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Microplastics hot spots at the South Iberian Margin

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ABSTRACT

The persistent accumulation of microplastics (MPs) in sediments poses ecological risks to benthic organisms and contributes to the broader issue of marine pollution. This study quantitatively analysed MPs in sediments, water and mussels *Mytilus galloprovincialis* from eleven sites of the South Portuguese coast in two contrasting climatic seasons (summer and winter). MPs were detected in sediments, water, and *M. galloprovincialis* at all study sites, although their abundance, colour, size, and type varied across compartments, locations, and seasons. Three hot spots of MPs contamination were identified at the South Portuguese coast. In these areas, the concentration of MPs in sediments was three orders of magnitude higher than water and mussels. The MPs identified had distinct colour patterns: transparent particles dominated in sediments, while blue was the most common in water and mussels. A size-dependent accumulation pattern was observed in the sediments, suggesting selective retention of MPs according to natural particle size, and a relationship was observed between MP levels in sediments and in mussels. Polypropylene (PP) and polyethylene (PE) were dominant polymers in sediments while PP, PE and polyethylene terephthalate (PET) were consistently present in water and mussels. Polybuthyl methachrylate (PBMA) was also detected in surface water and ingested by mussels. These findings suggest that variability in MPs abundance and polymer composition is linked to differences in local human activities. They also provide strong evidence for the importance of controlling land-based sources of MPs, particularly those transported to the coastal area by transported by rivers.

1. Introduction

Economic and technological development, population growth, and a lack of environmental awareness have contributed to one of the most critical challenges facing humanity: the invasion of the ocean by millions of tons of plastic each year. Therefore, plastics constitute one of the most damaging forms of human ecological impact. Their usage spans through numerous sectors, and global production reached around 414 million metric tons in 2023, of which only about 10 % was recycled (Plastics Europe, 2024). In 2015, nearly 5 % of the 275 million metric tons produced by 192 coastal nations entered marine ecosystems (Jambeck et al., 2015). Since then, plastic waste has continued to accumulate across all environments, including the ocean. It is estimated that 250 000 tons of plastic are currently present in marine environments (Isobe and Iwasaki, 2022) accounting for up to 80 % of marine litter (Barnes et al., 2009), approximately 90 % of which consists of microplastics (MPs; particles ranging from 100 μm to 5 mm) (Eriksen et al., 2014; Duan et al., 2021). Consequently, plastic pollution is widely recognized as one of the most urgent threats to the marine environment, owing to its persistence and toxicological impacts on ecosystems, wildlife, and human health (Chatterjee and Sharma, 2019).

Microplastics are now ubiquitous in all seas and ocean, present in the water column, sediments, and over more than 4000 marine species (Santos et al., 2021). According to recent estimates, more than 24.4 trillion plastic particles float on the ocean's surface, weighing over 25 0000 metric tons (Isobe and Iwasaki, 2022).

Microplastics in the marine environment originates from the direct release of manufactured particles (primary MPs), such as microbeads used in cosmetics and cleaning products, or from the breakdown of larger plastic debris (secondary MPs) (Bessa et al., 2019). Due to their small size, MPs are easily ingested by a wide range of marine organisms, from plankton to marine mammals, and accumulated throughout the

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food web (Parolini et al., 2023). Furthermore, MPs can act as vectors for other pollutants, viruses, and bacteria by adsorbing these from the surrounding water, exposing consumers to harmful substances (O'Donnovan et al., 2018, 2020; Chatterjee and Sharma, 2019; Islam et al., 2021).

The distribution of MPs in the marine environment is influenced by their physical characteristics, such as density, size, and shape (Murray and Cowie, 2011). While buoyant MPs remain afloat at the ocean surface, denser MPs, or those covered by biofilms, sink through the water column, becoming embedded in sediments or transported by ocean currents. However, the sea surface contains only about 1 % of the estimated total marine plastic load, with the remainder residing in deeper waters or on the seafloor, depending on the physical properties of the particles (Koelmans et al., 2017). Despite the significance of sub-surface and deep-water regions being MPs accumulation zones, these areas remain poorly studied (Kane et al., 2020). Research into the distribution, behaviour, and ecological impact of MPs in the marine environment is ongoing and presents considerable challenges.

Microplastics represent an allochthonous input of anthropogenic origin into marine sediments. They are transported either in suspension or as bedload, necessitating sampling methodologies like those used in sedimentology. However, the high variability, contamination risk, and sampling representativeness associated with MPs demand specialized approaches. Studies have found a positive relationship between MP concentrations, organic matter content, and fine-grained sediments (Vianello et al., 2013), indicating that MPs tend to accumulate in calm environments or geomorphological traps. This is especially true for low-density plastics, namely polypropylene (PP) and polyethylene (PE) (Eich et al., 2015).

The settling velocity of MPs, like that of mineral particles, is influenced by both particle properties (density, shape, and size) and fluid dynamics (density, viscosity, and flow velocity). Effective monitoring of MPs requires the collection of both bottom sediments and water to capture MPs in suspension. However, differences in residence time between suspended and settled MPs mean that sampling may only represent conditions at the time of collection, as currents can rapidly redistribute MPs particles.

Sampling design also varies greatly, particularly in terms of the area covered and sampling distribution, which can range from random (Karlsson et al., 2017) to transect-based approaches (Cauwenberghe et al., 2013; Díez-Minguito et al., 2020). Sediment sampling often focuses on the upper 5 cm (Frias et al., 2019), although in coastal areas influenced by wave action, the active layer can reach depths of up to 20 cm (Ciavola et al., 1997; Ferreira et al., 2000). Like other sedimentary particles, MPs distribution on beaches is influenced by hydrodynamic sorting caused by alongshore transport, which in turn is affected by wind patterns and coastal morphology (Butt et al., 2001; Bertin et al., 2008; Grasso et al., 2011; Oliveira et al., 2017; Horta et al., 2018).

An effective sampling strategy in coastal environments with complex morpho dynamics must therefore incorporate detailed knowledge of local hydrodynamic conditions. While bulk sampling methods can yield representative data, they often result in large sample volumes. This limitation can be addressed through well-designed sampling plans that include replicate samples.

In this study, a sediment sampling methodology was proposed that ensures site representativeness with minimal sample volume and MPs concentrations in sediments. Sediments, water, and mussels *Mytilus galloprovincialis*, were collected from eleven sites along the South Portuguese coast during two contrasting climatic periods—winter and summer - to assess the levels of MPs and identify "hotspots" of MP contamination, map MP distribution along the Southern Portuguese coast, and investigate potential land-based sources of plastic pollution.

2. Materials and methods

2.1. Sampling area

Two sampling campaigns were conducted in 2021 one in winter and the other in summer along the South Portuguese coast. The southern coast of Portugal exhibits significant geomorphological and hydrodynamic diversity, featuring rocky cliffs of various lithologies and low-lying areas. The Cape of São Vicente marks a change in the orientation of the coastline. North of this cape, the wave climate is vigorous with dominant NW swells. In contrast, the southern coast is much less energetic, with wave height rarely exciding 1 m, approaching from the WSW during 71 % of the observations over the course of a year. The region experiences a mesotidal, semidiurnal tidal regime, with tidal ranges from 3.5 m during spring tides to 1.3 m during neap tides (data from the Portuguese Hydrographic Institute, https://www.hidrografico.pt).

Along the southern Portuguese coast, eleven sites were selected, each exhibiting distinct abiotic and hydrodynamic conditions (Fig. 1; Supplementary Table S1): site 1, (Barriga): located on the west coast of Portugal, north of Cape São Vicente, in a more energetic sector. This is a sandy beach bordered by high rocky cliffs of schists and shale, strongly affected by the dominant NW swell; site 2 (Sagres): although located in the coastal sector influenced by swell, sampling was conducted inside the harbour in an area with significant commercial and recreational fishing; site 3 (Barranco): situated east of site 2, this sandy beach is backed by limestone cliffs. Large rocky blocks indicate significant coastline retreat; site 4 (Lagos): the coastline here is bounded by an estuary and a groin to the west, which protects the entrance to a marina. Both the marina and the beach experience intense touristic activity; site 5 (Portimão): an intertidal mixed sand-mud beach located at the estuary of the Arade river, which connects to several upstream cities. This area is primarily focused on tourism; site 6 (Vilamoura): a sandy beach cell situated between two groin systems, and samples were collected near the western groin; site 7 (Forte Novo): a sandy beach bordered by sandstone cliff. Sites 8 (Faro), 9 (Olhão), and 10 (Tavira): located in the Ria Formosa lagoon, a barrier-island system characterized by shallow depth (average ~2 m), tidal dominance, minimal freshwater inputs, and protection from oceanic waves by sandy barrier islands. This lagoon produces about 80 % of bivalves including *M. galloprovincialis* (Pilkey et al., 1989; Carrasco and Matias, 2019; Moura et al., 2019) (see Fig. 1). Site 11 (Vila Real de Santo António -VRSA): located in the of western groin of the Guadiana estuary.

Geographic coordinates (latitude/longitude) for each site, obtained via GPS, are provided in Supplementary Table S1. Current direction was visually estimated, wind direction was determined with an anemometer, and sea surface temperature and salinity were measured using a WTW ProfiLine Conductivity Meter LF 197-S. A summary of these parameters are summarized in Supplementary Table S1.

2.2. Sediment samples

Sediments (888 cm^3 per site) were collected only in winter because the study area is characterized by relative environmental stability with limited seasonal fluctuations (see Table S.1) and according to the Quality Status Report of OSPAR (https://oap.ospar.org › en › ospar-monitoring-programmes). The sampling strategy at beaches, lagoons, and estuaries was as follows: (i) a central point was selected near the site where the mussels were collected, and sediments samples were taken in the four cardinal directions (N, E, S, W) relative to this point; (ii) in each direction, two samples were collected approximately 30 cm apart yielding at total of eight replicate sediments samples per site, except for site 7, where only six samples were taken. This strategy allowed the relationship between the number of MPs and the direction of currents or other sediment dispersion factors to be assessed, while ensuring a broad sampling area (~28.3 m^2) without the need for large sediment volumes.

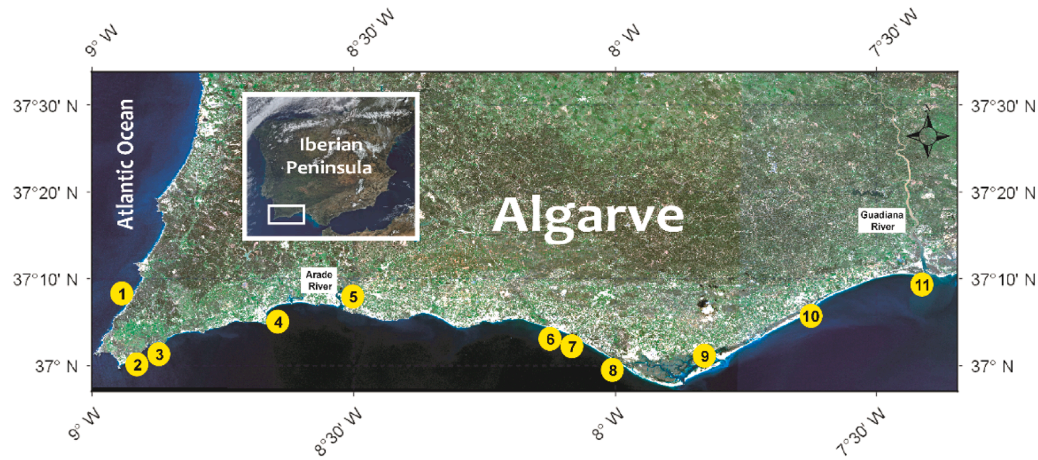

Fig. 1. Sampling sites in the South Portuguese Coast (The Iberian Peninsula image contains modified [Cristina, 2022] Sentinel-3 OLCI [01–03–2016] image, processed by ESA and the other satellite image containing modified [Cristina, 2022] Sentinel-2A Level 2 A data [22–03–2021], processed by the European Space Agency (ESA)).

Medium sand to muddy sediments was collected using a stainless-steel square-section sampler (47 mm×47 mm), whereas coarse sand was sampled with a custom-designed stainless-steel corer, assisted by a garden-type spoon to prevent sediments loss (the use of spoon depends on the type of the sediments). Using these tools, the top 5 cm of the sediments was sampled, resulting in approximately 111 cm^3 per sample and 888 cm^3 per site (except for site 7 where only 666 cm^3 were collected). Samples were transferred to 350 cm^3 glass jars with metal lids and 80.2 mm openings—sized to accommodate direct sediment transfer—requiring only eight jars per site.

The optimal sampling depth in muddy sediments was estimated from the sedimentation rate, typically ~1.6 mm/year in lagoons and estuaries, potentially reaching up to 4 mm/year. Thus, the top 2 cm of sediments can reflect plastic accumulation over the last 50 years. However, to maintain consistency with other studies (e.g. Frias et al., 2016), a 5 cm depth was used. Samplers were fitted with depth-limiting brakes for ease of use.

Sediments were processed in the laboratory using standard mechanical sieving and pipetting techniques (Lewis and McConchie, 1994). Grain size distribution statistics were determined using the Gradistat software (Blott and Pye, 2001), and terminal velocity was estimated using the Hjulström diagram. MP analyses followed the methodology outlined in Bebianno et al. (2025). Briefly, the entire amount of the sediments collected from each site was dried in an oven at 40 °C, and the organic matter oxidized using 30 % of hydrogen peroxide (H_2O_2). Following this procedure, a set of stainless sieves (mesh sizes from 500 to 63 µm) was used in a Retsch AS 200 digit shaker to separate the sample by grain size classes. Each fraction was then weighed and transferred to glass beakers, and MPs were density separated using a NaCl solution of 1.2 g/cm^{-3} (Hanvey et al., 2017). The supernatant was filtered using 47 mm diameter, 0.8 µm pore-size membrane filters, and stored in glass Petri dishes for later analysis. Microplastic polymers were identified by Fourier-transform infrared spectroscopy (FTIR) as described in below. MP_S in sediments are presented in number of MPs per cm^3.

2.3. Water samples

Coastal seawater is typically clear, with low suspended and dissolved organic matter. During the two sampling campaigns, ten litters of water were collected at each site using an aluminium bucket and then transferred into two 5 L glass bottles with a metal funnel. The bottles were then covered with aluminium foil to prevent light exposure. Microplastic levels in seawater were analysed according to the method described by Masura et al. (2015). Due to the low organic content, water samples were directly filtered with a 47 mm diameter, 0.8 µm pore-size membrane filters using a Vacuum pump (Pall®) to collect the MPs particles present in the water samples. Filters were stored in glass Petri dishes at room temperature for later analysis. MP results are expressed as the number of particles per litter.

2.4. Mussel samples

Mytilus galloprovinciais of commercial size (n = 550, 52.8 ± 5,9 cm, 4.4 ± 1.5 g) were collected during two campaigns. The marine mussel *M. galloprovinciallys* was selected because it is a filter-feeding organism that is highly abundant in the Portuguese coast and because they were present at all sampling sites in opposite to clams. It is also a well-known bioindicator species with significant economic importance. These bivalves can accumulate contaminants present in the marine environment, making them excellent sentinel species for environmental monitoring studies (Dellali et al., 2021). The mussels were collected in rocks near or in boat cables that are in contact to the sediment. At each site, 25 mussels were collected per site and season using a metal or wooden chisel, wrapped in aluminium foil, and stored at 4ºC during transport. Samples were frozen at −20°C upon arrival for further analysis. In the laboratory, mussels were measured and weighed, and the soft tissue of each specimen was individually digested in a 10 % KOH solution (ratio ≥5:1) in 250 mL Erlenmeyer flasks at 50°C for 48 h or until complete digestion. A density separation procedure followed, using a pre-filtered sodium chloride (NaCl) solution (1.2 g cm^{-3}) according to the methodology proposed by Avio et al. (2015, 2017a); Avio et al. (2017b). Blanks were processed in parallel. After digestion, the liquid was transferred to 100 mL glass cylinders, and the same separation and filtration procedure as for sediments and water was applied. Filters were analysed in the same way across all sample types. MP abundance in mussel tissues is reported as percentage, per individual and per gram of tissue.

2.5. Microplastic identification and quantification

Filters containing MPs from all matrices (sediments, water and mussels) were analysed using a Leica™ microscope with an Olympus™ camera at 40 x and 100 x magnification. Each particle was measured (±0.05 mm), photographed, and classified by size (1–100 µm, 0.1–0.5 mm, 0.5–1 mm, 1–5 mm), colour, and shape (fragment, fibre, film, bead, foam, pellet) following the method proposed by Frias et al. (2019).

2.6. Chemical analysis of the plastic polymers

Following visual identification, a subset comprising 240 MPs were randomly selected from all sites and matrices — representing 20 % of MPs from sediments, water, and mussel samples - and analysed using Fourier-transform infrared spectroscopy (FTIR) to identify the plastic polymers, as described in Edo et al. (2020). Each MP particle was isolated and placed on a KBr matrix. FTIR settings were 4 cm^{-1} resolution, 16 scans, 4000–650 cm^{-1} range. Spectra were obtained using a Thermo Scientific IN10® microscope equipped with an MCTA detector. Both reflection and ATR modes were used, with spectral interpretation aided by OMNIC™ software but only results above 70 % were considered for identification.

2.7. Quality control

No plastic materials were used during fieldwork. All equipment (glass flasks, corers, metal samplers, buckets, and funnels) was pre-cleaned with distilled water and wrapped in aluminium foil and was pre-rinsed three times with site water before sampling. Aluminium foil was also used to cover samples and minimize airborne contamination and photosynthetic activity.

Solutions (NaCl, KOH, water) were filtered before use. Blanks were processed concurrently with the microplastic analyses. To assess airborne contamination, blank control filters were exposed in the laboratory for three days in glass Petri dishes to capture airborne MPs. All glassware was rinsed with Milli-Q water during density separation to avoid plastic particle loss. An H_2O_2 blank was processed identically to detect potential contamination during digestion.

2.8. Statistical analysis

To validate differences among sites, the non-parametric Kruskal-Wallis test was applied, followed by Dunn's post-hoc analysis for seasonal comparisons. A two-way ANOVA assessed spatial, seasonal, and species-based differences. Analyses were performed using Primer6 software with a 95 % confidence level ($p < 0.05$).

To determine the relative frequency of MP attributes (colour, composition, and type), was applied the formula: $F = (s \times 100) / S$, where s represents the number of samples exhibiting a specific attribute, and S is the total number of samples analysed.

The similarity in MP composition in sediments between sites was assessed using Jaccard's similarity coefficient, defined as: $S = (2\,C) / (s_1 + s_2)$, where C is the number of shared variables (e.g., polymer types) between two sites, and s_1 and s_2 are the total number of variables observed at each respective site. Higher Jaccard coefficients indicate a greater resemblance in MP composition between the compared sites.

3. Results

To assess the occurrence and characteristics of MP particles in sediments, water, and mussels, a total of eleven sites were sampled along various parts of the southern Portuguese coast during two different contrasting seasons - winter and summer (Fig. 1). MPs were detected in sediments, water, and *M. galloprovincialis* at all study sites, although their abundance, colour, size, and type varied across compartments, locations, and seasons. Three hot spots of MPs contamination were identified at the South Portuguese coast (sites 2, 5 and 9). In these areas, the concentration of MPs in sediments was three orders of magnitude higher than water and mussels (Fig. 2 A, 3A-B and 5). Fibers were more common in sediments while in water and mussels' fragments were predominant. The MPs identified had distinct colour patterns: transparent particles dominated in sediments, while blue was the most common in water and mussels (Fig. 2 C, 3A-B, 6 A).

3.1. MPs quantification and size in sediments

MPs were found in all sediment samples. Sites 2, 5, and 9 showed the

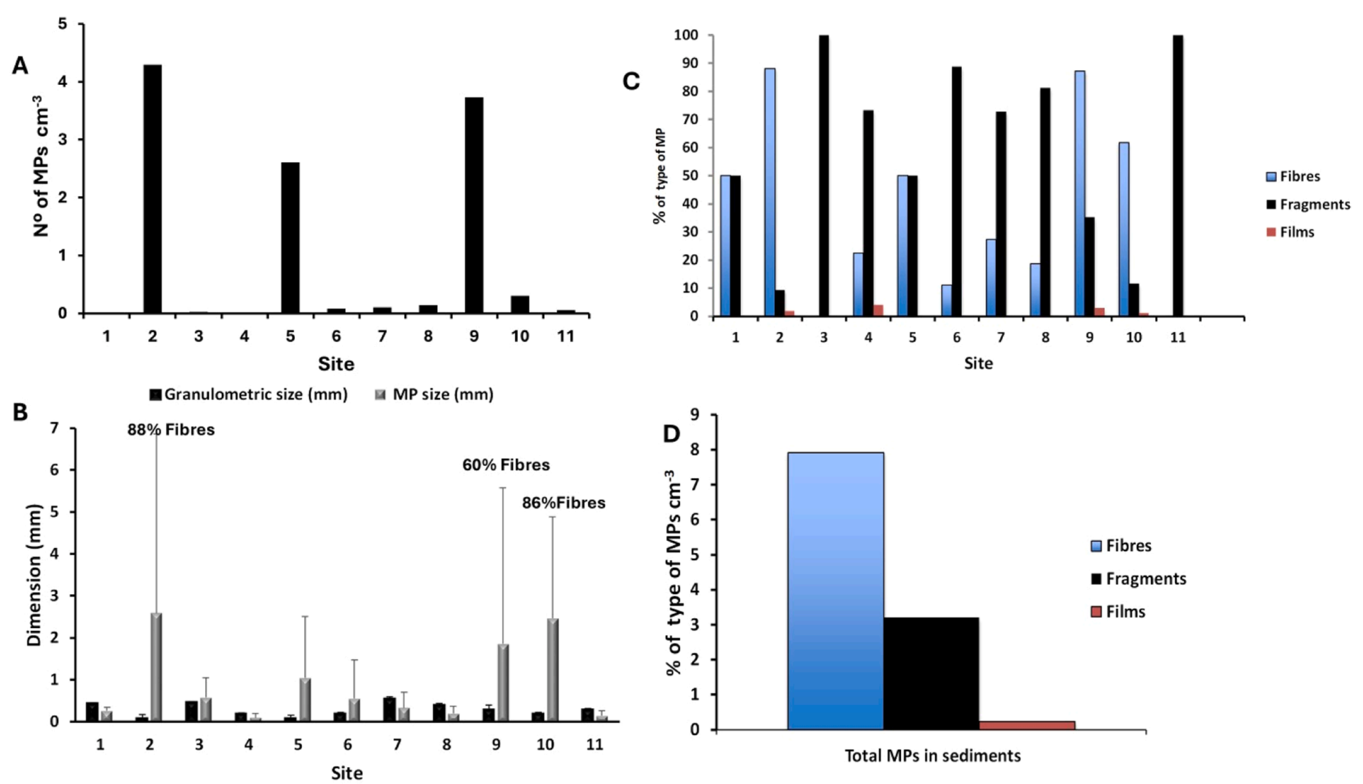

Fig. 2. (A) Number of MPs cm^{-3} in sediments from each site; (B) Relationship between granulometric (mean±s.d.) (mm) of the natural sediment and MPs size (mean ±s.d.) (mm) from each site; (C) percentage of types of MPs per site; (D) percentage of types of MPs in the whole sediments samples.

highest number of MP particles (Fig. 2 A). These site, along with site 10, had sediments classified as fine to very fine sand and muddy sand. In contrast, sites 1, 6, 7, 8, and 11 had sediments classified as fine to medium sand and showed a significantly lower number of MP particles (Fig. 2 A).

The most common type of MP found in sediments in the Southern coast was fibres, followed by fragments, with films being the least prevalent (Fig. 2 C and D). The size of MP fragments in the sediments ranged from 0.09 mm to 1.04 mm, overlapping with the natural grain sizes of fine to coarse sand. Exceptions were observed at sites where MP particles included fibres, as these sites had higher fibre counts (sites 2, 9 and 10) (Fig. 2C-D) and larger particle sizes (0.08 mm to 8 mm) (Fig. 2C-D). In sites 2, 9, and 10, MP particles were mainly fibres (88 %, 60 % and 86 %, respectively) (Fig. 2 C). These particles exhibit different hydrodynamic behaviour than fragments or natural sand grains. Despite their larger size (up to 8 mm long) they tend to co-deposit with fine sediments due to hydrodynamic sorting. At site 5, the difference between the mean diameter of natural sediments (fine sand) and the mean size of MP particles (coarse sand) is significant (Fig. 2B).

The terminal velocities of the particles were estimated based on their size using the Hjulström (1935)' curve (Table 1). As shown in Fig. 2B and Table 1, the co-deposition of large numbers of MP particles with finer sediments is evident, particularly at sites 2, 5, and 9, and to a lesser extent at site 10.

3.2. Qualitative analysis of MPs in sediments

The dominant composition of MP particles was polypropylene (PP), followed by polyethylene (PE), polyethylene terephthalate (PET), and polyvinyl chloride (PVC). Smaller quantities of nylon, polystyrene (PS), acrylic, polyurethane (PU), and polyester (PES) were also detected. PP and PE together represented most MPs, accounting for 77 % of the total. Although present in similar proportions - PP (39 %) and PE (38 %) - their distribution varied significantly across sites and colours (Table S2).

Polypropylene MPs, with a density range of 0.87–1.01 g cm^{-3}, was most prevalent at sites 2 and 9 (Fig. 8 A), while PE particles (density 0.92–0.96 g cm^{-3}) were primarily found in the sediments at site 5. At sites 2, 5 and 9, high-density polymers, denser than water, polyethylene terephthalate (PET: 1.33 – 1.37 g cm^{-3}) and polyvinyl chloride (PVC: 1.35 – 1.45 g cm^{-3}) were common. The highest number of MPs and the greatest diversity in composition were observed at site 2 (Fig. 8 A).

There is a relationship between the composition and the morphology of MPs (Table S2). Fibers, mainly composed of PP, dominated at sites 2 and 9 (Fig. 3 A), whereas fragments composed primarily of PE were most common at site 5. The other identified polymers appeared in much lower abundance. Films were composed of PE, PET and PVC. Transparent MP particles were the most common in the sediments, accounting for 31 % of the total, followed by blue particles (27 %). Black, green, white, and orange MP particles appeared in similar proportions, representing 9 %, 9 %, 8 %, and 8 % respectively. The remaining colours were present at lower percentages (below 5 %) (Fig. 3B). In terms of morphology and colour, fragments were primarily transparent and blue, making up 59 % of all fragments. Fibres were mostly transparent (37 %) but were also found in notable proportions in black and green (10 %) and blue (19 %). The remaining fibre colours accounted for a combined total of 24 % (Fig. 4 C). Among the dominant polymer types, PP and PE particles occurred in all colours but were most found in blue and transparent. (Fig. 3 C).

Table 1
Sediment granulometry and settling terminal velocity.

Site (see Fig. 1 for location)	Sediment type	Mean diameter of the grains (mm)	Terminal velocity (cm/s)
1	Medium sand	0.25 – 0.50	< 3
2	Bimodal, mud and coarse sand	0.063 – 0.50	0.8 – 2
3	Coarse sand	0.50 – 1.00	< 3
4	Fine sand	0.125 – 0.26	< 2
5	Muddy sand	0.063–0.125	< 0.3
6	Fine sand	0.125 – 0.26	< 2
7	Medium sand	0.25 – 0.50	< 2
8	Medium sand	0.25 – 0.50	< 2
9	Muddy sand	0.063–0.125	< 0.3
10	Muddy sand	0.063–0.125	< 0.3
11	Medium sand	0.3–0.4	< 3

3.2. Microplastics in surface water

Overall, the number of MPs in surface water were twice higher in winter than in summer, with the highest levels observed at site 9 (Olhão), followed by site 2 (Sagres) (Fig. 4A).

During the two seasonal periods (winter and summer), blue was the predominant colour of MPs, with site 9 (Olhão) exhibiting the highest frequency (30 %) (Fig. 4A - B). Other colours were sporadic and did not show any consistent pattern across sites or MP types. At several sites, no MPs were detected during one of the seasons (sites 1 and 6), or they were entirely absent in both seasons (at sites 8, 10 and 11) (Fig. 4A - B).

In contrast to the sediments, fragments were the most common type of MPs found in surface water (82 % and 72 % in winter and summer, respectively) and among the MPs colour, blue fragments were the most common type, representing 39 % of all particles, while fibres accounted for 25 % (Fig. 4C), with black being the most frequent fibre colour specially in summer (Fig. 4A). Only one film-type particle was identified in summer. In winter, the pattern remained similar: blue and black fragments comprised 48 % (mostly at site 9 - Olhão) and 15 % (from sites 9 and 2 (Olhão and Sagres), respectively, of the total particles. Like in the sediments, the other colours (green, yellow, red, white and transparent) were present at lower percentages (<10 %) (Fig. 4A).

The size of MPs detected in surface water ranged from < 100 μm to 5 mm. The highest percentage was in the range < 100 μm (62 %) and a decreasing trend was observed with the increase of size for both seasons although levels were higher in winter except for the size range of 100–499 μm. Moreover, no MPs with size > 5 mm were detected in summer (Fig. 4B).

In water PP was the dominant type of MPs at sites 2 (Sagres), 4 (Vilamoura) and 5 (Portimão). On the other hand, polybutyl methacrylate (PMA) was present at sites 2 (Sagres) and 9 (Olhão), while PET was only present at site 6 (Vilamoura). The greatest diversity in composition of MPs was at site 9 (PBMA, PVC and PE) (Fig. 8C).

3.3. Microplastics in mussels

The average wet weight of mussel soft tissues ranged from 0.92 ± 0.40–10.23 ± 2.46 g in winter and from 0.66 ± 0.17–11.1 ± 6.46 g in summer (Table S3). Similarly to the hot spots of MPs detected in the sediments, mussels from sites 2, 5, and 9 had the highest percentage of MPs ingested in winter (93.3, 63.7 and 46.7 %, respectively) while in summer the percentage of MPs in mussels from sites 2 (Sagres) and 5 (Portimão) was similar (60 %). The number of MPs detected per mussel and per gram of wet weight of the soft tissues from the different sites are presented in Fig. 5A-B. The number of MPs ingested by each mussel ranged in winter between 1 and 9, with 7 and 9 MP particles present in mussels from sites 9 (Olhão) and 5 (Portimão) respectively, while in summer the number of MPs ingested per mussel was lower (between 1 and 3). The number of MPs ingested by mussels from sites 2 and 5 in summer was similar between these two sites and significantly different from the other sites ($p < 0.05$). Nevertheless, two-way ANOVA indicated that there were no significant differences among seasons ($p > 0.05$). When the number of MPs ingested was expressed per gram of wet weight of mussel whole soft tissues (Fig. 5B), a different pattern was observed. The highest variability of the number of MPs per gram of mussel's tissue was at sites 3 (Barranco) and 7 (Quarteira) in both seasons. Similarly,

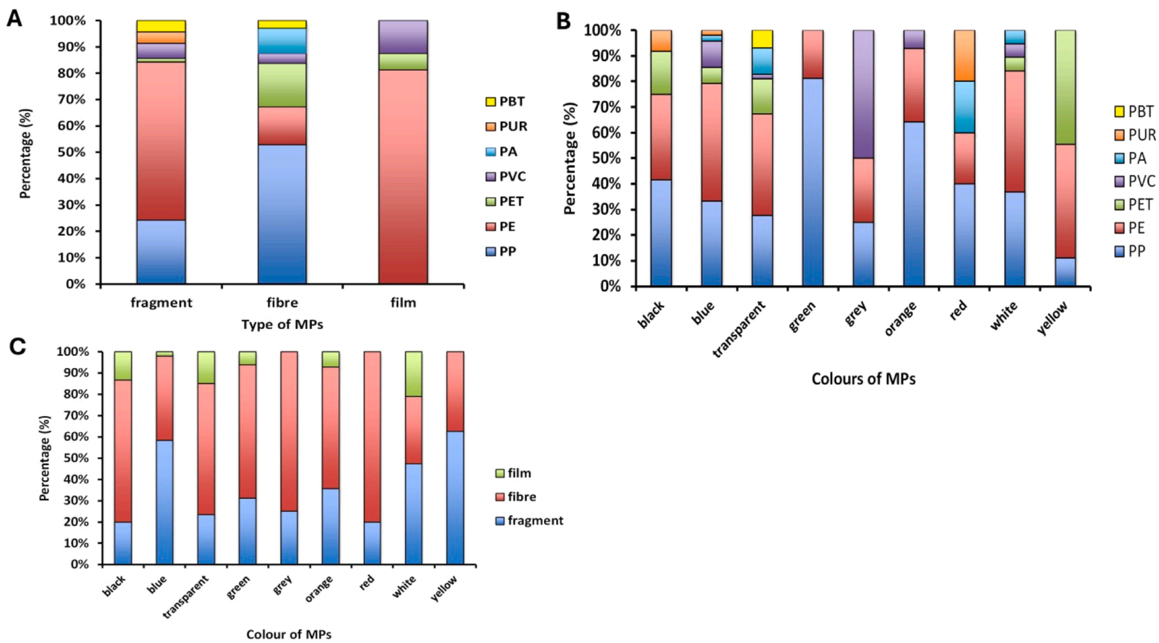

Fig. 3. (A) Percentage of type of MPs in the sediments versus polymer composition. (B) percentage of MPs colour versus polymer composition and (C) percentage of type of MPs versus colour.

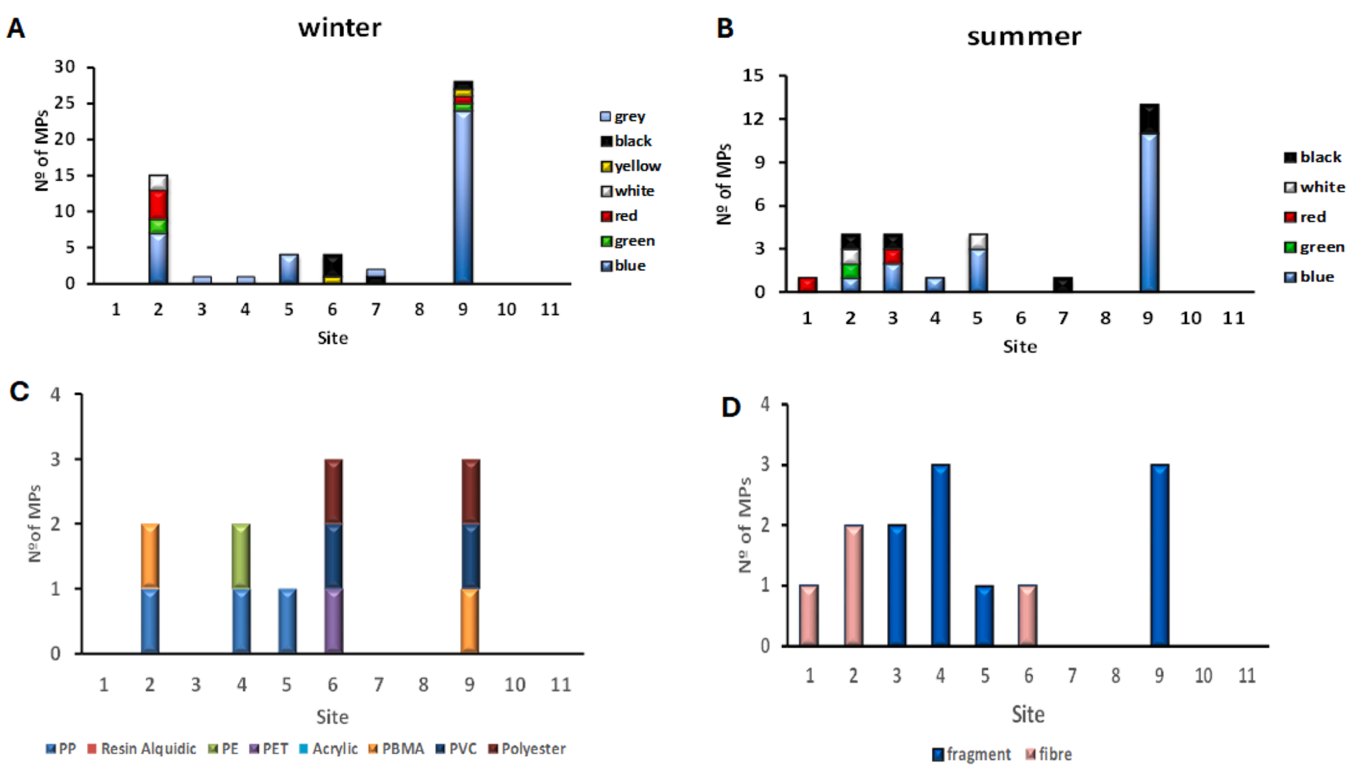

Fig. 4. Number of MPs in surface water in (A) winter and (B) summer; (C) type of MPs polymer composition per site and (D) type of MPs per site and season.

there were significant differences between the number of MPs ingested per gram of mussel tissues from these sites when compared to the other sites ($p < 0.05$). However, there were no significant differences among seasons ($p > 0.05$) (Fig. 5B).

Like in surface water, the predominant colour of MPs ingested by mussels was blue in both seasons (40–29 % in winter and summer) although the higher percentage was detected in winter (Fig. 6A). Moreover, the percentage of black particles was of the same order of magnitude in both seasons (32 %) consistent with the trends observed in both sediments and surface water (Fig. 6A).

Similarly to the size of MPs detected in surface water, the size of MPs ingested by mussels ranged from < 100 µm and > 5 mm (Fig. 6B). However, in contrast to the size of MPs in surface water, the bigger number of MPs ingested by mussels was in the size range 100–499 µm for both seasons (> 50 %) but the highest number was in winter from all size ranges except for those of size 500–900 µm. Like in the surface

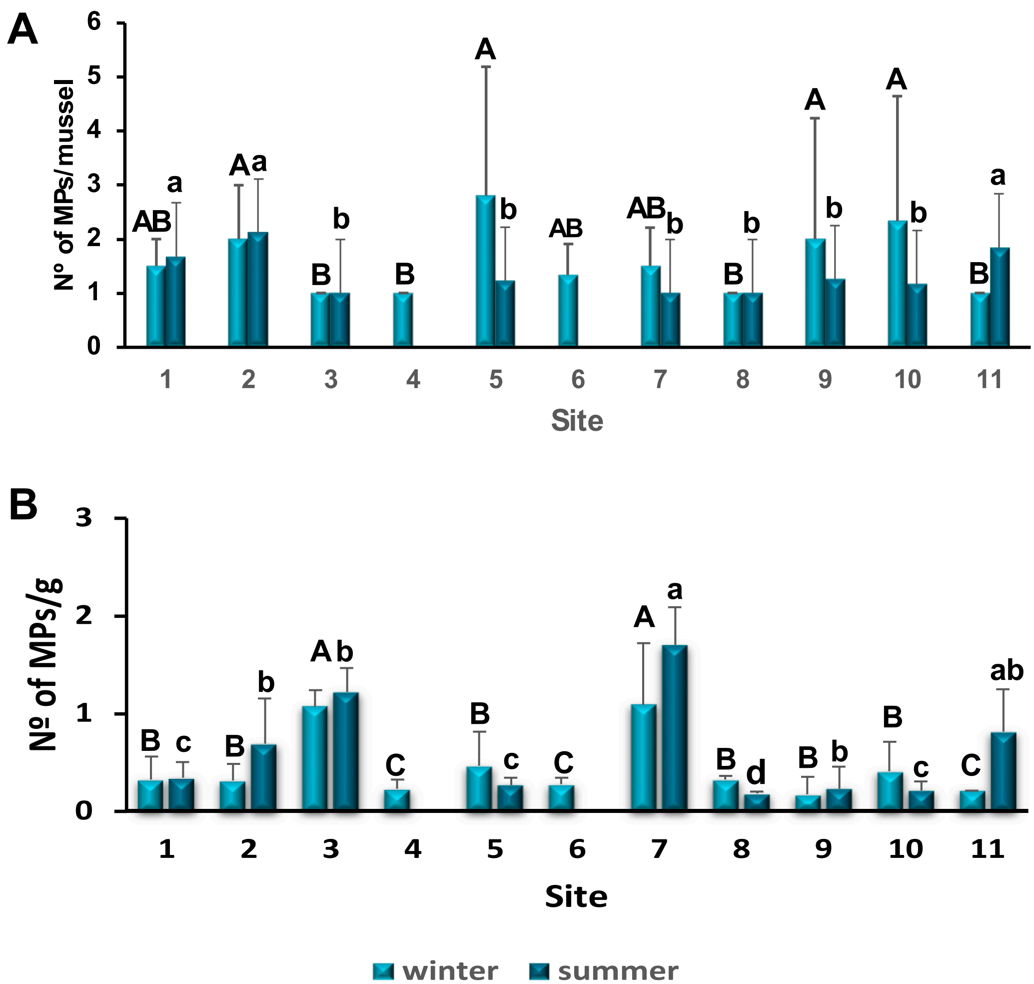

Fig. 5. Number of MPs ingested per mussel (A) and expressed as MPs per gram w.w. mussels' soft tissues (B). Capital letters indicate significant differences among sites and lower-case letters indicate significant differences between seasons ($p < 0.05$).

water, the most significant type of MPs was fragments in both seasons (73 and 52 %) while in summer besides fragments and fibres, film, foam and beads were also detected (Fig. 6C).

In mussels PE was predominant at sites 5 (Portimão) and 10 (Tavira), while PP was detected in mussels from sites 2 (Sagres), 3 (Barranco), 6 (Vilamoura) and 11 (VRSA) as well as PET in mussels from site 5, PVC in mussels from site 2 (Sagres) and PBMA in mussels from sites 3 and 4 (Barranco and Lagos), respectively. In winter however, PP was predominant in mussels from sites 2 and 3 (Sagres and Barranco) and PE and PS in mussels from site 5 (Portimão) while mussels from site 1 (Barriga) have ingested polyester urethane MPs (Fig. 8 C). Due to analytical constraints, the polymer composition of MPs ingested by mussels from site 9 (Olhão) was not possible.

3.4. Polymer composition across sediments, water and mussels

As previously noted, PP was the dominant polymer in the sediments at sites 2 and 9 (Sagres and Olhão), while PE was predominant at site 5 (Portimão). This pattern mirrored in mussels (Fig. 8A-B). Mussels from site 2 (Sagres) primarily ingested PP, and those from site 5 (Portimão) showed a predominance of PE, suggesting a correspondence between sediments and ingested MP composition in mussels at these sites (Fig. 8).

Interestingly, PBMA frequently used in coatings and in biomedical materials, which was not identified in sediments, was found in surface water at sites 2 and 9 (Olhão and Sagres) and in mussels from several other sites ($p < 0.05$) (Fig. 8). Due to its density (1.09 g/cm^{-3}) being similar to that of water, this polymer exhibits buoyant behaviour and tends to remain suspended in the water rather than depositing in the bottom sediment.

The present findings indicate a dominant association of PP and PE in sediment samples, which is mirrored by mussels and water, performing 76.7 % of relative frequency (Fig. 7A). A significant positive relationship was found between sediments and mussels concerning the composition of MP particles ($r = 0.980$), while a weaker but still significant relationship was observed between mussels and water ($r = 0.750$) and sediment and water ($r = 0.780$).

Sagres and Olhão (sites 2 and 9 - Fig. 7) exhibit the highest similarity in MPs composition across sediments, water and mussels with a Jaccard́s coefficient of 0.91 indicating a strong compositional resemblance. Conversely, Sagres and Portimão (sites 2 and 5 - Fig. 7), despite their geographical proximity, display the greatest dissimilarity, with a Jaccard́s coefficient of 0.77. Sites 5 and 9 (Portimão and Olhão) present an intermediate level of similarity, with a coefficient of 0.83.

The correlation analysis of polymer colour indicates a weaker association than among the composition sediments, water and mussel samples, with $r = 0.74$ emerging as a significant relationship between water and mussels and a weaker relationship between sediments and mussels ($r = 0.61$) and sediment and water ($r = 0.55$). Dominant colours across sediment water and mussels were blue and transparent performing 55.0 % of relative frequency (Fig. 7B)

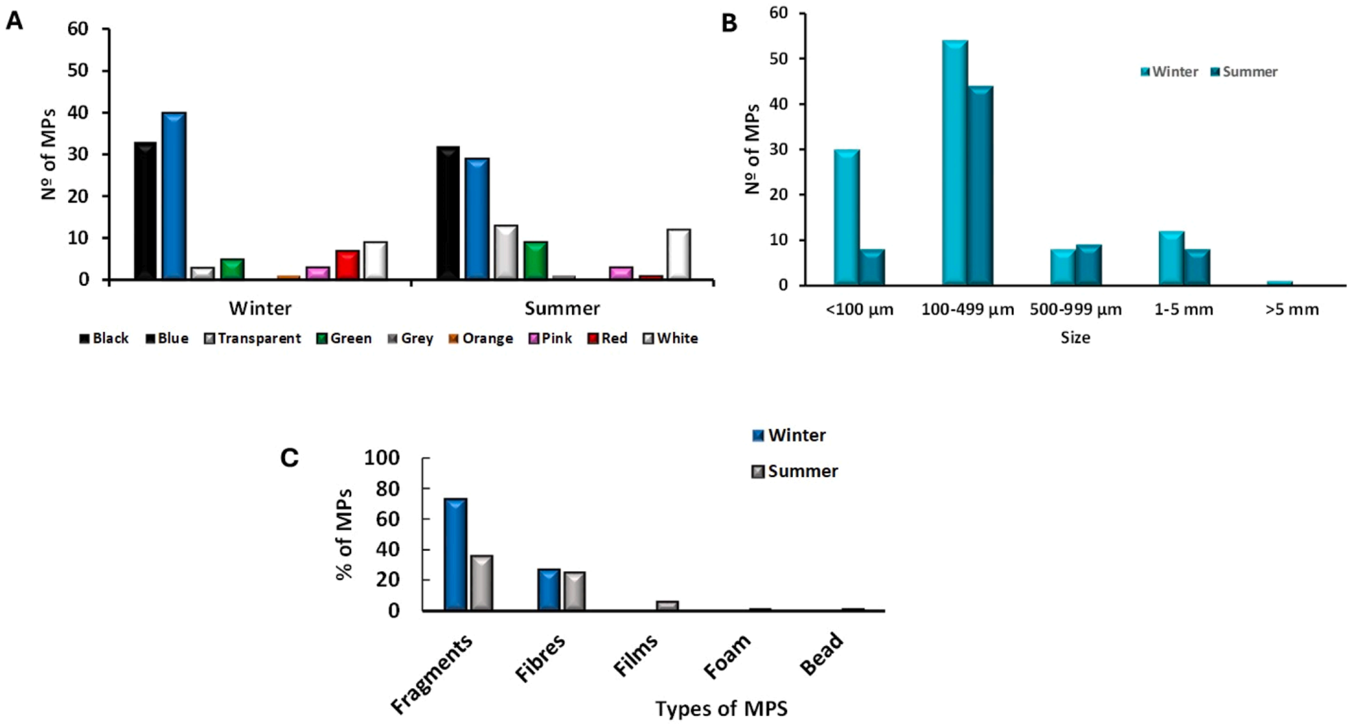

Fig. 6. (A) Colour, (B) size and (C) type of MPs ingested by mussels.

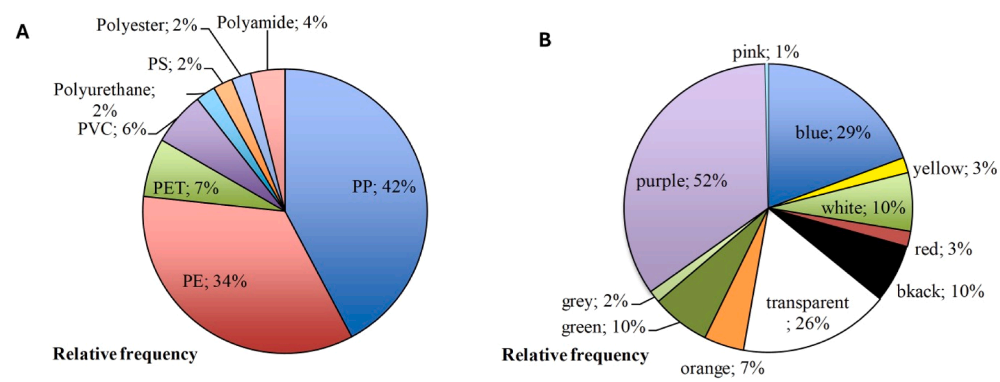

Fig. 7. Relative frequency (%) distribution of MPs composition (A) and colour (B) across sediment, mussels and water samples.

4. Discussion

4.1. Microplastic accumulation in sediments

Understanding the processes behind MPs accumulation and dispersion in coastal environments is essential for interpreting the current discrepancy between global plastic production and the relatively small amount observed floating at sea (Eriksen et al., 2014). Microplastics accumulate persistently in marine sediments, posing ecological risks to benthic communities and contributing to long-term marine pollution. The high incidence of MPs accumulation is linked to various anthropic activities such as washing clothes, hygiene products and thermoplastic road-surface marking paints (e.g., Frias et al., 2016; Horton et al., 2017; Peng et al., 2017).

Currently, there is a limited understanding of the processes governing MPs accumulation in coastal zones. This study seeks to address this knowledge gap and contribute to a deeper understanding of the factors influencing MPs dynamic in coastal areas one important compartment of MP sink.

One of the constraints for studying the distribution of MPs in coastal areas is the sampling strategy. Indeed, if the processes and mechanisms of MPs dispersion and accumulation are not understood, a biased scenario in quantification MP pollution may arise due to inadequate sampling strategies (Cauwenberghe et al., 2015; Zhao et al., 2025).

The complexity of the factors influencing the MP accumulation and dispersion makes difficult to elucidate the mechanisms involved, thereby hindering a thorough understanding of their distribution (Zhao et al., 2025). Several key variables influence the amount, distribution, and typology of MPs in sediments: (i) input from human activity, (ii) dispersion and transport by currents, (iii) substrate type, (iv) terminal settling velocity, which typically ranges between 3–7 cm s^{-1} (Leng et al., 2024), besides being influenced by the salinity of water and MPś density (Isachenko, 2020), and (iv) physical properties of MPs, such as density, shape, and composition. However, settling velocity is not determined by size alone - it is also strongly influenced by particle shape and density, which are dependent on the chemical composition of the plastic polymers.

In this study, three coastal MPs hotspots were identified along the southern coast of Portugal: Sites 2, 5, and 9 (Sagres, Portimão, and Olhão, respectively; Fig. 1). MP concentrations in sediments at these sites were up to three orders of magnitude higher than in the other surveyed locations of the current research. Some MPs resemble natural sediment particles in their hydrodynamic behaviour. Notwithstanding their lower density compared to minerals, some MP particles are found to co-deposit in the same sedimentary environment, suggesting complex interactions and processes governing their transport and deposition. This is the case of PE (density 0.97–1.05 g cm^{-3}) and PP (density ~0.90 g cm^{-3}), which have lower densities than typical mineral sediments (~2.7 g cm^{-3}) although they perform the dominant association in MP accumulation in hotspots. Here, as previously mentioned, the substrate nature is very fine sand and muddy sand (Table 1). The observed preference for MP to accumulate in muddy substrates consistent with findings from other works (e.g., Vianello et al., 2013) may be attributed to the comparable grain size and terminal velocities of these particles (Fig. 2B; Fig. 3B and Table 1). However, the primary driver is likely the adsorption capacity of clay minerals (phyllosilicates), which facilitates the retention of several particles including MPs. In addition, the cohesive nature of muddy sediments enhances retention and long-term accumulation of MPs in these environments.

The substantial difference in MPs accumulation between the identified hotspots and the remaining sites cannot be attributed to hetero aggregation. This process, known to be enhanced by the presence of sodium chloride (NaCl) in aquatic environments (Li et al., 2019) is unlikely to be the main driver to the formation of larger and denser particles incorporating suspended sediments and MP particles, given the similar salinity values across all sampling sites (Table S1).

In contrast, denser polymers like PTFE, or teflon (~2.3 g cm^{-3}), PVC (1.35 – 1.45 $g.cm^{-3}$) and PET (1.33 – 1.37 $g.cm^{-3}$) can behave similarly to quartz grains of the same size depositing in energetic coastal areas where they are susceptible to resuspension and removal by wave action and currents (Ceccarini et al., 2018).

Considering our findings and their implications, to assess MPs contamination in coastal environments, sampling sites should be characterized by fine muddy substrates and low-energy settings such as ports, marinas, bays and estuaries to obtain representative and meaningful data.

4.2. Composition and microplastic typology in sediments

Focusing on the identified hotspots, at sites 2 and 9 (Sagres and Olhão), PP fibres predominate, whereas at site 5 (Portimão), fibres and fragments of PE coexist in roughly equal proportions (Fig. 2 A and table S2). Since these three sites share comparable substrate characteristics and environmental conditions (Table S1), the disparities observed in MPs composition and typology can be reasonably attributed to variations in the source generating MPs pollution, rather than environmental factors.

Polypropylene, which predominates at sites 2 and 9, is often used in products such as ropes, nets and textiles. Areas with high fishing activity as the sites 2 and 9 (Sagres and Olhão) may have more PP particles, while areas with high commercial activity may have more PE. The present findings agree with previous research that reported the co-occurrence of PP and PE as the dominant polymer association (e.g., Vianello et al., 2013; Zhang et al., 2015). In addition, in Europe, the polymer PP is the most used to produce diverse products due to its widespread application in various industries (Plastics Europe, 2024). Anyway, comparisons between different studies must be made critically because sampling strategies and analytical techniques vary greatly (see Hanvey et al., 2017; Frias et al., 2019).

The dominant polymer in site 5 (Portimão) located in the intertidal zone of the Arade River estuary was PE, suggesting a distinct source of MPs pollution compared to sites 2 and 9, probably incoming from upstream sources such as water treatment plants and disposable plastic waste that exist in the area (Gonzalez-Rey et al., 2015). The present findings provide strong evidence for the important role of land-based sources of MPs pollution transported by rivers to the ocean as also previously reported by Zhang et al. (2015) and Horton et al. (2017). Leonor (2020) revealed high concentrations of PE fragments particularly black and blue in the water column offsite 5 (Portimão), specifically in the area affected by the discharge from the Arade River. Leonor (2020)' observations are consistent with the MPs composition and characteristics reported in the present work from site 5 (Portimão) located in the Arade estuary.

Densiometric screening as the cause of differences in the composition of MPs trapped in the sediments of the studied sites can be ruled out, since the dominant MPs association belong to low-density specimens, although some high-density MPs are also present (Table S2). This means that variations in MP composition likely reflect differences in input sources, sedimentary environment and hydrodynamic regimes.

Fibers have been interpreted as a proxy for sewage source released by synthetic fabrics (Frias et al., 2016). The present study demonstrates a large predominance of fibres (ca. 70 %) over fragments and films (Fig. 3 A and C). Sites 2 (Sagres) and 9 (Olhão) are in small harbours that accommodate the MPs resulting from the degradation of equipment used in fishing, sports and tourism activities. The high amounts of fibres at site 10 (Tavira) located in the inner part of the Ria Formosa lagoon (Fig. 1), may be related to urban sewage and laundry from several small tourist villages located in the area.

4.3. Microplastics in surface water

Coastal waters act as a significant reservoir for MPs owing to their proximity to land-based sources, which facilitates the influx of plastic debris into the marine environment (Zhao et al., 2025).

In all three hotspots (sites 2, 5 and 9 - Fig. 1), sediments MPs levels were substantially higher than those in surface waters - by factors of 58 (Portimão), 34 (Sagres), and 15 (Olhão). It is noteworthy that the number of MPs in surface water samples varies inversely with hydro dynamism. That is, as the energy of the environment increases, the quantity of MP at surface water deceases. In site 5 (Portimão) located in the intertidal zone of the Arade estuary, experiences strong current fluctuations. Sedimentary conditions alternate between accretion during calm periods and erosion during high-energy spring tides (Gomes et al., 2025). The estuary's strong tidal and riverine currents facilitate the export of suspended load to the ocean. Conversely, in sites 2 and 9 (Sagres and Olhão) located in sheltered harbours facilitate the permanence of MP in water, mainly due to low-density particles. This trend is consistent with MP accumulation in low-energy sedimentary environments, where currents and wave action are insufficient to resuspend particles (Yuan et al., 2019).

Microplastic concentrations in surface water varied between the two seasonal periods. In summer, surface temperature was ~5°C higher, and salinity was slightly lower than during winter. Consequently, water density was lower in summer, reducing the capacity to suspend particles. This seasonal variation likely accounts for higher MPs concentrations during the first campaign across all sites (Table S1). Notably, the settling velocities of particles ranging from 0.3 to 3.6 mm are not significantly influenced by water temperature or salinity (Leng et al., 2024).

The occurrence of MPs in sediments and water appears to be influenced by local anthropogenic activities. Sites 2 and 9 were characterized by fishing, harbour and tourism activities. Nevertheless, nylon particles, commonly used in fishing gear, were detected only in trace amounts (Table S2).

4.4. Microplastics in mussels

Microplastics have been detected in over 4000 marine species (https://litterbase.awi.de; Santos et al., 2021). Among these, mussels and other bivalves are widely used as bioindicators of MP contamination due to their filter-feeding behaviour, economic value, and popularity as seafood. Moreover, because mussels are typically consumed whole, they may serve as a vector of MPs to humans. However, mussels exhibit selective ingestion and tend to egest longer fibres (Ward et al., 2019), which limits their effectiveness as direct proxies for MP concentrations in surrounding waters.

In the present study, MPs were detected in *M. galloprovincialis* from all sites during both seasons, except at sites 4 (Lagos) and 6 (Vilamoura) in summer. The percentage of mussels containing MPs ranged from 93 % at Site 2–7 % at Site 11, with individual mussels ingesting between one and nine MP particles. These values exceed those observed in mussels from the North of Portugal, where a maximum of five MPs per individual was reported (Ferreira et al., 2023; Barboza et al., 2024).

When expressed per gram of wet weight, MP concentrations ranged from 0.17 $\pm$ 0.18–1.09 $\pm$ 0.39 MPs g^{-1} w.w., confirming the widespread presence of MPs in mussels along the Portuguese coast (Fig. 5B). The highest variability of the number of MPs per gram of mussel's tissue was observed at sites 3 (Barranco) (1.08 $\pm$.17 and 1.22 $\pm$ 0.25 MPs g^{-1} w.w.) and 7 (Quarteira) (1.09 $\pm$ 0.63 and 1.73 $\pm$ 0.39 MPs g^{-1} w.w.) in both seasons, probably related to the lower weight and smaller size of the mussels from these two sites (Table S3). Similarly, the highest MPs concentrations were detected in small-size clams *D. cuneatus (*1.37 $\pm$ 0.49 MPs g^{-1} w.w.) (Narmatha Sathish et al., 2020). This might be related to the increase in filtration rate in smaller bivalves. Sites 2, 4, 6, 8, 9, 10, and 11 exhibited slightly lower levels than those recorded at similar locations three years before (0.44 – 1.29 MPs g^{-1} w.w.; Vital et al. (2021), and were also lower than the levels reported by Marques et al. (2021) at sites 1 and 10. These findings suggest a possible reduction of MP inputs to the south coast of Portugal and to the Ria Formosa lagoon that need to be confirmed.

MP levels recorded in mussels from this study were of the same order of magnitude as those reported in mussels from the North Coast of Portugal (0.21 $\pm$ 0.07–0.71 $\pm$ 0.10 MPs g^{-1} w.w.; Botelho et al., 2023). In contrast, higher MP levels were observed in mussels from the Aveiro lagoon, with values ranging from 0.77 MPs g^{-1} in winter to 4.3 MPs g^{-1} in summer, showing significant seasonal variations (Botelho et al., 2023). However, no significant differences were observed between the two campaigns in the present study, indicating that MP retention by mussels may not be strongly influenced by oceanographic changes or metabolic cycles.

The size range of MPs ingested in the current study was similar to that found in mussels from the Tagus Estuary, Porto Covo (90 – 2574 μm; Pequeno et al., 2021), and the North Atlantic coast (98 – 2960 μm; Barboza et al., 2024), as well as to seasonal patterns observed in the Aveiro lagoon (634 – 725 μm in winter and 131 – 215 μm in summer; Botelho et al., 2023). Across all studies, fibres were the predominant MP shape, accounting for up to 80 % of the total in some regions.

In terms of colour, blue was the dominant MP colour in mussels from the South Coast of Portugal, consistent with previous findings (Vital et al., 2021), as well as from the Tagus estuary and Porto Covo (Pequeno et al., 2021). However, in mussels from the Aveiro lagoon, red, black, and transparent MPs were more common (Botelho et al., 2023), while mussels from the North coast exhibited a mix of white, blue, red, black, and transparent MPs (Barboza et al., 2024).

No significant relationship was observed between MP concentrations in mussels and surface waters; however, a weak positive correlation was found between MP concentrations in mussels and sediments, while a strong relationship was observed between MPs in sediments and surface waters (r = 0.8397). Similarly, in San Francisco Bay on the west coast of North America, a relationship was reported between MP levels in sediments and in a hybrid population of *M. galloprovincialis* and *Mytilus trossulus* (Klasios et al., 2021). In contrast, a significant relationship was found between mussels (*Mytilus edulis* and *Perna viridis*) and surface waters along the coast of China (Qu et al., 2018), while no relationship was detected between sediments and mussels (*Mytilus californianus*) collected in British Columbia, Canada (Noel et al., 2022). Conversely, a positive relationship was observed between the MP content in the clam *Donax cuneatus* and in sediments from the Tuticorin coast, India (Narmatha Sathish et al., 2020), as well as between the MPs ingested by the clam *Donax trunculus* and the MP levels in sediments from the Mediterranean coast (Secco et al., 2025a). These findings suggest that clams inhabiting sediments may serve as better bioindicators for assessing the presence of MPs in marine environments. This may be explained by the ability of mussels to eject larger particles as pseudofaeces, which then sink and contribute to sediment contamination (Shumway et al., 2023). Moreover, the selective retention of MPs based on size and shape may account for the lack of correspondence between waterborne MPs and those retained in mussel tissues (Ward et al., 2019). In the current study, fragments were the most common MP shape in mussels, differing from previous observations by Marques et al. (2021), where fibres dominated at sites 1 and 10.

Comparisons of polymer types across environmental compartments revealed that mussel-ingested MPs often reflected sediment composition, supporting the idea that habitat plays a key role. However, some polymers, such as PBMA and polyester, were found only in mussels (Fig. 8 C) and surface waters (Fig. 8B), suggesting additional sources or selective uptake. In mussels from the Tagus Estuary and Porto Covo, PET was the most common polymer (60 %), followed by PP (20 %) and PS (20 %) (Pequeno et al., 2021). Mussels from the Aveiro lagoon contained PE, PES, PP, and PA, with PE comprising 60–80 % of MPs in spring, summer, and autumn (Botelho et al., 2023). Similarly, on the North coast, PE (50 %) was most prevalent, followed by PS (15 %), PEVA (14 %), PA (12 %), and PP (9 %) (Botelho et al., 2023). This polymer profiles align with those found globally in bivalves from various marine environments (Abidli et al., 2019; Cho et al., 2019; Hermabessiere et al., 2019; Joshy et al., 2022). In the current study, the detection of low-density polymers such as PS at site 5 (Portimão) suggests complex interactions between environmental availability, particle buoyancy, and biological selectivity. Understanding these dynamics, along with polymer properties and usage patterns, is essential for interpreting MP pollution in marine organisms.

Certain MPs, particularly specific polymers like PE, PP, PS and PET, either individually or in combination with other types of MPs or other contaminants, have been associated with neurotoxicity, oxidative stress, alterations in immune system composition and functioning, disruption in redox homeostasis, and changes in lipid metabolism in the tissues of mussels (*M. galloprovincialis* (Vilke et al., 2024; Nardi et al., 2024) and *Mytilus sp*. (Daniel et al., 2024)) and clams (*Scrobicularia plana* (Ribeiro et al., 2017) and *D. truculus* (Tlili et al., 2020, Secco et al., 2025b)). Moreover, the accumulation of MPs in bivalves is known to pose potential adverse effects on human health (Lithner et al., 2011). Therefore, transformative measures are urgently needed to reduce both land- and sea-based plastic inputs to the marine environment and protect ocean health and biodiversity.

Finally, although Barboza et al. (2024) concluded that, based on various consumption parameters, the human health risk from MP-contaminated mussels appears low, this conclusion requires confirmation for the South coast of Portugal, given its specific environmental and anthropogenic context.

5. Conclusions

Muddy substrates are favourable for the accumulation of MPs due to their high adsorption capacity and cohesive nature. Low-energy hydrodynamic regimes promote the retention of particles trapped within sediments. Conversely, high-energy hydrodynamic regimes facilitate the export of MP particles to adjacent, calmer environments. This study highlights the importance of carefully selecting sampling sites with low hydrodynamic energy and fine sediment characteristics to enable a meaningful assessment of MPs pollution in coastal environments.

MPs were detected in sediments, water, and *M. galloprovincialis* at all study sites, although their abundance, colour, size, and type varied across compartments, locations, and seasons. The MPs identified in sediments, water, and mussels displayed varied colours: transparent

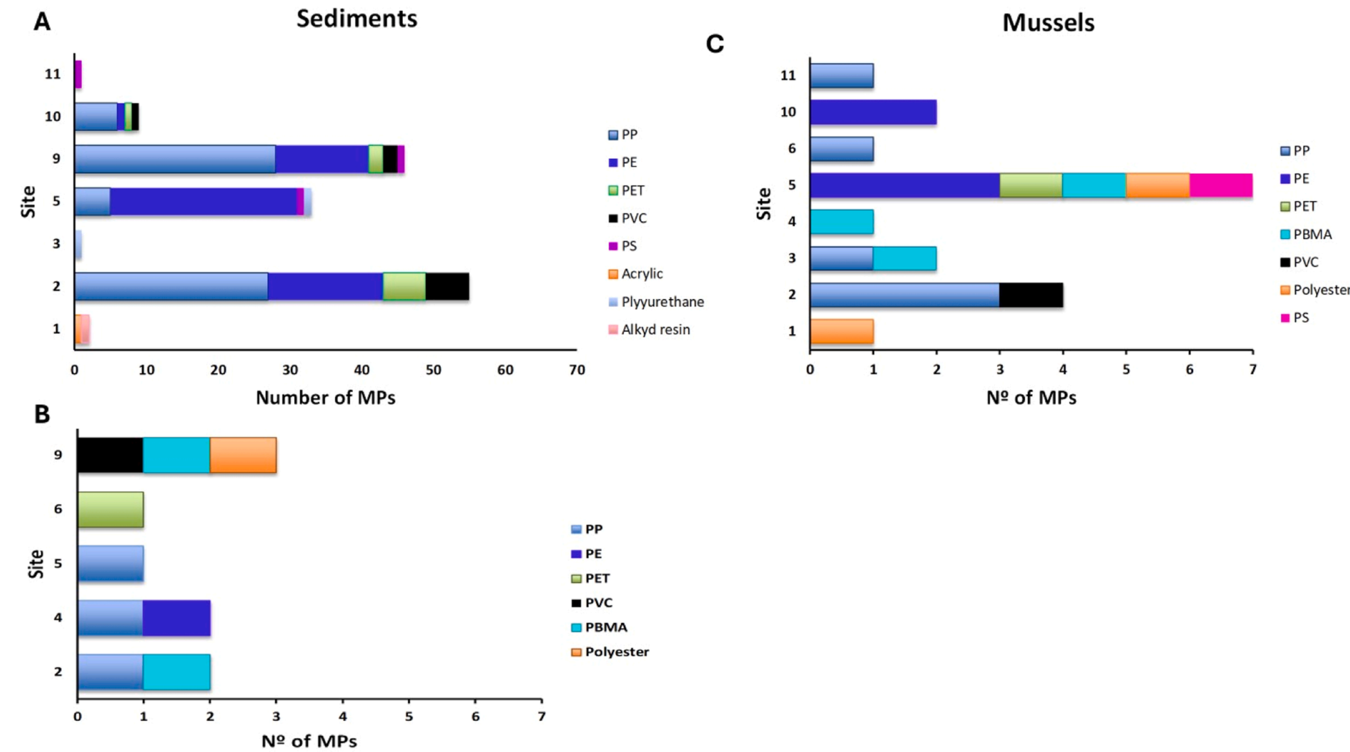

Fig. 8. Type of MPs polymers in (A) sediments, (B) water and (C) mussels.

particles dominated in sediments, while blue was the most common in water and mussels. Based on the data from this study, sites 2, 5, and 9 can be considered hotspots of MP contamination along the South coast of Portugal. The current findings suggest that the variability of MP abundance and polymer composition across the three identified hotspots is linked to differences in local human activities. In Sagres (site 2) and Olhão (site 9), the type and composition of MPs appear to be influenced by activities such as fishing and tourism. In contrast, MP pollution in Portimão (Site 5) seems to be primarily affected by land-based sources, including fluvial transport of debris.

Author Statement

Ai was used in some parts of the text to correct the English

CRediT authorship contribution statement

Delminda Moura: Writing – original draft, Validation, Supervision, Investigation, Data curation. **John Icely:** Visualization, Validation, Investigation. **Bruno Fragoso:** Supervision, Data curation. **Priscila Goela:** Visualization, Formal analysis. **Justine Nathan:** Methodology, Investigation, Formal analysis. **Sónia Cristina:** Validation, Methodology, Formal analysis. **Bebianno M. J.:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rsma.2025.104709.

Data availability

Data will be made available on request.

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