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Composition and abundance of microplastics in the marine and coastal areas in the Azores (North-Eastern Atlantic)

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Abstract:

Every year, millions of tons of solid waste are thrown into the sea with negative implications for the environment and, consequently, for the ecosystems and species that inhabit it. Commercial maritime traffic and ocean gyres lead to a significant increase in the amount of pollution in the waters and coasts of remote oceanic islands. Most of this type of pollution is plastics items, and those that are smaller than 5 mm are considered microplastics. These particles are ubiquitous throughout the marine environment, dispersed among beaches, estuaries, on the water surface and even on the seafloor, affecting ecosystems and impairing species. The objective of this study was to estimate the abundance and dimension of microplastics along the coast of São Miguel Island, Azores, following an inshore-offshore gradient along a stream until the ocean. Sediment samples were collected and analysed for across 8 areas covering the entire coastline of the island, each one divided among 4 connected sites, along an inland-coastal gradient, from the stream until the ocean (upstream, downstream, coastal, and submerged marine sediments), following a nested design approach. Also, apart from this first approach, 15 beaches, covering all island, were also tested and compared. In both sampling approaches (areas and beaches), the highest abundance of microplastics was 0.74 MP/g (Ribeira Quente), and the lowest 0.20 MP/g (Ribeira Praia), both in South beaches. The largest category of microplastics was fibres, followed by microbeads and fragments, and the most abundant colours were transparent, black, and blue. There was significant variability in the abundance among areas, sites and beaches, and only among sites and beaches in the dimension. Factors like granulometry, sites and pollution sources are detected as significant in microplastics abundance. This study results are important to the scientific community and particularly for local government concerning litter management and mitigation.

Keywords: Plastic; marine litter; sediment; coastal zone; oceanic islands.

Resumo:

Todos os anos, milhões de toneladas de resíduos sólidos são lançados no mar com implicações negativas para o meio ambiente, os ecossistemas e as suas espécies. A poluição marinha pode ser entendida pelo aumento da concentração de uma substância, normalmente poluente, introduzida pelo ser humano, direta ou indiretamente, no ambiente oceânico, de onde resultam implicações negativas para os organismos, saúde humana e atividades marítimas. Os microplásticos são o resultado da libertação ou fragmentação de pedaços de plástico em partículas menores que 5 milímetros. Esses detritos são omnipresentes em todo o ambiente marinho, como praias, estuários, superfície da água e fundo do mar. Esta problemática põe em perigo inúmeros organismos marinhos, incluindo zooplâncton e ovos, embriões e larvas de peixes, contaminados quer por ingestão de partículas microscópicas, quer pela sua adesão às carapaças e apêndices dos organismos.

Os Açores possuem uma das maiores Zonas Económicas Exclusivas da União Europeia, associada a uma grande diversidade de espécies e habitats marinhos. Apesar da inexistência de indústria pesada, este arquipélago tem vindo a experimentar um aumento exponencial de turismo e rotas comerciais entre o continente americano e europeu. Uma vez que o principal pilar económico dos Açores é a pesca, e na ausência de indústria pesada, é natural que a maior parte do lixo seja proveniente desta fonte. Devido à localização remota, e não só, os sistemas de resíduos e aterros sanitários desta comunidade não estão bem preparados para lidar com grandes quantidades de lixo. Além disso, estando no centro de um giro oceânico, os Açores estão sujeitos a um aumento significativo da quantidade de poluição nas águas e costas.

O objetivo do presente estudo é estimar a abundância, composição e dimensão dos microplásticos ao longo da zona costeira da ilha de São Miguel, seguindo um gradiente litoral-mar aberto ao longo das ribeiras que correm em direção ao oceano, e em várias praias que cobrem toda a ilha. Especificamente, pretende-se identificar as categorias de microplásticos presentes; determinar a quantidade e o tamanho do microplástico em cada categoria; e identificar e discutir diferenças e fatores que possam contribuir para sua distribuição.

Foram estabelecidos dois desenhos de amostragem:

- Primeiro, a ilha de São Miguel foi dividida em oito áreas (3 no setor Norte, 3 no setor Sul, 1 no sector Oeste e 1 no sector este), onde foram obtidas amostras de sedimentos em quatro locais distintos ao longo de uma ribeira (a uma distância mínima de 300 metros), seguindo um gradiente a partir do interior em direção à costa, nomeadamente: montante, jusante, zona costeira (praias) e zona submersa. Em cada local foram obtidos 5 replicados, com aproximadamente 5-10 metros de distância. Ainda é importante referir que este estudo tem um desenho não balanceado devido à existência de apenas uma área e uma praia no sector Este e Oeste;

- O segundo delineamento abrangeu a colheita de 5 replicados (com a mesma distância entre si) em 15 praias, distribuídas por toda a costa de São Miguel.

As amostras recolhidas nas praias de ambas as abordagens foram obtidas um pouco acima da linha de maré-alta. Em todas as recolhas, a camada superficial foi removida, com uma espátula com o intuito de remover matéria orgânica, mesoplásticos e outros possíveis lixos. O sedimento foi colocado num recipiente de metal com uma etiqueta identificando a data, local e número da amostra, sendo aquele vedado com parafilme. Quando a quantidade de sedimento seco não era suficiente, o mesmo foi retirado do monte mais alto sob a água. As amostras na região marinha foram obtidas em mergulho, mediante o mesmo método, e sempre no ponto mais alto. Em laboratório, as amostras secaram em estufa a 60ºC durante 48h em placas de Petri previamente pesadas e registadas. As amostras foram então imersas em

400ml de solução salina, em cada litro com 400 gramas de sal, e deixadas em repouso por 5 horas. Foram então bombeadas a vácuo com filtros de papel Millipore 0,45µm, de 47 mm. O sobrenadante foi filtrado com o auxílio de uma peneira de 100 micrômetros para evitar que objetos grandes dificultassem a visualização das partículas de interesse ao microscópio. Esse processo foi repetido 3 vezes com diferentes papéis de filtro, de modo que cada amostra passasse por três imersões para garantir que cada microplástico fosse capturado e registado. Após a filtração, o filtro foi observado em lupa estereoscópica com uma magnificação de 4,0x, registando o número, cor, comprimento e a composição de microplástico, podendo os mesmos ser fibras, microesferas ou fragmentos.

A abundância e dimensão das partículas de microplásticos foram determinadas para cada local de amostragem, de acordo com cada categoria. Para a determinação do significado estatístico das variações encontradas, foram estabelecidos quatro (2x2: abundância ou dimensão para cada delineamento amostral estabelecido) delineamentos do teste PERMANOVA: Três fatores, tratados como aleatórios, com dois termos aninhados, para as variáveis de abundância e dimensão: setor da ilha, áreas dentro dos setores e Sítios em áreas e setores; Dois fatores, tratados como aleatórios, com design de um termo aninhado, para as variáveis de abundância e dimensão: setor ilha e praias dentro dos setores.

Para avaliar os fatores que influenciam a variação na abundância e tamanho de microplásticos, foram aplicados modelos lineares generalizados com diferentes combinações de conjuntos de preditores, incluindo setor de ilha, área, local, granulometria, proximidade da poluição. A granulometria foi classificada entre as classes, argila (<1/256 mm); lodo (1/16–1/256mm), areia (2-1/16mm) e seixo (64 – 2mm). No setor insular, as amostras foram divididas entre Norte, Sul, Leste e Oeste. A proximidade de uma fonte de poluição foi classificada de acordo com a distância de cada local ao centro urbano mais próximo.

A categoria mais abundante encontrada foi a das fibras, seguida da de microesferas e da dos fragmentos. O setor da ilha com mais microplásticos amostrados foi o Oeste da ilha, sendo também o sector com a maior dimensão dos microplásticos. Nas áreas, a maior abundância foi de 0,56 MP/g na Ribeira Quente (A3) e a menor foi de 0,26 MP/g na Ribeira da Praia (A7). As cores mais abundantes foram transparente, preto e azul e a média de dimensão de microplásticos foi de 2,19 mm. Nas praias, a maior abundância foi de 0,72 MP/g na praia da Ribeira Grande (B10) e a menor foi de 0,20 MP/g (B11) na praia da Ribeira da Praia. Aqui as cores mais comuns foram igualmente transparente, preto e azul, sendo a média do tamanho das partículas 2,14 mm. Os resultados do teste PERMANOVA mostraram variabilidade significativa entre áreas, locais e praias na abundância, e entre locais e praias na dimensão. A maior componente de variação ocorreu na menor escala espacial, seguida de locais e depois áreas, principalmente para a dimensão dos microplásticos. A abundância de microplásticos parece aumentar significativamente com fontes de poluição próximas, em locais com menor granulometria dos sedimentos. A dimensão de microplástico diminui significativamente em direção a áreas mais costeiras e é afetada pela poluição próxima. Os resultados do teste PERMANOVA mostram uma variabilidade significativa entre as praias, mas não entre os setores tanto para a abundância quanto para a dimensão dos microplásticos. As praias funcionam como um local de armazenamento de detritos residuais, devido à concentração e deriva de lixo nas correntes, e taxa de deposição.

Palavras-chave: Plástico; lixo marinho; sedimento; zona costeira; ilhas oceânicas

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1. Introduction

Marine litter is defined as any waste of anthropological origin intentionally discarded, lost, or placed in the environment, representing a global environmental and ecological threat, affecting large bodies of water, harming wildlife and human health, and promoting greenhouse gases (Pieper et al., 2021). Its abundance and distribution depend on several factors, including its origin (maritime or terrestrial), ocean currents, wind patterns, and even physiographic characteristics (Consoli et al., 2018). Nevertheless, by examining oceanographic models and through empirical observations, it is proven that these discarded residues float on the ocean surface and tend to accumulate in the ocean gyres. Consequently, the coast of oceanic islands, with the action of currents, usually tends to present high levels of this type of pollution (Rodríguez et al., 2020), also because it focuses on the litter that originated from land.

Marine litter items are also responsible for affecting a wide range of economic sectors, increasing costs in cleaning budgets carried out by parties involved in marine activities, and impairing tourist activities as well as the fishing and shipping industries (Rodríguez et al., 2020). Nevertheless, there is still a limited worldwide understanding of the economic implications of marine litter for coastal communities, particularly in remote regions. Since human society is currently predominantly driven by economic interests, economic assessments focused on marine litter could control the entry of these items and warn of the consequences of increasing consumption of plastics (Rodríguez et al., 2020). On the other hand, in these remote locations, the resources needed to tackle problems related to marine litter can strongly impact the local economy, in addition to sometimes having to process quantities of litter that exceed the capacity of available landfills (Rodríguez et al., 2020).

Plastic, a major component of marine litter, is a synthetic material, produced from hydrocarbons, with a malleability that allows it to have all shapes and dimensions (van Emmerik & Schwarz, 2020). Its worldwide production and consumption rates prevent it from being recycled in a sustainable way (Sartain, 2021). Currently, the sectors that use plastic are divided into packaging, construction, transport, electronics, textiles, security, and leisure. Also, the gradual expansion of the world's plastic production directly affects greenhouse gas emissions. Zheng and Suh (2019) found that, in 2015, the global life cycle of greenhouse gas emissions of plastic was 1.7 Gt of CO_2 in a total of 40.3 Gt in that year (Le Quéré et al., 2015). This material is responsible for 80% of all marine litter found from deep-sea sediments to surface waters (IUCN, 2021)

Microplastics are any type of plastic smaller than 5 millimetres (Lots et al., 2017). They can be grouped into primary and secondary microplastics. Primaries are microscopic in dimension, such as clothing fibres, polyester, and acrylic fibres, which are likely to be admitted into the environment by wastewater treatment plants and industrial drainage systems (Lots et al., 2017). Secondaries are derived from the fragmentation of large plastics due to sun exposure and mechanical erosion (Oerlikon, 2009; Lots et al., 2017). Depending on their density in relation to seawater, microplastics can remain on the surface or sink, as in the case of PVC. Plastics such as polyethylene and polypropylene tend to float and drift through marine currents in the open ocean (Gross, 2015). There are many compositions of shapes of microplastics that are abundant in marine ecosystems, like fibres, microbeads, fragments, foam, films and pellets (Kumar et al., 2021). It was predictable that the accumulated number of microplastic particles in 2014 varieties from 15 to 51 trillion particles, weighing around 93 and 236 thousand metric tons, which represents only 1% of worldwide plastic waste estimated to enter the marine ecosystems in 2010 (Sebille et al., 2015; García Rellán et al., 2022).

Microplastics are ubiquitous throughout the marine environment (Lots et al., 2017), occurring in beaches, estuaries, water surfaces, and seafloor, travelling great distances when suspended in water or remaining within sediments on the seafloor (Xanthos & Walker, 2017). The distribution of plastic debris depends on various elements such as winds, currents, coastal geography, and human factors such as trade routes and urban areas. The Mediterranean Sea and the Atlantic Ocean are examples of how this happens, where the density of plastic debris is high (Li et al., 2016). An expedition carried out in the Mariana Trench showed that microplastics were found in the stomachs of all amphipods analysed (Jamieson et al., 2019). Another, performed in the Western Pacific Kuril-Kamchatka Trench, revealed that at a depth of up to 9,450 m, there were between 215 and 1,596 microparticles per kg in 13 sediment samples (Abel, 2022). They have also been found in samples of snow and stream water on Mount Everest, at about 8,440 m above sea level (Napper et al., 2020). It is also important to note that the presence of microplastics has been confirmed to increase water evaporation and the rate of cracking in soil (Wan et al., 2019) and it negatively affects the oceans' carbon retention (Shen et al., 2020).

The microplastics present in marine ecosystems bioaccumulates in various organisms, including humans, and crosses the food chain (Crawford & Quinn, 2016). It is already known to affect plankton physiology (Lönnstedt & Eklöv, 2016; Shen et al., 2020) and feeding, and impairs fish dimension, hatching rate, activity, locomotion, and mobility time, hence turning these organisms more susceptible to predation (Cannon et al., 2016). Microplastics might decrease feeding stimuli because of the false sense of fullness, causing the bird to not eat, and eventually, die of malnutrition or starvation (Susanti et al., 2013).

Microplastics in contact with lung and intestinal epithelial linings in humans can cause physical, chemical, and microbiological toxicity (Vethaak & Legler, 2021). Microplastics were first detected in human blood in March 2022 in nearly 80% of humans tested. This discovery shows how particles can be transported through the body and inserted into organs. Half of the samples contained polyethylene terephthalate (PET), commonly used in beverage bottles, polystyrene, used in food and another product packaging, and polyethylene, used in plastic bags. Although the impact of this specific microplastic is still unknown, scientists are concerned about the damage it can cause to cells (Carrington, 2022). In April 2022, microplastics were found for the first time in the lungs of living humans, mostly polyethylene terephthalate and polypropylene (PP), used in plastic packaging and pipes (Jenner et al., 2022). Lastly, in June of the same year, they were found in human breastmilk, mostly compounded by polyethylene (Ragusa et al., 2022).

Marine pollution studies have been increasing considerably over the last decade, reflecting its importance and worldwide concerns, however there is still limited information regarding plastic quantification and distribution, particularly around oceanic islands (Thompson et al., 2009).

The Azores archipelago is subjected to different types of ocean/atmosphere variability and ocean dynamics at diverse scales (Martins et al., 2007; Bashmachnikov et al., 2009). Pham et al. (2020) reported that the beaches on the islands capture significant amounts of fragments, with a maximum of 15.000 fragments per m^2 (Pham, et al. 2020). This may be explained by the proximity to oceanic gyres, that consequently, express higher levels of pollution on the coasts of oceanic islands (Rodríguez & Pham, 2017). This trend has a tendency to increase in the winter and spring months, due to the Southern polar-front jet migration (Pieper et al., 2021). Nevertheless, there is still very limited knowledge about the presence and quantification of marine litter in ocean islands.

The objective of the present study is to estimate the abundance, composition and dimension of microplastics along the coast of São Miguel Island, following an inshore-offshore gradient along a stream until the ocean, and in several beaches covering the whole island. Specifically, it is pretended to identify the categories of the microplastics present; determine the amount and dimension of microplastic in each category; and identify and discuss the differences and factors that may contribute to its distribution.

2. Materials and Methods

2.1 Study Area

This study was carried out on São Miguel Island, Azores (36–40° N, 24–32° W; Figure 2.1). It is the largest island of the archipelago with a surface area of 748.82 km², a coastline with a full extension of 1.170 km, and an estimated human population of 133,390 (SREA, 2021).

The climate is temperate and oceanic regulated by the Atlantic Ocean and the Gulf Stream. Rainfall is a regular factor that increases in the winter (Valente et al., 2004). It has occasional storms characterized by strong winds and precipitation from September to March due to the migration of jet streams in the atmosphere from the South-polar front (Pieper et al., 2021).

The Azores have a large marine territory where the main economic pillars are marine activities such as fishing and tourism. This archipelago enjoys one of the largest Exclusive Economic Zones in the European Union, about 1,000,000 km^2, located in the middle of the Atlantic Ocean (Rodríguez & Pham, 2017). It condenses a great diversity of marine species associated with a large diversity of habitats and ecosystems such as coastal reefs, island slopes, seamounts, deep water corals, reefs, and sponge aggregations, as well as deep hydrothermal vents and abyssal plains, along with a diverse pelagic fauna (Rodríguez & Pham, 2017).

2.2 Data collection

Two distinct sampling designs were performed.

1. First, sediment samples were collected in four sites - upstream (U) and downstream (D) stretches of water courses, and adjacent beach (B), and underwater marine environment (UW), distributed among eight Areas (A1-A8; marked with black circles in Figure 2.1), covering all the coastline of São Miguel in the four sectors (North, South, East and West), following a nested approach (sector, area and site). Sites were separated by a minimum of 300 m and in each one, 5 replicates were collected, with approximately 10 m apart. The design was used to analyse microplastic composition and abundance gradient from inshore areas until the sea;

2. The second design covered the sampling of 15 beaches (B1 – B15; marked with red crosses in Figure 2.1), nested in the four sectors (North, South, East and West) during the same period. Again, on each beach, 5 replicates were collected 10 m apart from each other. This second methodology was used, due to greater accessibility to these zones and the fact that a large part of marine litter is accumulated on the coastline of beaches, allowing reasonable comparisons with other studies (Smith & Markic, 2013).

Both sampling designs were conducted during the autumn/winter of 2021, due to the tendency of marine litter to increase during these seasons (Pieper et al., 2021). When retrieving the samples, the surface layer was removed with a metal spatula to take out organic matter and mesoplastics. Sediment samples were then placed in a metal container with a capacity of approximately 100g to avoid contamination, labelled and sealed with parafilm until arrival at the laboratory. Samples from beaches were collected slightly above the high tide line (Hidalgo-Ruz et al., 2012; Karthik et al., 2018; Lefebvre et al., 2021). Underwater samples were collected from the higher sediment blanket (at 15 m depth), and the same process was used in overflood streams.

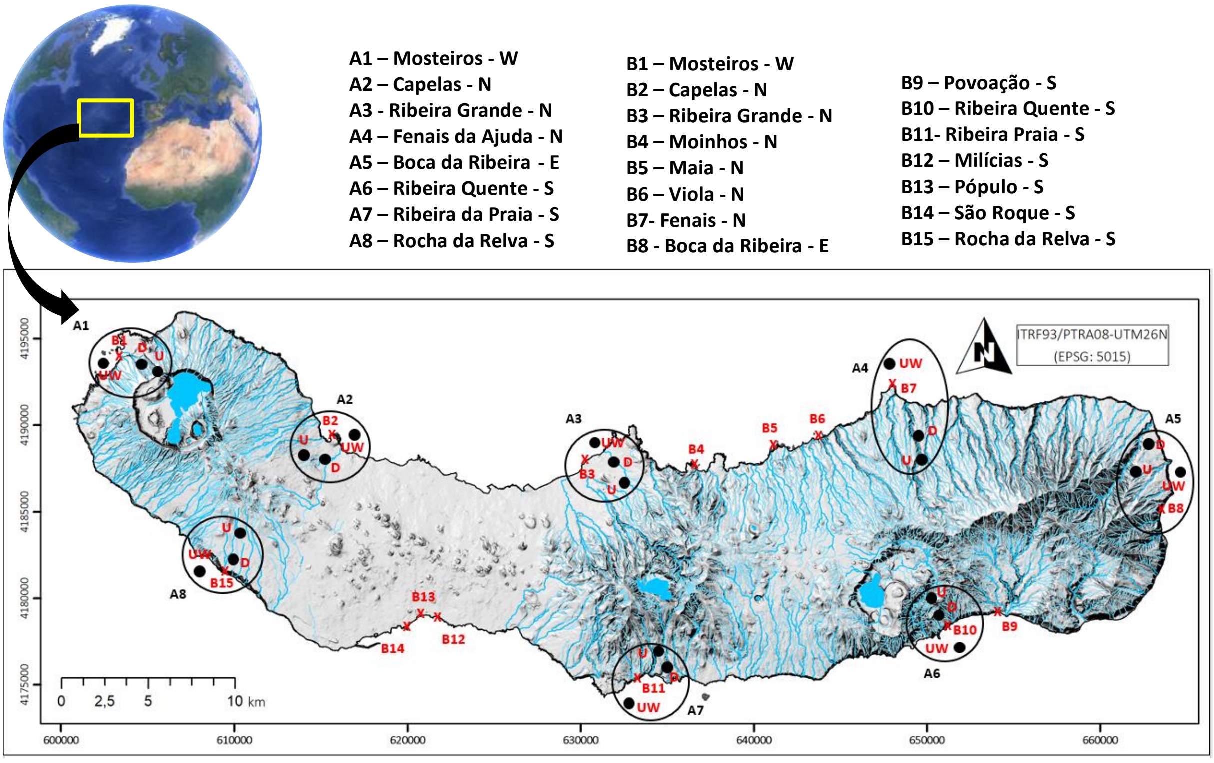


Figure 2.1 São Miguel Island with sampled locations and respective island sector (W-West, N-North, E-East, and S-South). Areas (A1-A8) are represented by black circles divided by 4 sites: upstream (U), downstream (D), beach (B), and underwater marine environment (UW). Beaches (B1-B15) are represented by red crosses.

2.3 Laboratory Processing and Analysis

Each sample was weighed and then oven-dried at 60ºC for 48h (Cozzolino, 2019; Frias et al., 2016; Lots et al., 2017; Piñon-Colin et al., 2018). After that period the samples were removed and weighed again, to estimate its dry weight.

A salt solution was prepared in a beaker with a capacity of 3 L, previously washed, by adding 1 L of demineralized water and 100 g of salt. Whenever it was dissolved, another 100 g of salt was added until reaching 400 g (Laglbauer et al., 2014). The mixing process was aided by a hot plate and a magnetic mixer. The reagent was chosen due to its ability to reach high densities, being cheap to obtain, widely available, and environmentally friendly (Crawford & Quinn, 2016), and having a large movement in heavier polymers like high-density polyethylene (HDPE) (Mai et al., 2018).

Each sample was placed in a beaker with the aid of a funnel, and about 400ml of the salt solution (Quinn et al., 2017; Nel & Froneman, 2018) was mixed for 2 minutes with a glass rod (Laglbauer et al., 2014). The sample was left to rest for 5 hours. The vacuum pump was prepared with 47 mm Millipore 0.45 µm paper filters (Desforges et al., 2014; Minor et al., 2014; Besley et al., 2017; Lots et al., 2017;

Batrinescu et al., 2022), previously divided into 4 quadrants and identified on the edge. The supernatant was filtered with the aid of a 100 µm sieve to avoid large objects making it difficult to see under the microscope (Besley et al., 2016). This whole process of decantation and filtration was repeated 3 times with different filter papers, to optimize the capture of all microplastics present in each sample (Liebezeit & Dubaish, 2012) (Figure 2.2).

After all the supernatant was filtered, the filter was carefully removed with forceps and placed in a Petri dish. With the stereoscopic magnifying glass in 4.0x (Besley et al., 2017; Lots et al., 2017), microplastics were identified by composition as fibres, microbeads, or fragments (since pellets, foams and films were inexistent), counted, and their length and colour recorded.

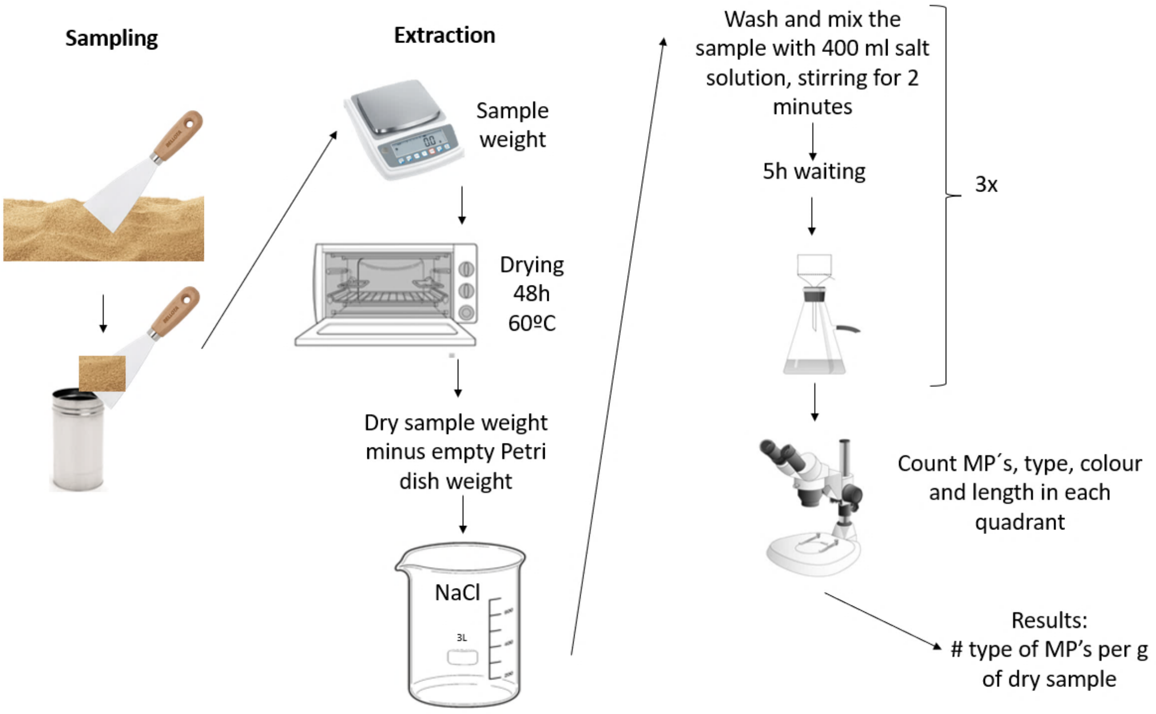


Figure 2.2 Microplastic extraction method based on Besley et al. (2017).

2.4 Quality control

Contamination is likely and normal to occur during each stage of sampling, processing, and characterizing micro samples. To avoid cross-contamination, during the sampling and treatment procedures, the samples were never in contact with plastic. All the equipment used during the process was always made of glass or metal and properly washed between tasks.

2.5 Data analysis

Microplastic abundance and dimension categories were computed for each sampling site, according to each category. To examine potential differences four (I-IV) PERMANOVA nested designs (one for each combination of sampling design and analysed variables) were used:

- Three factors, treated as random, with two nested terms design, for abundance (I) and dimension (II) variables: Island Sector (North, South, East and West), Areas (A1-A8) within Sectors and Sites (U, D, C, UW) within Areas and Sectors;
- Two factors, treated as random, with one nested term design, for abundance (III) and dimension (IV) variables: Island Sector (North, South, East and West) and Beaches (B1-B15) within Sectors.

These analyses were performed using the PERMANOVA add-on in Primer software (PRIMER-E.Permanova and Primer v, 2019). The tests were run one at a time on square-root transformed Bray-Curtis resemblance matrices of the abundance data and Euclidian distances for dimension data and each term in the analyses was tested using 9.999 random permutations.

To determine the factors influencing variation in microplastic abundance and dimension, Generalized Linear Models (GLM, normal error distribution and identity-link functions) with different combinations of predictor sets were applied, including island sector, area, site, granulometry and proximity to pollution potential sources/centres. These models have been chosen due to its use in similar studies (Lusher et al., 2015; De-la-Torre et al., 2020; Dent et al., 2023; Lagos et al., 2023). For each model the variables were retained based on the Akaike Information Criterion (AIC), to compare different models that include different combination of variables (Stoica & Selén., 2004). For the island sector (location) factor, samples were divided between North, South, East and West. Granulometry was classified according to Valentine (2019) and Blott & Pye (2012) among classes: 1 - clay (<1/256 mm); 2 - silt (1/16–1/256mm); 3 - sand (2-1/16mm); and 4 - pebble (64 – 2mm). The two additional classes (boulder (>256 mm) and cobble (256 – 64 mm)) were discarded due to the lack of samples that could be grouped into them in the study area. Proximity to a potential pollution source/centre was scored according to the distance of each site from an urban centre measure in a straight line in a map: 1 – more than a mile; 2 – less than a mile; 3 – inside towns. These analyses were undertaken using IBM SPSS software v.28 (SPSS, USA).

A significance lever of $p < 0.05$ was considered in this work for statistical significance, for all cases.

3. Results

In this survey, a total of 10,829 microplastic (MP) items were collected throughout the 8 areas and 15 beaches, within 160 samples. Fibres constitute the dominant category (92.3%), followed by microbeads (6.6%), and finally fragments (1.1%) (Figure 3.1 A). The most abundant colours were transparent (39.5%), black (36.2%), and blue (17.4%) (Figure 3.1 B). The average abundance was 0.37MP/g, with a minimum of 0.20 MP/g and a maximum of 0.74 MP/g. The minimum dimension was 0.1 mm, and the maximum was 5 mm (the upper limit for a plastic particle being classified as microplastics), with an average of 2.15 mm. All collected data by sampling site can be consulted in Annex I.

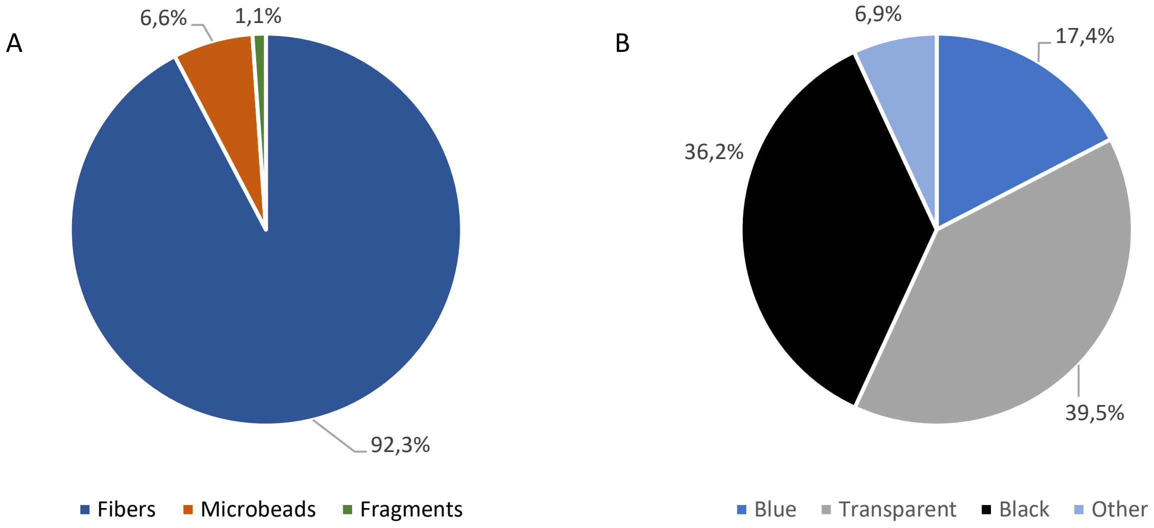


Figure 3.1 Percentage of total microplastics categories (A) and colours (B) among all samples.

Overall, along the land-sea gradient, MP abundance is higher towards the ocean, but decreasing in size in the same direction (Figure 3.2). Also, microbeads are more abundant and larger near the coast and almost insignificant inland. Fragments, although much less frequent, are more uniformly distributed.

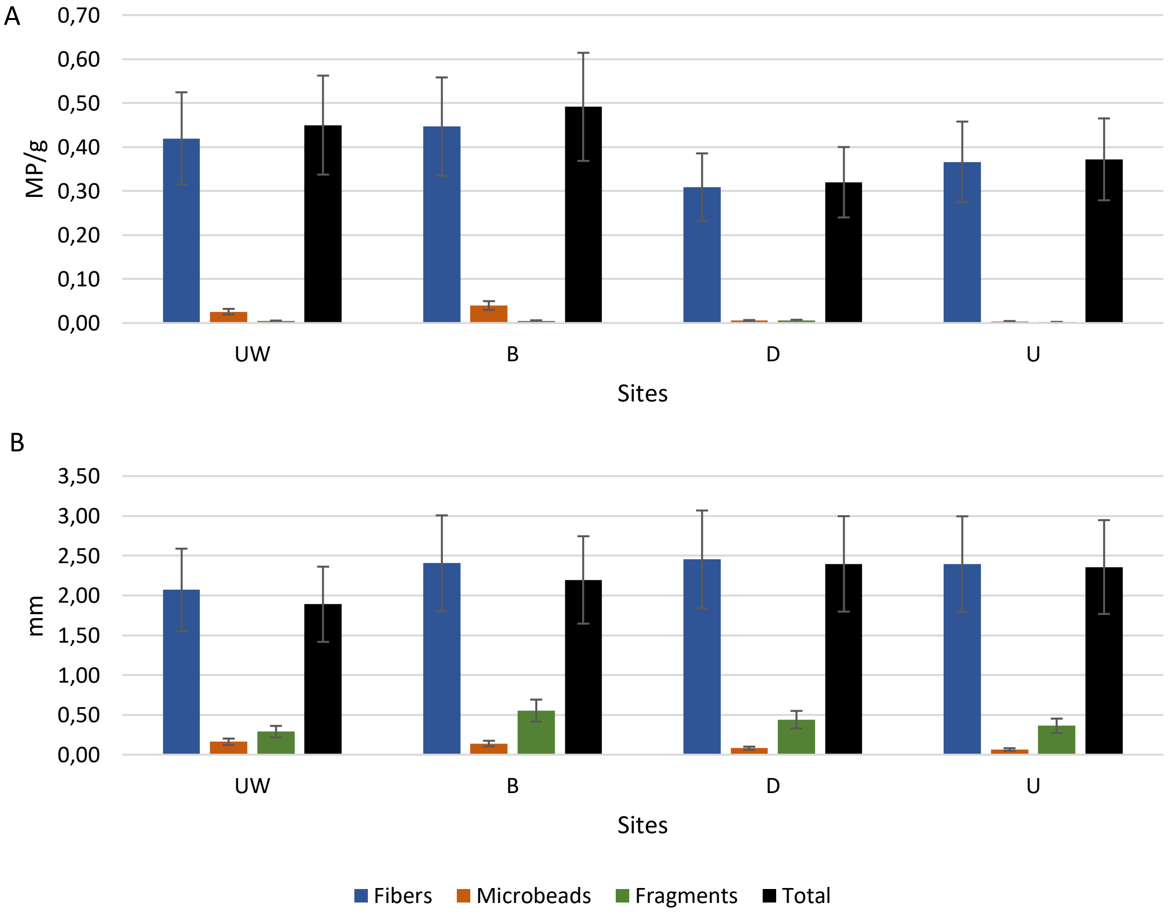


Figure 3.2 Mean abundance ± SD (A) and dimension ± SD (B) of each category of microplastics sampled in each site, independently of sectors: upstream (U), downstream (D), beach (B), and underwater marine environment (UW).

3.1 Island Sectors and Areas

Considering the sampling design by Areas within island Sectors, the fibres were the most frequent category (91.3%), followed by microbeads (7.6%), and finally fragments (1%) (Figure 3.3 A). The minimum dimension of microplastics was 0,1 mm and the maximum dimension was 5 mm, with an average dimension of 2.19 mm. The most abundant colours observed in this sampling design were transparent (40.4%), black (36.7%), and blue (16.2%) (Figure 3.3 B).

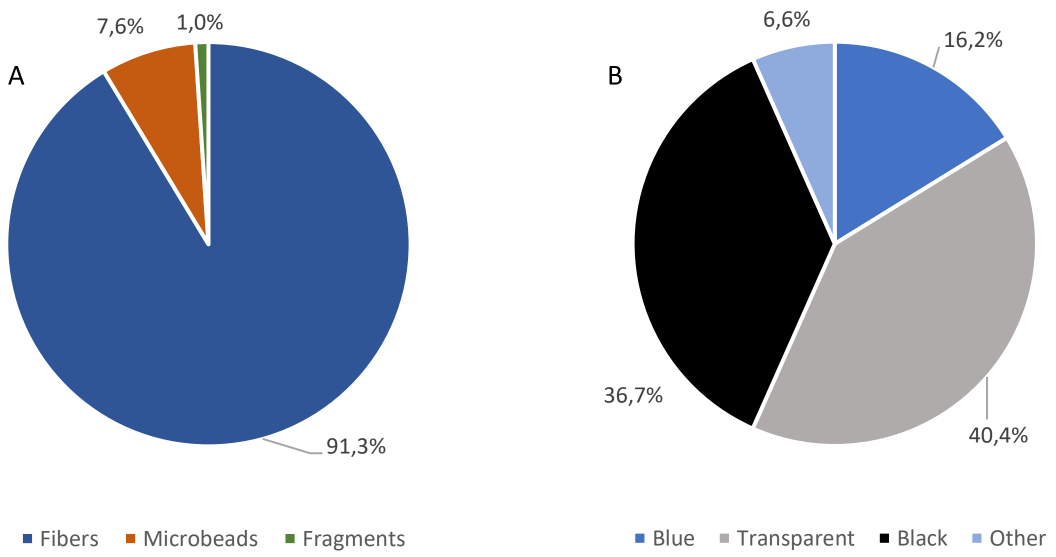


Figure 3.3 Percentage of microplastics categories (A) and colours (B) in sampled areas within Sectors.

The sector with the highest average abundance of microplastics was West (0.43 MP/g), with also the largest average dimension of these particles (2.32 mm), while the lowest abundance was found in the South (0.35 MP/g), and lowest dimension in the East (2.01 mm) (Figure 3.4 A, B). The West, East and South presented a higher abundance near the coast (underwater and beach) than inland (downstream and upstream), while in the North, the higher abundance was upstream. Regarding the variation of dimension among sites, the smallest particles were found in underwater samples, except in the East, where were found in beach samples. The largest particles were observed normally inland, downstream and upstream, except in the South, where they occurred on the beach.

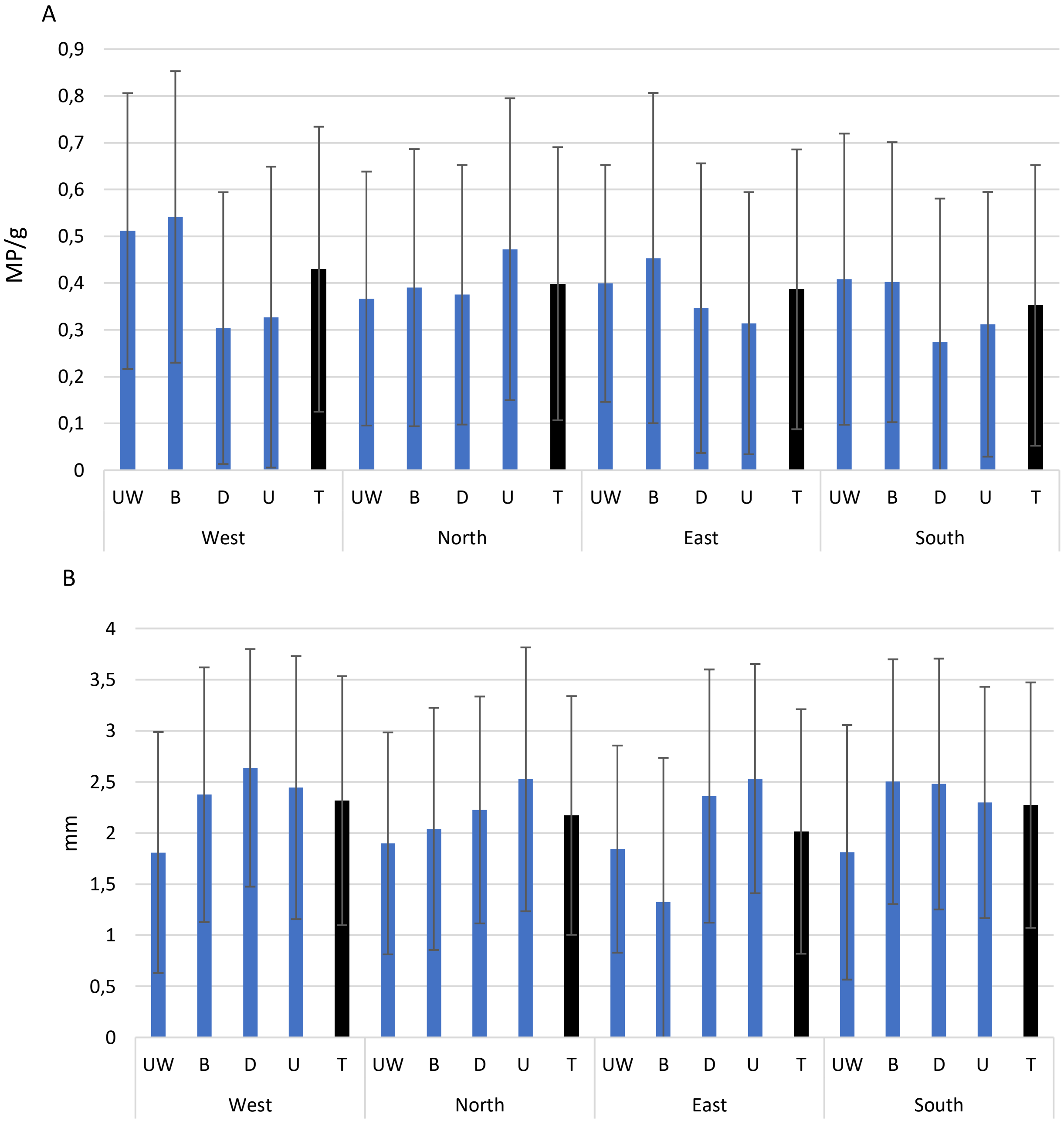


Figure 3.4 Mean abundance ± SD (A) and dimension ± SD (B), of microplastics sampled in island Sectors in each site: upstream (U), downstream (D), beach (B), and underwater marine environment (UW). Black bars represent the total samples for each Sector.

The area with the highest average abundance was A3 (0.56 MP/g), and the one with the lowest was A7 (0.26 MP/g). Regarding the dimension of microplastics, it was quite similar, with fibres being the largest MP category. Microbeads were usually found near the coast, and the higher abundance was found in A5. Fragments were the least abundant, but the dimension varied, with the largest particles being found in A5. The area with the average largest microplastics was A8 (2.41 mm), while that with the smallest was A4 (1.94 mm) (Figure 3.5 A). Considering the abundance among sites, in A1, A4 and A5 there was a clear division between coast and land, where the coast presented higher values. In A2 and A6, the site with more abundance was the beach. In A3, the higher abundance was upstream, with downstream showing the lowest abundance, while A7 and A8 showed the higher abundance in the underwater sediments (Figure 3.6 A). Regarding the dimension within the areas, in A1, A2, A3, A5, A7 and A8, the smallest particles were found in underwater sediments. The smallest particles in A4 and A6 were found in the beach and upstream, respectively. The largest particles among the sites were normally found inland, except in A6 and A8, detected on the beach site (Figure 3.6 B).

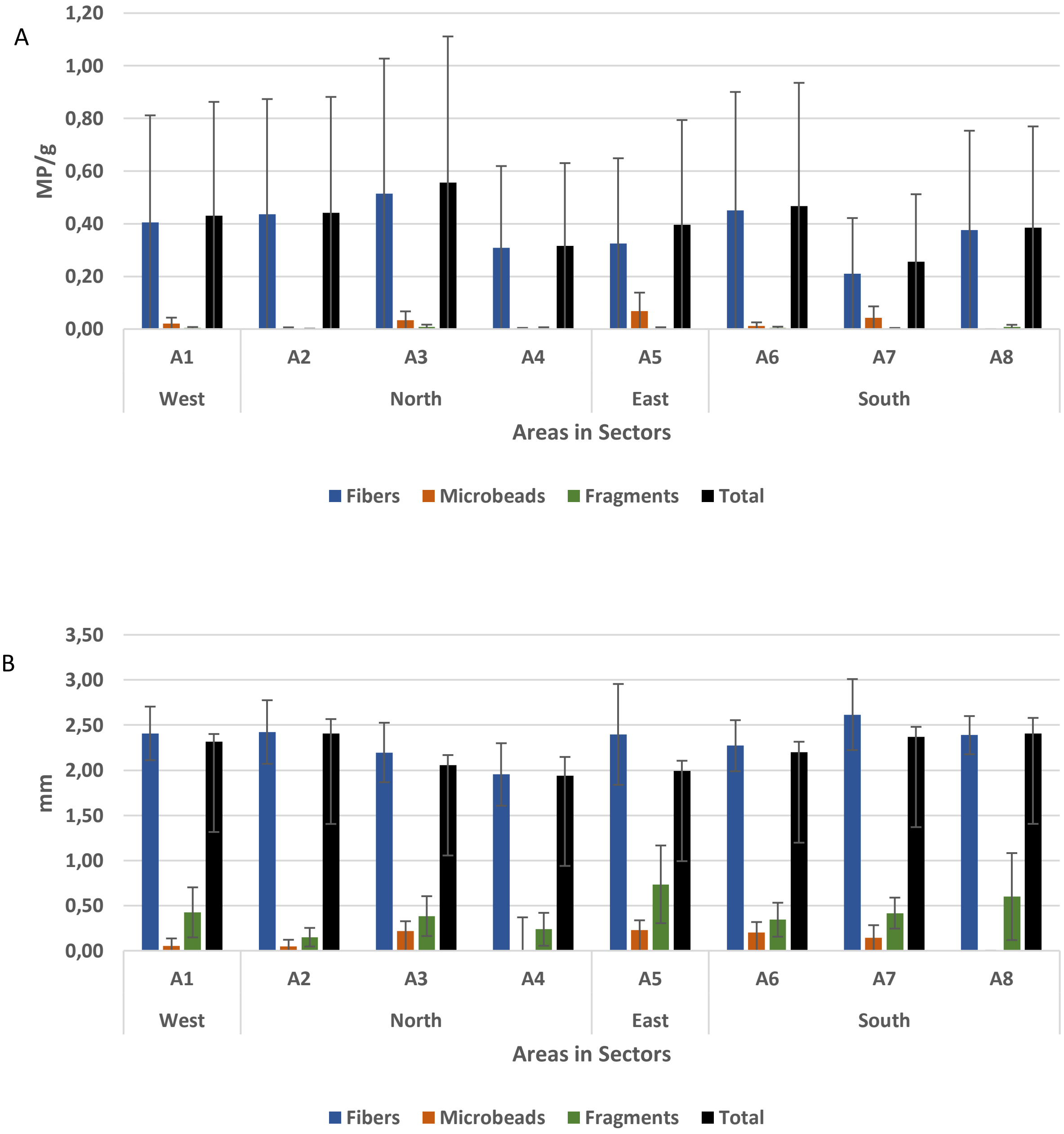
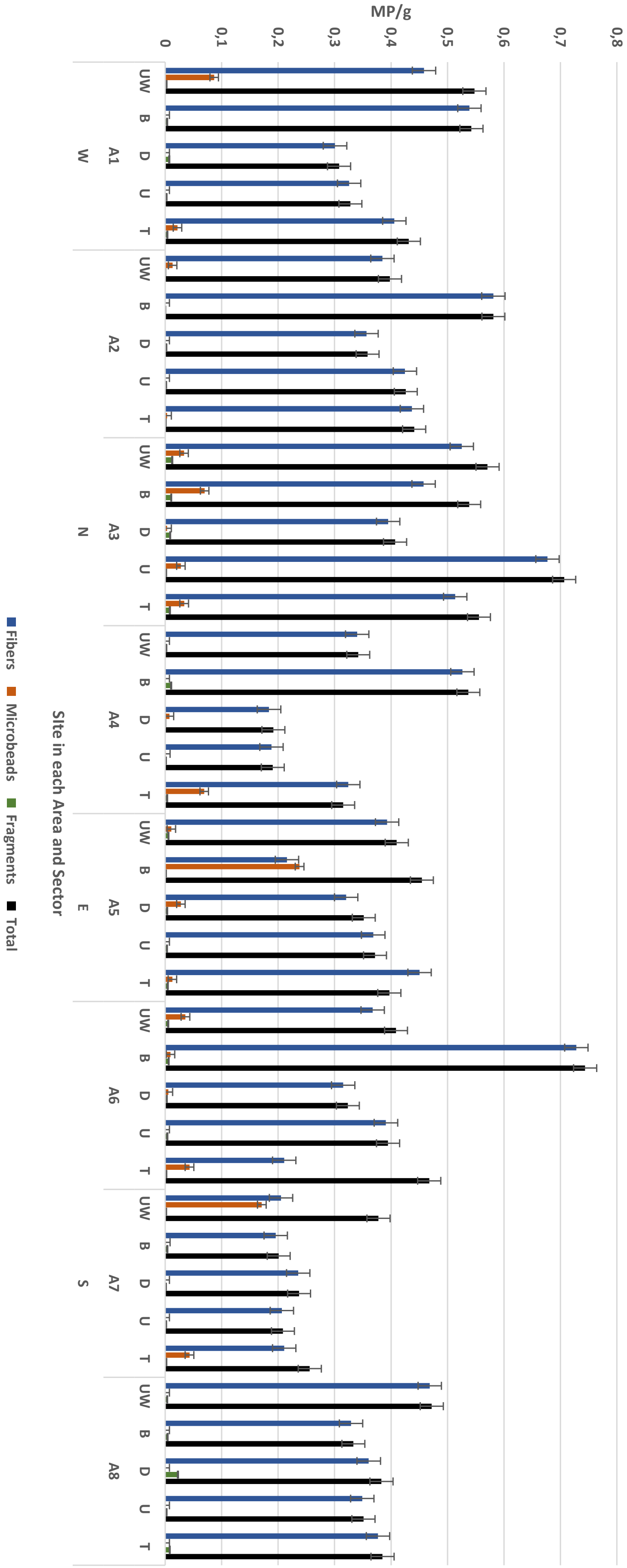


Figure 3.5 Mean abundance ± SD (A) and dimension ± SD (B) of each category of microplastics sampled in island Areas (A1-A8) in each sector. Black bars represent the total samples for each Area.

A


MP/g
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
UW
B
D
U
T
A1
A2
A3
A4
A5
A6
A7
A8
W
N
E
S
Site in each Area and Sector
■ Fibers
■ Microbeads
■ Fragments
■ Total

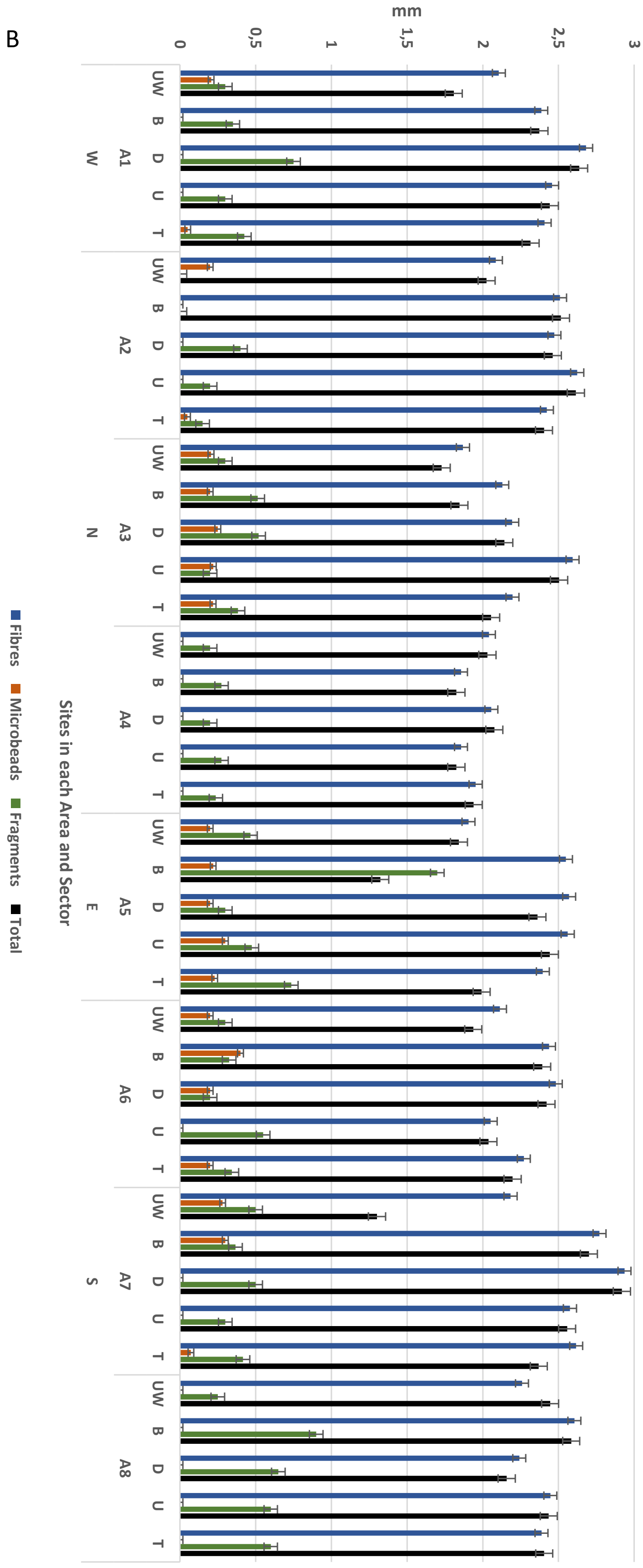


Figure 3.6 Mean abundance ± SD (A) and dimension ± SD (B) of each category of microplastics sampled in island Areas (A1-A8) in each site, and each sector. Black bars represent the total samples for each Area.

Despite the variation referred before, PERMANOVA results showed significant variability among Areas and Sites for the abundance but only among Areas regarding microplastic dimension (Table 3.1). Generally, in nested designs, using obviously random factors, pair-wise comparisons are not performed among levels of a random factor, however, a logical step is to estimate the dimension of each factor component of variation and ascertain the amount of variability explained by each factor. Thus, the greatest component of variation occurred at the smallest spatial scale (the residual, level of individual replicate holdfasts), followed by Sites and then Areas, especially for the microplastics dimension (Table 3.1).

Table 3.1 Results of permutational multivariate analyses of variance (PERMANOVA) testing the effect of Sites (UW, B, D and U) nested in Areas, and Areas (B1-B15) nested in Island Sectors on the abundance and dimension of microplastics.

Variable	Source of variation	df	SS	MS	Pseudo-F	*p*	Components of variation
Abundance	Sector	3	2638.3	879.44	0.50151	0.791	-
	Areas (Sector)	5	9230.5	1846.1	2.6592	**0.011**	71.535
	Sites (Areas (Sector))	24	19158	798.23	5.4046	**0.001**	130.97
	Residual	127	18757	147.69	-	-	147.69
	Total	159	50154	-	-	-	-
Dimension	Sector	3	0.71178	0.23726	0.53572	0.806	-
	Areas (Sector)	5	2.298	0.4596	1.6631	0.105	0.011381
	Sites (Areas (Sector))	24	7.2266	0.30111	2.0596	**0.001**	0.031187
	Residual	127	18.567	0.1462	-	-	0.1462
	Total	159	29.252	-	-	-	

The best GLM model detected significant effects of site, granulometry and proximity to a potential pollution source/centre (Table 3.2). More specifically, microplastic abundance seems to significantly increase with nearby pollution potential sources, towards more coastal ground, and among the smallest granulometry dimension classes (see data in Annex I). Similarly, the microplastic dimension decreases significantly towards more coastal grounds and is affected by nearby potential pollution source.

Table 3.2 Results from the final GLM models explaining microplastic variability in the study area, including significant factors, statistical estimates and p-value.

Parameter	Factors	Test (Wald)	p-value
Abundance	Sites	7.929	**0.047**
	Granulometry	22.586	**<0.01**
	Proximity to a potential pollution centre	8.985	**0.011**
Dimension	Sites	94.888	**<0.01**
	Proximity to a potential pollution centre	24.437	**<0.01**

3.2 Beaches

In the 15 beaches analysed, 4643 microplastics particles were found. In this case, fibres were the most dominant category (92%), followed by microbeads (6.9%), and fragments (1.1%) (Figure 3.6 A). Regarding colour, the most abundant was transparent (36.6%), black (34.3%), and blue (20.2%)

(Figure 3.6 B). The average abundance of microplastics in sampled beaches was 0.44 MP/g, with a minimum of 0.20 MP/g and a maximum of 0.72 MP/g. The minimum dimension was 0.1 mm, and the maximum dimension was 5 mm, with an average of 2.14 mm. All collected data by sampling beach can be consulted in Annex I.

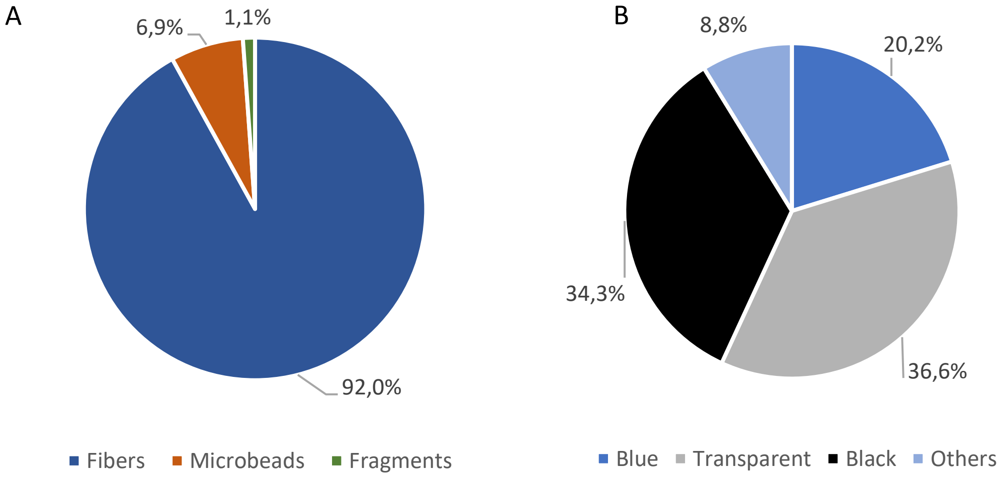


Figure 3.6 Percentage of microplastics categories (A) and colours (B) in sampled Beaches.

The beach with higher MP average abundance was B10 (0.72 MP/g), and the one with their lowest abundance was B11 (0.20 MP/g) (Figure 3.7 A). Microplastics were larger in B11 (2.70 mm), with fibres being the largest microplastics category. The smallest were detected in B8 (1.32 mm) (Figure 3.7 B).

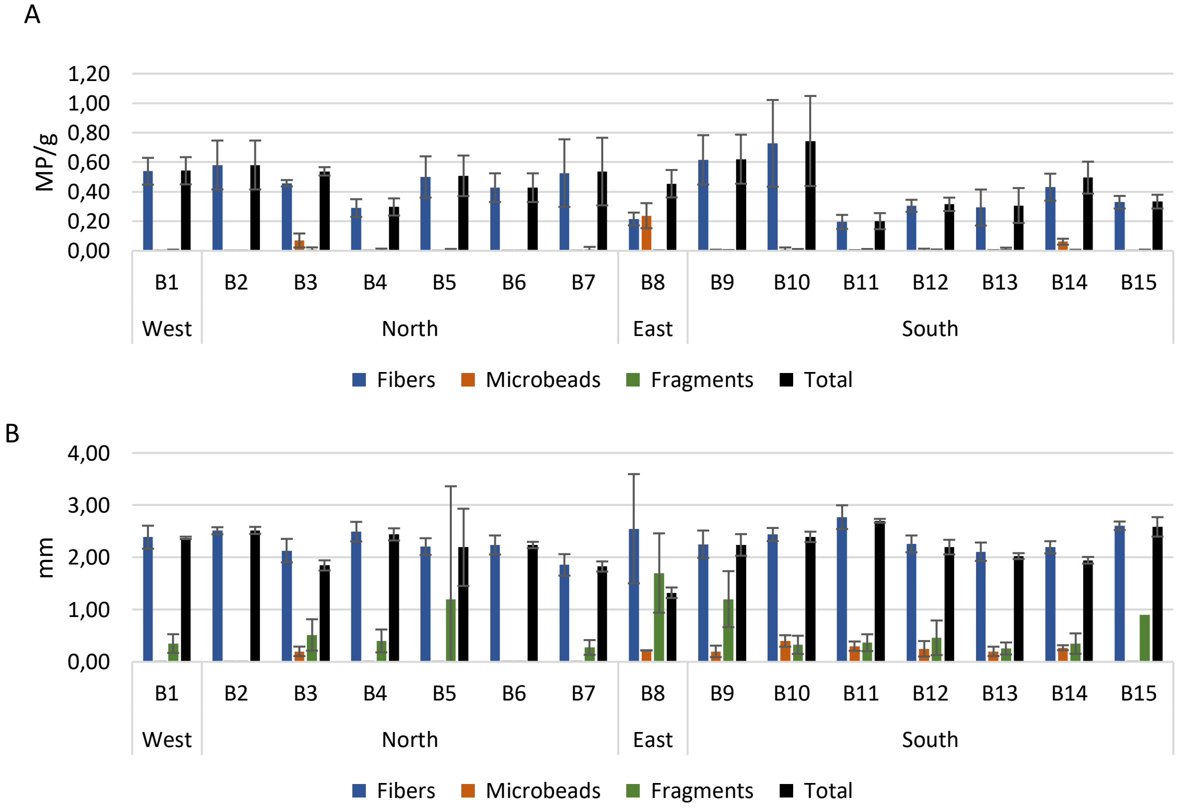


Figure 3.7 Mean abundance ± SD (A) and dimension ± SD (B) of each category of microplastics sampled in island Beaches (B1-B15) in each sector. Black bars represent the total samples for each Beach.

PERMANOVA results show significant variability among beaches but not for Island Sectors for both the abundance and dimension of microplastics (Table 3.3). In this case, GLM model did not detected any significant pattern with granulometry or proximity to a potential pollution source/centre.

Table 3.3 Results of Permutational Multivariate Analyses of variance (PERMANOVA) testing the effect of Beaches (B1-B15) nested in Island Sectors on the abundance and dimension of microplastics.

Variable	Source of variation	df	SS	MS	Pseudo-F	p(perm.)	Components of variation
Abundance	Sector	3	7453.7	2484.6	2.9139	0.114	-
	Beaches (Sector)	11	9379.3	852.66	7.9601	**0.001**	149.11
	Residual	60	6427	107.12	-	-	107.12
	Total	74	23260	-	-	-	-
Dimension	Sector	3	1.1042	0.36808	0.89299	0.555	-
	Beaches (Sector)	11	4.5341	0.41219	1.9848	**0.01**	0.040903
	Residual	60	12.46	0.20767	-	-	0.20767
	Total	74	18.099		-	-	-

4. Discussion

This study revealed that marine litter, particularly microplastics, is ubiquitous although variable along the coastline and water courses of São Miguel Island. Microplastics were found in all sediment samples from all sampled sites, revealing that sediments are vulnerable to microplastic pollution and that this can be considered a good representation of the long-term accumulation of microplastics (Wang et al., 2017).

4.1 Categories and Colours

Fibres are usually derived from the washing machine water outflow, which contains synthetic fabrics. For each standard wash, up to 700,000 fibres can be released into the aquatic environment via wastewater, which is believed to be the origin of many of the fibres distributed throughout the marine ecosystem (Murphy et al., 2016; Napper and Thompson, 2016). These can also enter the environment through the fragmentation of ropes and fishing nets (Thompson et al., 2004), It is believed to represent 18% of the debris (Andrady, 2011). It is estimated that the disintegration of abandoned, lost or otherwise discarded fishing gear can generate around 1277 MPs, with fishing rope (44%) and net (49%) the main sources (Wright et al., 2021). Designers of clothing and washing machines should contemplate the necessity to reduce the release of fibres into wastewater and more research is adequate to develop methods for removing MP from sewage. Once that this study was done mostly during the winter, and people tend to wear more clothes in that season, and more washing machine usage in households, consequently it is expected that more fibres enter sewage treatment (Browne et al., 2011). Graca et al. (2017) raised the possibility that density separation with NaCl solution probably allows separation of plastic fibres than MP of other shapes and types regardless of their density. Herrera et al. (2020) also found fibres as the most common debris after fragments in the Northeastern Atlantic.

Microbeads are microplastics that are used in personal care products such as scrubs, hand cleansers, and toothpaste. These types of microplastics are harmful due to their ability to absorb and concentrate toxic hydrophobic substances in water. Several studies point to the inability to remove these microplastics during water treatment, often resulting in their release into water courses (Wu, et al. 2016). Microbeads are widely dispersed in the environment and are particularly prevalent in coastal grounds (Mishra et al., 2019). In this study, they were especially found in underwater and beach sediments, just as expected, probably originated from the discharges of plastics wastes into the environment. Considering that overall, the most common colour was transparent, and size ranged between 0.2 mm and 1 mm, is acceptable to conclude that these microbeads are originated from personal care and cosmetics products sold in the region. Sewage treatment have been indicated to effectively, but not totally, captured this type of MP in the grease of the wastewater treatment (Murphy et al., 2016; So et al., 2018).

Fragments are usually related to the secondary microplastics aforementioned, originated from larger plastic items that have suffered the process of erosion and fragmentation due to the action of current waves and/or exposure of solar radiation, breaking the items into small pieces of plastic. Fragments are also the dominant type in the open ocean (Cózar et al., 2014), however in this study they were the least detected category. In an investigation conducted in coastal sediments from southern Portuguese shelf waters, in 31 MP, only 6 were fragments (Frias et al., 2016). In addition, in an investigation located in the North Atlantic Ocean, beach sediment revealed a higher concentration of fibers relatively to fragments (Dodson et al., 2020). The different abundances of fragments within beach and underwater marine environment sediments is caused by the underlying hydrophysical processes in sea coastal zones caused by stormy weather, functioning like a mill and, consequently, making floating pieces migrate repeatedly between beaches and underwater slopes until they are fragmentated into smaller particles that can be transported by currents to deeper areas and deposited out of reach of stormy waves (Chubarenko & Stepanova., 2017). This is particularly evident in oceanic islands exposed to violent and long storms, especially during winter season (Lincoln et al., 2022).

The microplastics identified in this study were predominantly transparent, black, and blue. Several studies have found that the most common colours are blue and black (Lots et al., 2017; Firdaus et al., 2020; Cincinelli et al., 2021). This colour variation, and significant transparent coloration, may be due to the different origin of the plastic material, or to the degradation processes in the marine environment (Filgueiras et al., 2019).

4.2 Abundance

Analysing the variation between the Sectors of the island, the highest abundance, although not significant, was found in the West. This can be explained by the prevailing marine currents coming from the West of the Island (Gyory et al., 2023). It is important to note that these values were the highest on the beach sites. The overall significant MP accumulation near more coastal grounds is associated with greater anthropogenic pressure and mismanaged waste (Mani & Burkhardt-Holme., 2019). These differences of abundance may potentially reflect varying plastic emission along the streams. The higher MP input into large watersheds, may be explained by several stream sources, in addition to aeolian transport (Mani & Burkhardt-Holme., 2019). High discharge periods may wash shoreline plastic waste into a watercourse of a stream, therefore, high discharge is often associated with rainfall events, that can stimulate additional urban and agricultural run-off, increasing MP input. It is proven that smaller size ranges of MP tend to accumulate in locally restricted high-abundance hotspots, in either natural or artificial traps (harbour areas or groyne fields) (Mani & Burkhardt-Holme., 2019).

Given that the island has a mild maritime climate, with a big precipitation rate, and consequently, high flow velocity, it makes sense that the sedimental microplastics can be found in higher number in offshore areas, due to the transportation that they suffer in the stream-sea path (He et al., 2021). Only the A3 had higher abundance in onshore, upstream accurately, probably because this was the only case sampled within a waterfall, where the strength and speed of the water may cause some variation in the settlement of these particles, preventing the motion.

The area with the highest litter density was found at Ribeira Grande beach (B10), the second-most populous municipality in the island (SREA, 2021). The Povoação beach (B9), and Capelas beach (B2) also showed a high litter density. According to the Regional Secretariat for the Environment and Climate Change of the Azores (SREA, 2021), the level of pollution in the beaches of Ribeira Quente (B10) and Povoação (B9) is justified by the frequent rains, making access difficult, and the use of the land above the hill being of the agricultural type, which can cause landslides. It is also important to note that Ribeira Quente beach has a "blue flag", that is, it complies with a set of environmental quality requirements, since 2014, and Povoação beach had it since 2021. The beaches concentrated litter from the nearby waters considering the deposition rate and the drift that plastic particles suffer, making the beaches a perfect storage place for this type of litter.

The average litter density throughout both sampling designs (15 sites and 8 beaches) was lower when compared with other beach and stream sediments studies (Wang et al., 2017; Rahmana et al., 2020; Lots et al., 2017). Studies carried out in the Azores archipelago (Islands of Corvo, Santa Maria, Flores, Graciosa, and Faial) showed a larger quantity of collected MP (about 39,000 microparticles), compared with this study (Pham et al., 2020), although the methods were slightly different, using a mechanical shaker with different sieves sizes. However, comparisons between studies should be conducted carefully, as microplastic concentrations may not only be related to pollution levels but also be affected by differences in the sampling methods used as well as the processing and analysis techniques applied, local oceanographic conditions such as tides and currents, and weather (Wang et al., 2020).

Freshwater sediments analyses attract less attention than works involved in marine ecosystems. Klein et al., (2015) analysed the sediments of a river shore in Germany, and all sediments analysed contained microplastics. Short-distance transport of plastic particles from the tributary to the mainstream was confirmed by the identification of pellets, that were separated from shore sediment samples of the river.

High densities of litter can be explained by exceptional adverse weather conditions, like strong storms, before sampling. The elevated number of litter items found likely represents extended periods of accumulation. Furthermore, studies on islands mention the importance of how currents and winds can influence the direction and accumulation of litter in coastal areas (Ríos et al., 2018) influencing the production and origin of microplastics. Despite the apparent absence of heavy industry, the archipelago's location in the middle of the North Atlantic, between the American and European continents, is associated with the exponential increase in tourism witnessed in the last decade (Calado et al., 2011). The growth of commercial and recreational maritime traffic and activities might reflect the increase marine pollution along the coast. Fishing and tourism activities are also paramount in the region, and important sources of marine litter (Newman et al., 2015). On the other hand, its location at the Northern edge of the North Atlantic Subtropical Gyre, concentrates the oceanic marine litter within the islands.

Hence, the MP higher abundance detected along the shore is probably from inshore origin although a portion of plastic microparticles seems to be derived from the prevailing winds and marine currents of the Atlantic North. The subtropical jet stream may cause an atmospheric circulation that may increase the MP levels on the island (Brahney et al., 2020). It is important to note that data may be missing, since some types of plastic, such as PVC, do not float and therefore were not accounted for in the analysis (Shent et al., 1999).

The variation in the abundance of MP between upstream and downstream sites can be attributed to effluent, liquid waste, or sewage discharged into the watercourse. These can serve as point sources of microplastics in these samples, as these systems are not equipped to remove non-biodegradable particles within the size range of microplastics. (McCormick et al., 2016; Ziajahromi et al., 2016).

Although gravel beaches usually have higher litter densities than sandy beaches because of the different substrate retention capacities, in the present study it was witnessed the contrary, with an increase of abundance in areas with sediments with small granulometry. The increased terrain complexity provided by gravel can trap litter when the tide is low. For similar reasons, rocky shores are expected to promote the retention of washed litter. Items may be stuck between rocks and therefore become unreachable, making it complicated to detect and collect them (Moore et al., 2001; Kuo and Huang, 2014; Ríos et al., 2018). The transport of MP in coastal environments is one of the most important processes, controlling the environmental fate and risks from MP because it regulates their temporal and spatial distribution among various marine and coastal habitats (Zhang 2017).

4.3 Dimension

Analysing the sectors, the largest MP were found in West of the island, although with no statistical significance. This may be explained by the intensity of direct waves that may increase the transportation of “raw” MP, e.g., microparticles of plastic that were not fragmentated, due to being flowing in the sea surface. Plastic microparticles also breaks down far faster on a bright, hot and abrasive place like a salt marsh or beach than it does in colder, deeper water (Tibbetts, 2014) which explains the significant decrease in size towards the coast.

The large dimension of MP in the beach of A2 and A8, may be explained by the low patterns of ripples, since the marine currents prevails from the West, inflicting less damage to the particles from winds and waves due to the reduced mechanical stress and limited turbulence, since microplastics are less expected to collide with each other or with solid surfaces in low-velocity flow circumstances, which can minimize the potential for fragmentation or breakage.

Comparing the beaches MP dimensions in this study with previous investigations, these results were larger, being the normally registered in other investigations around 1 mm (Lots et al., 2017; Herrera et al., 2020; Wang et al., 2020; Rahmana et al., 2020). This may be explained by different factors such as weather conditions, geomorphology of the islands, season of sampling and methodology.

4.4 Future Perspectives

Beach clean-ups are key factors that most likely influenced the results obtained. It is crucial to notice that litter abundance and typology on the coastline are guided by a multifaceted combination of various factors like proximity to urban centres and water streams, exposure to oceanic currents and winds, beach slope, orientation, and geomorphology (Ríos et al., 2018), just as noticed by the results of the present work.

Further investigations are needed regarding the distribution, occurrence and fate of these micro plastic particles in oceanic island such as the Azores archipelago. Therefore, additional analyses are needed to be conducted, studying different courses of water in the island, different sampling depths, different seasons, and a more profound investigation on the types of polymers of the MP. Analysing and comparing the data with other island of the archipelago can be productive, analysing the differences and variations within the three groups (Central group, Western group and Eastern Group), and the different islands, since all of them have their own distinct geomorphological characteristics that make them unique. More work is also needed to identify and mitigate the sources of microplastics in the environment, just as establishing standardized sampling programs and therefore to a more comprehensive understanding of the fluxes, sinks and behaviour of microplastics in coastal environments.

The presence of microplastics in water bodies near urban areas is often overlooked due to the influence of various anthropogenic factors. Understanding these factors is crucial for comprehending the variability and occurrence of microplastics in different ecosystems. Therefore, effective environmental management practices play a significant role in controlling the transmission and production of microplastics in watercourses. It is essential to design and implement different environmental management measures based on specific hydrological or weather conditions to reduce microplastic inputs and alter their flow patterns in the region (Chen et al., 2020).

Furthermore, tracking the mechanisms, efficacy, and sustainability of these management measures in future studies is important, as well as monitoring changes in microplastic flow patterns. Various urban environmental management systems affect the fate of microplastics. Disinfection methods used in drinking water treatment plants may induce degradation of plastic microparticles, while wastewater treatment plants can decompose them, leading to an overall removal rate of 70% to 99% for all microplastic particles (Shen et al., 2020). However, regardless of the treatment method used, microplastics are not entirely eliminated and can eventually be released into the environment. It is crucial to pay more attention to the treatment and modification of microplastics during disinfection processes, as limited knowledge exists regarding their ecological behaviour, such as migration, fragmentation, and leaching of additives. Efficient methods for microplastic elimination are currently lacking and considering the direct ingestion of these particles through drinking water, it is crucial to develop practical methods to address this issue (Liu et al., 2022).

Environmental management actions should involve public awareness and education campaigns regarding marine pollution, including MP pollution, and its impact on the environment. It is important to implement waste management practices that focus on reducing plastic use and ensuring proper disposal. Efficient waste management systems should be established, encompassing collection, sorting, recycling, and disposal facilities. Additionally, promoting the separation and recycling of plastic waste and encouraging the adoption of eco-friendly alternatives to single-use plastics is crucial. Standardized and regular beach cleanup events should be organized, involving local communities, tourists, environmental organizations, and school field trips.

Measures should also be implemented to prevent microplastic runoff of reaching the ocean, such as utilizing litter traps, sediment ponds, or biofiltration systems to capture and eliminate MP from stormwater. Promoting responsible fishing practices and ensuring the proper management and disposal of fishing gear and/or agriculture residues are important steps. Encouraging the use of biodegradable or recyclable material and the retrieval of lost or abandoned items can also help prevent its fragmentation into MPs. Sanctions and regulations should be in place to reduce the use of plastic bags, including potential outright bans. Simultaneously, promoting the use of reusable or biodegradable bags is essential. Supporting scientific research and monitoring programs to assess the extent of MP pollution and understand its sources and impacts is vital.

Implementing and encouraging sustainable tourism or eco-tourism practices that minimize plastic waste generation, promote responsible tourism activities, and educate visitors about the importance of protecting the marine environment is crucial. Finally, it is important to develop and enforce policies and legislation specifically targeting plastic and MPs pollution. This can include regulations on microbeads in personal care products, restrictions on single-use plastics, and guidelines for MPs monitoring and mitigation across various economic sectors. It is also crucial to adapt these measures to the specific characteristics and needs of each island and involve local stakeholders for a successful implementation.

5. Conclusion

This study provides a baseline value of beaches and water courses litter on São Miguel Island, where microplastics, especially fibres, are ubiquitous within Atlantic Northeast sediments. The results of the present study showed that microplastic pollution is abundant and dispersed in coastal areas and water courses on the island, although differing significantly among the various coastal zones, but lower when compared to other works around the world. The most common category of microplastics was fibres, followed by microbeads and finally fragments. Significant differences were particularly recorded between the different sites for abundance and dimension. Although it is not possible to verify the sources, it can be deduced that these microplastics are introduced by long range transport processes, such as currents and winds, or by anthropological introduction such as illegal discharges, accumulating in more coastal grounds. The abundance of these items differs geographically, showing particularly high concentrations on beach and underwater marine sediments.

The evidence points out that microplastics are present and consistent in all types of life and ecosystems. Current scientific consensus reveals substantial damage to the global economy, the loss of human livelihoods and lives, and irreversible damage to the environment and world. The fragmentation of plastic debris should be considered in new monitoring programs and studies, particularly because of the slow degradability of these materials. The impact of microplastics in the ocean on the marine carbon cycle is increasing, and this type of pollution still raises more questions than answers. Therefore, this study and its results are important to the scientific community and particularly for local government concerning litter management and mitigation.

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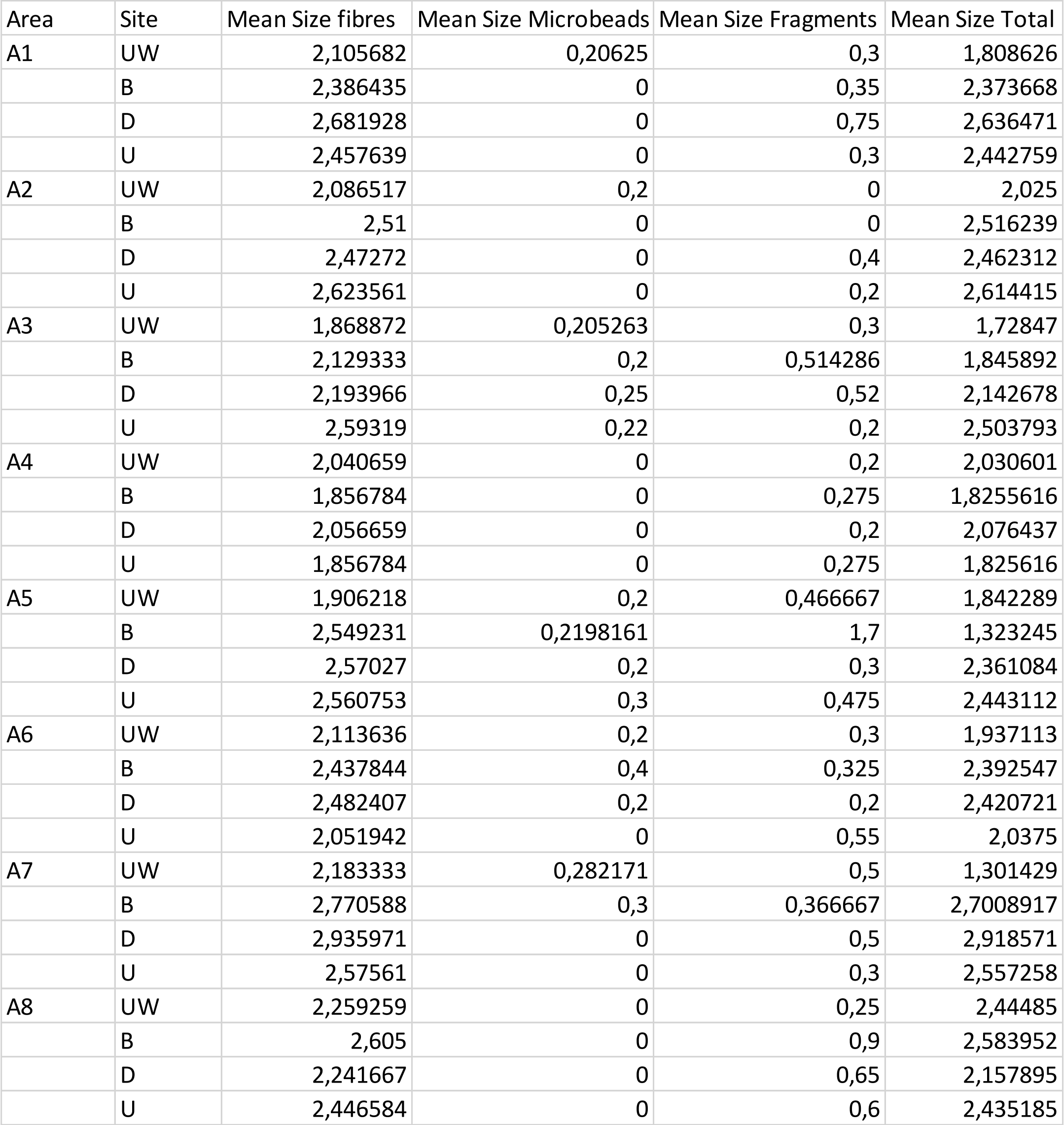
7. Annex 1

Table 1 Microplastic values in the different areas, in each site, with the total number of each category and minimum and maximum values

Area	Site	Total MP	Total fibres	Total Microbeads	Total Fragments	Min	Máx	Granulometry	Setor island	Proximity urban center
A1	UW	313	264	48	1	0,2	4,7	3	O	2
	B	319	317	0	2	0,2	5	3	O	2
	D	170	166	0	4	0,4	5	1	O	2
	U	145	144	0	1	0,3	5	1	O	2
A2	UW	184	178	6	0	0,2	5	3	N	2
	B	234	234	0	0	0,4	5	3	N	2
	D	199	198	0	1	0,4	5	1	N	2
	U	265	264	0	1	0,2	5	1	N	2
A3	UW	281	257	19	5	0,1	5	3	N	1
	B	353	300	46	7	0,2	5	3	N	1
	D	239	232	2	5	0,2	5	1	N	1
	U	290	279	10	1	0,2	5	1	N	1
A4	UW	183	182	0	1	0,2	5	2	N	3
	B	201	199	0	4	0,2	4,9	2	N	3
	D	183	181	0	1	0,2	5	2	N	3
	U	193	189	0	4	0,2	4,9	2	N	3
A5	UW	201	193	5	3	0,2	5	3	E	3
	B	413	195	217	1	0,2	5	3	E	3
	D	203	185	16	2	0,2	5	2	E	3
	U	392	372	16	4	0,2	5	2	E	3
A6	UW	194	176	16	2	0,2	4,6	3	S	2
	B	483	473	6	4	0,2	5	3	S	2
	D	222	216	4	2	0,2	5	1	S	2
	U	208	206	0	2	0,3	5	1	S	2
A7	UW	280	150	129	1	0,1	5	3	S	2
	B	157	153	1	3	0,2	5	3	S	2
	D	140	139	0	1	0,5	5	1	S	2
	U	124	123	0	1	0,3	5	1	S	2
A8	UW	272	270	0	2	0,2	5	4	S	3
	B	243	240	0	3	0,4	5	4	S	3
	D	152	144	0	8	0,1	4,5	4	S	3
	U	162	161	0	1	0,6	5	4	S	3

Table 2 Microplastic dimension in the different areas, in each site, with the average dimension of each category

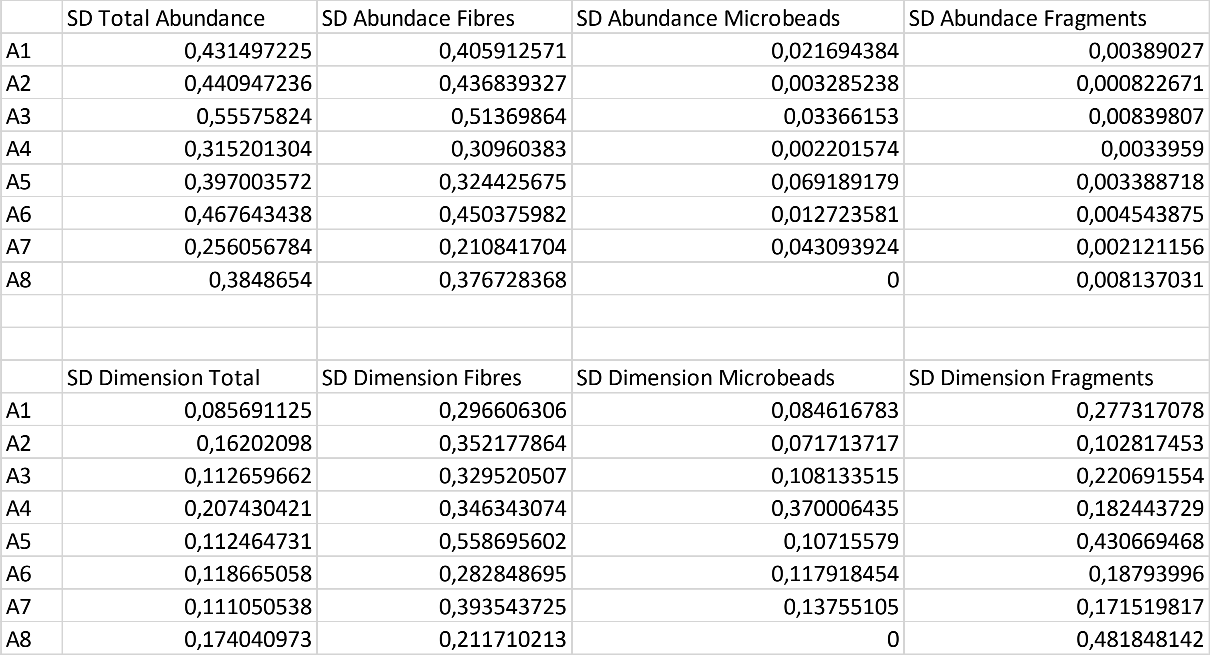


Area	Site	Mean Size fibres	Mean Size Microbeads	Mean Size Fragments	Mean Size Total
A1	UW	2,105682	0,20625	0,3	1,808626
	B	2,386435	0	0,35	2,373668
	D	2,681928	0	0,75	2,636471
	U	2,457639	0	0,3	2,442759
A2	UW	2,086517	0,2	0	2,025
	B	2,51	0	0	2,516239
	D	2,47272	0	0,4	2,462312
	U	2,623561	0	0,2	2,614415
A3	UW	1,868872	0,205263	0,3	1,72847
	B	2,129333	0,2	0,514286	1,845892
	D	2,193966	0,25	0,52	2,142678
	U	2,59319	0,22	0,2	2,503793
A4	UW	2,040659	0	0,2	2,030601
	B	1,856784	0	0,275	1,8255616
	D	2,056659	0	0,2	2,076437
	U	1,856784	0	0,275	1,825616
A5	UW	1,906218	0,2	0,466667	1,842289
	B	2,549231	0,2198161	1,7	1,323245
	D	2,57027	0,2	0,3	2,361084
	U	2,560753	0,3	0,475	2,443112
A6	UW	2,113636	0,2	0,3	1,937113
	B	2,437844	0,4	0,325	2,392547
	D	2,482407	0,2	0,2	2,420721
	U	2,051942	0	0,55	2,0375
A7	UW	2,183333	0,282171	0,5	1,301429
	B	2,770588	0,3	0,366667	2,7008917
	D	2,935971	0	0,5	2,918571
	U	2,57561	0	0,3	2,557258
A8	UW	2,259259	0	0,25	2,44485
	B	2,605	0	0,9	2,583952
	D	2,241667	0	0,65	2,157895
	U	2,446584	0	0,6	2,435185

Table 3 Microplastic abundance in the different areas, in each site, with the average of each category

Area	Site	Abundance fibre	Abundace Microbeads	Abundace Fragments	Abundace Total
A1	UW	0,54765548	0,458396861	0,086777537	0,002481082
	B	0,5423308	0,53885366	0	0,00347714
	D	0,30799132	0,300780235	0	0,007211085
	U	0,328011301	0,325619529	0	0,002391772
A2	UW	0,398048159	0,384907206	0,013140953	0
	B	0,581248605	0,581248605	0	0
	D	0,358469874	0,356675186	0	0,001794688
	U	0,426022307	0,424526309	0	0,001495998
A3	UW	0,570895435	0,525214787	0,033362644	0,012318003
	B	0,538399222	0,457731449	0,069984666	0,010683107
	D	0,407162809	0,394801218	0,003440985	0,008920607
	U	0,706575494	0,677047104	0,027857825	0,001670565
A4	UW	0,341872202	0,339917359	0	0,001954843
	B	0,536837824	0,526377427	0	0,010460397
	D	0,191555028	0,183917093	0,007637935	0
	U	0,190540164	0,188203442	0,001168361	0,001168361
A5	UW	0,410039939	0,393182266	0,011044842	0,005812831
	B	0,454679819	0,215622319	0,237976828	0,001080672
	D	0,351628588	0,320470194	0,027735047	0,003423347
	U	0,371665942	0,368427921	0	0,003238021
A6	UW	0,408705119	0,367442704	0,03589987	0,005362545
	B	0,743729359	0,727995138	0,009514251	0,00621997
	D	0,323460186	0,315118342	0,005480203	0,002861641
	U	0,394679088	0,390947745	0	0,003731343
A7	UW	0,377769366	0,205043207	0,171130754	0,001595405
	B	0,200990103	0,195928124	0,001244942	0,003817037
	D	0,237016256	0,235666729	0	0,001349528
	U	0,208451408	0,206728756	0	0,001722653
A8	UW	0,47203023	0,468453373	0	0,003576858
	B	0,333268328	0,329033514	0	0,004234813
	D	0,383008843	0,360510276	0	0,022498567
	U	0,351154198	0,348916311	0	0,002237887

Table 4 SD of Microplastic abundance and dimension in the different areas, of each category



	SD Total Abundance	SD Abundace Fibres	SD Abundance Microbeads	SD Abundace Fragments
A1	0,431497225	0,405912571	0,021694384	0,00389027
A2	0,440947236	0,436839327	0,003285238	0,000822671
A3	0,55575824	0,51369864	0,03366153	0,00839807
A4	0,315201304	0,30960383	0,002201574	0,0033959
A5	0,397003572	0,324425675	0,069189179	0,003388718
A6	0,467643438	0,450375982	0,012723581	0,004543875
A7	0,256056784	0,210841704	0,043093924	0,002121156
A8	0,3848654	0,376728368	0	0,008137031
	SD Dimension Total	SD Dimension Fibres	SD Dimension Microbeads	SD Dimension Fragments
A1	0,085691125	0,296606306	0,084616783	0,277317078
A2	0,16202098	0,352177864	0,071713717	0,102817453
A3	0,112659662	0,329520507	0,108133515	0,220691554
A4	0,207430421	0,346343074	0,370006435	0,182443729
A5	0,112464731	0,558695602	0,10715579	0,430669468
A6	0,118665058	0,282848695	0,117918454	0,18793996
A7	0,111050538	0,393543725	0,13755105	0,171519817
A8	0,174040973	0,211710213	0	0,481848142

Table 5 Microplastic values in the different beaches with the total number of each category, minimum and maximum values, the island sector factor (North, South, East and West), granulometry classified according to Valentine (2019) and Blott & Pye

(2012) (1 - clay (<1/256 mm); 2 - silt (1/16–1/256mm); 3 - sand (2-1/16mm); and 4 - pebble (64 – 2mm)). Proximity to a pollution source/centre (1 – more than a mile; 2 – less than a mile; 3 – inside towns).

Sample Local	Total MP	Total Fibres	Total Microbeads	Total Fragments	Min	Máx	Granulometry	Setor island	Proximity urban center
B1	319	317	0	2	0,2	5	3	O	2
B2	234	234	0	0	0,4	5	3	N	2
B3	353	300	46	7	0,2	5	3	N	1
B4	198	193	0	5	0,3	5	3	N	2
B5	342	337	0	5	0,1	5	4	N	2
B6	322	322	0	0	0,3	5	4	N	3
B7	201	199	0	4	0,2	4,9	2	N	3
B8	413	195	217	1	0,2	5	3	E	3
B9	375	372	2	1	0,2	5	3	S	1
B10	483	473	6	4	0,2	5	3	S	2
B11	157	153	1	3	0,2	5	3	S	2
B12	276	267	4	5	0,2	5	3	S	2
B13	220	210	1	9	0,1	5	3	S	2
B14	323	281	40	2	0,2	5	3	S	1
B15	243	240	0	3	0,4	5	4	S	3

Table 6 Microplastic dimension in the different beaches with the average dimension of each category

Sample Local	Size fibres	Size Microbeads	Size Fragments	Size Total
B1	2,386435	0	0,35	2,373668
B2	2,51	0	0	2,516239
B3	2,129333	0,2	0,514286	1,845892
B4	2,493264	0	0,4	2,440404
B5	2,207122	0	1,2	2,192398
B6	2,236957	0	0	2,236957
B7	1,856784	0	0,275	1,8255616
B8	2,549231	0,2198161	1,7	1,323245
B9	2,252151	0,2	1,2	2,2384
B10	2,437844	0,4	0,325	2,392547
B11	2,770588	0,3	0,366667	2,7008917
B12	2,258427	0,25	0,46	2,196739
B13	2,108571	0,2	0,255556	2,024091
B14	2,19395	0,27	0,35	1,944272
B15	2,605	0	0,9	2,583952

Table 7 Microplastic abundance in the different beaches with the average of each category

	Abundance Total	Abundace Fibers	Abundance Microbeads	Abundance Fragments
B1	0,54	0,54	0,00	0,00
B2	0,58	0,58	0,00	0,00
B3	0,54	0,46	0,07	0,01
B4	0,30	0,29	0,00	0,01
B5	0,51	0,50	0,00	0,01
B6	0,43	0,43	0,00	0,00
B7	0,54	0,53	0,00	0,01
B8	0,45	0,22	0,24	0,00
B9	0,62	0,62	0,00	0,00
B10	0,74	0,73	0,01	0,01
B11	0,20	0,20	0,00	0,00
B12	0,31	0,30	0,00	0,01
B13	0,31	0,29	0,00	0,01
B14	0,50	0,43	0,06	0,00
B15	0,33	0,33	0,00	0,00

Table 8 SD of Microplastic abundance and dimension in the different beaches, of each category

	SD Dimension Total	SD Dimension Fibres	SD Dimension Microbeads	SD Dimension Fragments
B1	0,022520811	0,220570828	0	0,178885438
B2	0,067438831	0,067562344	0	0
B3	0,097769723	0,224768186	0,090664216	0,300832179
B4	0,116441394	0,187012417	0	0,219089023
B5	0,739405528	0,160130617	0	2,161712284
B6	0,060892668	0,182678005	0	0
B7	0,097217081	0,205300781	0	0,141421356
B8	0,100599163	1,045031631	0,002224388	0,760263112
B9	0,207066038	0,2619523	0,109544512	0,536656315
B10	0,099342303	0,125636002	0,109544512	0,174642492
B11	0,036964422	0,22707036	0,089442719	0,160996894
B12	0,139904335	0,161408066	0,147580487	0,331662479
B13	0,056912603	0,175375743	0,089442719	0,115412304
B14	0,063809886	0,116020698	0,047760771	0,194935887
B15	0,186059688	0,081242259	0	0,554977477
	SD Total Abundance	SD Abundace Fibres	SD Abundance Microbeads	SD Abundace Fragments
B1	0,092163643	0,090962685	0	0,004765331
B2	0,16556567	0,16556567	0	0
B3	0,028377721	0,021635789	0,047449222	0,012611841
B4	0,057958631	0,059948394	0	0,007490426
B5	0,137532691	0,13990031	0	0,005308286
B6	0,09729583	0,09729583	0	0
B7	0,228994546	0,228880362	0	0,016151434
B8	0,092899027	0,043136123	0,084801766	0,002416456
B9	0,16605265	0,167325754	0,004362954	0,003779696
B10	0,305154682	0,293863576	0,013202448	0,006072758
B11	0,054492931	0,047426852	0,002783776	0,008535154
B12	0,045162769	0,040782103	0,009942499	0,003854332
B13	0,118173978	0,122139719	0,002866754	0,008986653
B14	0,108118747	0,091613185	0,020273389	0,004320187
B15	0,046418957	0,042810895	0	0,003952646