. In addition, W2 is one of the few beaches on the island with good available infrastructure, easy access and suitable conditions for swimming and snorkelling, which make it very popular for tourists, increasing the human impact on the beach (Cristiano et al., 2020). Even though most of the plastic debris in W2 probably come from the sea, tourism may also contribute to the local generation of litter, as observed in other beaches (Garcés-Ordóñez et al., 2020). In the Caribbean Islands, higher microplastic concentrations were associated with high human traffic (Schmuck et al., 2017).

W3 is protected by a coral reef with a shallow inner lagoon, which may act as a physical barrier for wave action. Previous studies have associated the presence of hard structures parallel to the beach with higher amounts of microplastics being deposited on the strandline (Pinheiro et al., 2019). Furthermore, W3 has a southeast orientation (Table 1), facing the prevailing SE trade winds and the SEC (Calliari et al., 2016; Tchamabi et al., 2018). Together, these morphological characteristics are a good combination for the intense arrival and accumulation of microplastics on the beach.

W2 and W3 also showed a high variability within each of them, with very different concentrations among replicates of the same day. This small scale heterogeneity along the beach has been reported in other places and it is suggested to be dependent on morphological settings of the beaches and oceanographic conditions (Chubarenko et al., 2018; Constant et al., 2019; Reinold et al., 2020). In W2, the west side of the beach, where higher microplastic concentration were observed, is also where Barcellos et al. (2017) reported a higher accumulation of sediment due to wind action and longshore drift.

4.3. Microplastic characteristics

The main characteristics of microplastic particles observed in the present study are similar to those previously reported on the beaches of Fernando de Noronha (Ivar do Sul et al., 2017). The predominance of fragments is consistent with what was observed on the sea surface around Fernando de Noronha and other oceanic islands of the Western Tropical Atlantic Ocean (Ivar do Sul et al., 2014). Furthermore, a prevalence of plastic fragments and white/transparent particles was also observed in studies from beach sediment in different parts of the world, such as Hawaii (Young and Elliott, 2016), Azores archipelago (Pham et al., 2020), India (Patchaiyappan et al., 2020) and Taiwan (Bancin et al., 2019). These fragments originate from larger items that break down into smaller particles under the action of sunlight, microbes, high temperatures, etc. (Andrady et al., 2011). On the swash zone, mechanical fragmentation of plastics may be even more intense because of wave action (Efimova et al., 2018). Therefore, the large number of fragments on the beach sediment of the archipelago was already expected.

Signs of deterioration observed on the microplastic particles (i.e. cracks and pits) and yellowish colors suggest that they had been exposed for a long time in the marine environment (Brandon et al., 2016). In addition, the pellets found on the island probably come from far away, as there is no plastic industry on the island or near it. These evidences reinforce the influence of surface currents on the long-distance transport of microplastics in the open ocean (Ivar do Sul et al., 2017).

XPS particles, which were found on both sides of the island, also probably have exogenous sources. Foamed polystyrene items have been reported as the most frequently observed macroplastic type floating in the open ocean (Eriksen et al., 2014). As their specific gravity is less than that of seawater, they tend to stay on the surface of the water column and are likely to be transported by currents and wind (Sagawa et al., 2018). When exposed in the environment, larger items of XPS easily break down into small particles, which have been reported on beaches in the Brazilian coast (Castro et al., 2020), Guatemala (Mazariegos-Ortíz et al., 2020), Peru (De-la-Torre et al., 2020) and Japan (Sagawa et al., 2018). However, despite the recent ban of several types of single-use plastics on the island, XPS is still allowed. Residents frequently transport food from the mainland in XPS containers, which are disposed once they arrive on the island (Daniele Mallmann, personnal communication). Thus, this could be an additional source of the XPS microplastic particles found on this study.

The fibres reported on the island could be from fishing activity or from sewage discharge (Figure 2e and 2f), which have been demonstrated as relevant sources of microplastics (Browne et al., 2011; Cole et al., 2011). In Fernando de Noronha, fishing is an important activity (Dominguez et al., 2016), and large pieces of derelict fishing nets were observed on W2 (personal observations). The fragmentation of these items could have originated microplastics. Furthermore, wastewater treatment system on the island is deficient and irregular effluent disposal on the beaches are observed (Cristiano et al., 2020), possibly contributing to microplastic pollution. However, fibres only accounted for 0.84% of sampled particles, suggesting these are not the main sources of LMP in the island. On the other hand, fibres corresponded to 90% of all SMP found by Monteiro et al. (2020) in Fernando de Noronha. The predominance of fibres was also observed in other studies, especially among particles < 1mm (Lots et al., 2017; Piñon-Colin et al., 2018).

In relation to colour, transparent and blue microplastics, which were prevalent in the present study, are also the most abundant colours of microplastics detected in the biota in China (Fu et al., 2020). White and light coloured particles may be mistaken with natural food sources, especially by visual predators such as fish and fish larvae, increasing their bioavailability, as indicated by Wright et al. (2013) in a review study. This is alarming as Fernando de Noronha has high biodiversity and endemic species, which could be potentially affected (Serafini et al., 2010).

4.4. Temporal variability

A high daily variation of microplastic concentration was reported in the present study, indicating that the distribution of these particles in the sandy beaches of Fernando de Noronha is highly dynamic and it is possibly influenced by the combination of a number of physical drivers. A high daily variation of microplastics was also reported on the Maldives, where an up to 40 fold difference in daily plastic abundance was observed, but no direct relationship was observed with wind speed or direction (Imhof et al., 2017).

It was not possible to establish a correlation between microplastic abundance and wind or wave action, however a slight trend was observed, especially on the windward side, with maximum concentrations associated with higher wind speed and wave height. The association of high microplastic contamination levels with strong winds and waves have also been observed in the Canary Islands by Herrera et al. (2018) and González-Hernández et al. (2020). The latter analysed the concentration of these particles during a whole moon cycle and reported the highest amounts of debris when wind was strongest. The authors suggest that even though contamination levels were significantly different between moon phases, this difference was mainly related to the wind pattern and not to the tides.

A modelling study conducted on the Scottish North Sea Coast has demonstrated that the deposition of floating marine macro-litter on the beach is a complex function of variable wind and water level, and it cannot be correlated with the wind variability alone (Turrell, 2018). In addition, other processes such as the degradation of macroplastics into microplastics at the sea and on the beach, may also influence the accumulation of these particles on the sediment (Critchell and Lambrechts 2016).

In Fernando de Noronha, a significant difference was observed between spring and neap tides, however further studies would be necessary better understand the relative influence of each of these physical processes and how they act together. Variabilities in different space and time scales should also be considered, as well as surface currents around the island, in order to improve our understanding of microplastic deposition and removal mechanisms in sandy beaches.

5. CONCLUSION

In summary, microplastic pollution is recurrent in the beach sediment of Fernando de Noronha and the South Equatorial Current plays a key role in the long-distance transport of these particles to the island. Microplastic distribution was highly heterogeneous in small-scales of time and space, hindering inferences about large-scale trends in beach loading rates and relative influences of physical processes such as wind and waves. Great care is needed for spatial and temporal sampling design of microplastic surveys in beach sediment and meteo-oceanographic parameters should be taken into account in future studies and monitoring programs.

Even though three different units were used in this work, comparison between studies was still limited due to a wide range of sampling approaches and analytical techniques, as well as different size fractions analysed. It reinforces the need for standardized methods in order to make data comparison more accurate and reliable.

Within the existing literature, a wider comparison was possible with little additional effort to obtain microplastic concentration in different units. Therefore, it is advisable to report the area, volume and the dry weight of the collected sediment samples, whenever possible.

The microplastic pollution in Fernando de Noronha poses a risk to the unique biodiversity found on the archipelago and conservation strategies are extremely important to mitigate anthropogenic impacts on the ecosystem. Even though the island is a marine protected area, some management measures (i. e. sewage treatment) are not implemented satisfactorily and should be improved in order to effectively protect the local species.

Furthermore, the underlying causes of marine litter should be addressed in environmental education activities and public awareness-raising campaigns, encouraging pro-environmental behaviour. The findings of the present work, together with our current knowledge about microplastic pollution on the archipelago may provide support to management and educational strategies aiming to tackle the marine litter issue.

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5 CONSIDERAÇÕES FINAIS

Em conclusão, o presente estudo evidencia que a poluição por microplásticos é recorrente no arquipélago de Fernando de Noronha e que a Corrente Sul Equatorial possui um papel importante no transporte dessas partículas até o arquipélago. A distribuição dos microplásticos é altamente heterogênea em pequena escala temporal e espacial, dificultando a compreensão de tendências de longo prazo dos níveis de poluição das praias e da influência relativa de processos físicos como ondas e ventos. Estes fatores devem ser levados em consideração durante o planejamento de futuras campanhas de amostragem. Estudos de modelagem das correntes superficiais também podem trazer informações relevantes a respeito do transporte de microplásticos na região.

Mesmo com a utilização de três diferentes unidades de concentração, a comparação com diferentes trabalhos foi limitada devido à variedade de metodologias e frações de tamanhos analisadas nos estudos. Reforça-se então a necessidade de gerar resultados comparáveis para que variações espaciais e temporais de maior escala possam ser bem compreendidas. Diante da literatura já disponível no momento, uma comparação mais ampla foi possível sem a necessidade de grandes esforços adicionais para obter a concentração de microplásticos em diferentes unidades. Portanto, aconselha-se que em futuras coletas de sedimento, sejam registrados a área, o peso e o volume das amostras, sempre que possível.

A poluição por microplásticos em Fernando de Noronha representa um risco evidente à biodiversidade local, e estratégias de conservação são de grande importância para amenizar os impactos antrópicos no ecossistema. Embora as fontes marinhas de microplásticos não possam ser controladas a partir de estratégias na ilha, as fontes locais dessas partículas podem ser reduzidas. Sendo assim, a determinação da origem dos microplásticos através de experimentos é fundamental para auxiliar no desenvolvimento das estratégias de conservação. Os efluentes domésticos são potenciais fontes dessas partículas para o oceano e medidas relacionadas ao saneamento básico devem ser melhoradas para que haja cada vez menos contaminação dos efluentes. Além disso, atividades de educação ambiental e campanhas de sensibilização do público podem incentivar hábitos mais sustentáveis, diminuindo assim o uso e descarte do plástico. A redução da manipulação desse material na ilha poderá, por consequência, reduzir a possibilidade de ação das fontes locais de microplásticos.

Por fim, os resultados do presente trabalho e o conhecimento prévio a respeito da poluição por microplásticos no arquipélago demonstram a importância de entendermos os processos de deposição e retirada dessas partículas no sedimento das praias. Assim será possível fornecer apoio a medidas de gerenciamento e de educação, visando contribuir para o combate ao lixo no mar.

Apesar dos efeitos negativos deste material no ambiente marinho, os resíduos plásticos no oceano também podem ser usados para indicar tendências e fornecer informações importantes sobre o seu comportamento ao longo de todo o ciclo de vida e sobre os níveis de impactos antrópicos. Por estar amplamente distribuído em depósitos sedimentares, este material também funciona como registro paleoecológico, atuando como marcador da nova era geológica, Antropoceno (Zalasiewicz et al., 2016). Além disso, por ser um problema bastante visível, o plástico depositado nas praias pode ter a função de uma espécie bandeira, chamando a atenção para os impactos que esses ambientes sofrem e criando um apelo para a necessidade de conservação.

Como continuação deste estudo, sugerimos a investigação da variabilidade de microplásticos em diferentes escalas temporais e espaciais, bem como da conectividade entre diferentes compartimentos (ex.: sedimento e água do mar). A importância relativa de cada potencial fonte de microplásticos para a ilha também deverá ser investigada, para que exista uma maior possibilidade de combatê-las. Reconhecendo a importância de analisar a composição química dos microplásticos presentes no meio ambiente (Ivar do Sul, 2021), trabalhos já em andamento determinarão os tipos de polímeros encontrados no sedimento do arquipélago, através de espectroscopia Raman. Esta análise química, junto com a análise visual de características como tipo e cor, serão indispensáveis na determinação da conectividade entre os compartimentos.

Dentro de um projeto mais amplo, estes resultados serão comparados com amostras das Ilhas Galápagos, que assim como Fernando de Noronha, são um conjunto de ilhas oceânicas diretamente impactadas pela poluição por plástico (Zambrano-Monserrate e Ruano, 2020). Este trabalho também irá contribuir com o desenvolvimento de um método mais rápido e acessível para identificação e contagem de microplásticos, baseado em fotografias (Silva, 2019).

Portanto, espera-se que os resultados do presente estudo, possam ir além daqueles apresentados até momento e que as crescentes descobertas a respeito dos microplásticos no ambiente marinho auxiliem a implementação de medidas efetivas para redução dos seus impactos no oceano.

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