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Differences in distribution and characteristics of microplastics in sediments of the south-eastern part of the Gulf of Trieste

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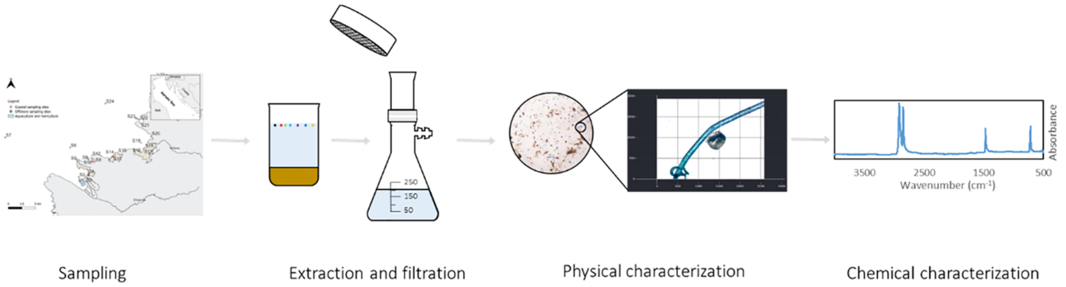
Introduction: The Gulf of Trieste is prone to the accumulation of various pollutants and microplastics due to its geomorphological and hydrological characteristics. However, the distribution and sources of microplastics in this semi-enclosed area are poorly studied. The aim of our study was to determine the distribution and chemical composition of MP particles in the sediments of the Gulf of Trieste.

Methods: In this study, we collected 24 surface sediment samples using a Van Veen grab. Microplastics were extracted by density separation using NaCl. The size, shape, and color of the extracted microplastics were determined using an optical microscope, and the composition of the polymers was determined by Fourier transform infrared spectroscopy.

Results and discussion: The highest concentrations of up to 125 microplastic particles per 100 g dry sediment were found in coastal areas. Concentrations in the open sea were much lower, with an average of 3 particles per 100 g of sediment. Most of the microplastic was fibrous, made of polypropylene, 100–300 μm in size, and blue. This is the first study showing that microplastics are present in the sediments of the south-eastern part of the Gulf of Trieste. The findings suggest that microplastics exhibit a tendency to be retained within the sediment, leading to their accumulation primarily in a narrow coastal area rather than dispersing offshore. Our results will contribute to a better knowledge of the distribution and possible sources of plastics and microplastics in the Gulf of Trieste and even beyond in similar semi-enclosed marine areas.

KEYWORDS

microplastics, Gulf of Trieste, sediment, infrared spectroscopy, contamination



GRAPHICAL ABSTRACT

1 Introduction

Plastics have become an integral part of our daily lives due to their adaptability, versatility, and relatively low cost. Rather than degrading harmlessly, it was discovered that many plastics in the ocean often breakdown into smaller and long-lived particles (Carpenter and Smith, 1972). An estimated 14.4 million tons of small plastic particles measuring less than 5 mm in size (microplastics—MPs) have sunk to the ocean floor since polymers were first used (Barrett et al., 2020). They can be classified into primary MPs, which enter marine systems directly as small particles, and secondary MPs, which are fragments from the breakdown of larger plastic objects. MP volumes are generally higher in low-energy environments, such as shallow areas, estuaries, and bays that receive significant inputs from land, and much lower in deeper environments that are generally remote and distant from point sources (Wang et al., 2019). Some MP shapes, such as fibers, dominate bottom sediments in both shallow and remote areas that are far from the source (Harris, 2020; Uddin et al., 2021). There are still significant uncertainties regarding the contribution of these sources, including the many possible sources and their relative impacts (Su et al., 2022).

Microplastics build up in ocean sediments through processes like the breakdown of larger plastic pieces and their transport through the water. Weathering, caused by chemicals and physical stress, breaks down plastics into smaller particles that settle in the sediment. Factors like UV radiation and biofouling can change the properties of plastics (Hernandez et al., 2017; Liu et al., 2019), allowing them to adsorb pollutants and move through the food chain (Da Costa et al., 2020; Godoy et al., 2019; Verla et al., 2019; Zhu et al., 2021). The presence of MPs in marine sediments is influenced by various factors such as proximity to pollution sources, ocean currents, tides, seabed topography, shoreline shape, sediment composition, and water clarity (Uddin et al., 2021). Sediments are where MPs mainly accumulate, coming from various sources like land, water, and air (Boucher and Friot, 2017; Yang et al., 2022). Land-based sources are the biggest contributors to plastic pollution (Liubartseva et al., 2016; Vlachogianni et al., 2017; Vlachogianni et al., 2018), but activities at sea also play a part (Peng et al., 2020). Microplastics get into marine sediments through air deposition from waste sites and runoff from land sources like stormwater and rivers. Maritime activities, like waste disposal and fishing, also add to ocean plastic pollution (Folbert et al., 2022).

The Adriatic Basin is a significant area for MP accumulation in the Mediterranean Sea (Liubartseva et al., 2016; Ruiz-Orejón et al., 2016; Carlson et al., 2017; Zambianchi et al., 2017; Vianello et al., 2018; Digka et al., 2018) due to factors like extensive shipping, river inputs, aquaculture and coastal tourism (Suaria et al., 2016; De Lucia et al., 2018; Tisma et al., 2019). Studies have shown that a large portion of marine debris in this region comes from rivers and urban coastal areas (Liubartseva et al., 2016), with coastal environments having higher MP concentrations compared to the open sea (Strafella et al., 2015; Pasquini et al., 2016; Macic et al., 2017; Palatinus et al., 2019). The Adriatic Sea exhibits a wide range of MP concentrations on its surface (Gajšt et al., 2016; Kovač Viršek et al., 2017; Capriotti et al., 2021), and sediment samples have shown concentrations ranging from 10 to 100 MP/kg (Lots et al., 2017; Korez et al., 2019; Palatinus et al., 2019; Renzi and Blašković, 2020).

Various studies have explored the distribution of MPs in the waters and coastal sediments of the Adriatic Sea (Laglbauer et al., 2014; Gajšt et al., 2016; Pasquini et al., 2016; Kovač Viršek et al., 2017; Vlachogianni et al., 2018; Zeri et al., 2018; Renzi et al., 2018a; Fortibuoni et al., 2019; Korez et al., 2019; Ronchi et al., 2019; Vlachogianni, 2019). However, there has been limited research on the presence of MPs in seabed sediments. This is surprising given the Gulf of Trieste's shallow depth and proximity to densely populated coastlines, as well as its location as a receiving point for waste from major rivers. Therefore, this study aimed to investigate the distribution and chemical composition of MP particles in the surface sediments of the south-eastern part of the Gulf of Trieste, including both coastal and offshore areas.

2 Methods

2.1 Study area

The Gulf of Trieste is a shallow gulf between Italy and Slovenia in the north-eastern part of the Adriatic Sea (Figure 1). It is approximately 20 km long and 10 km wide, with an average

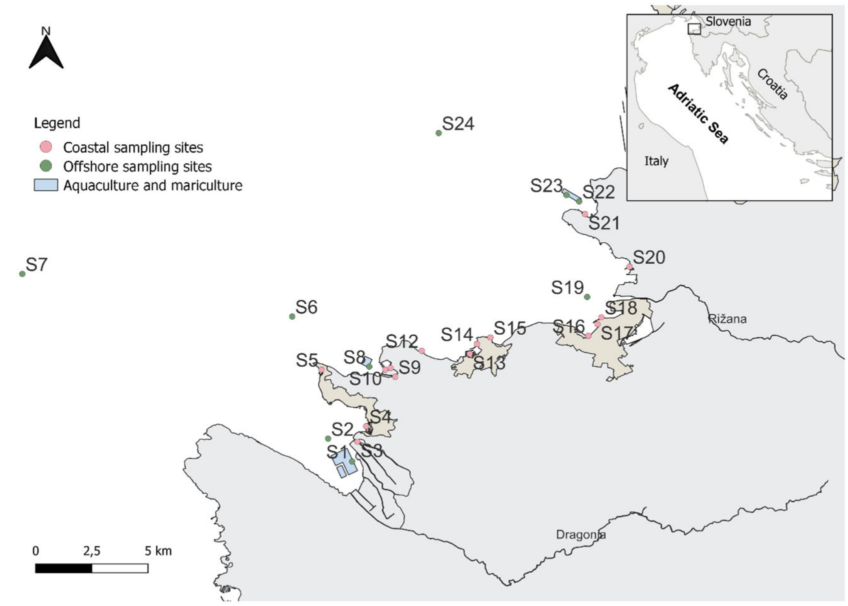


FIGURE 1
Location of coastal and offshore sampling sites for surface sediment samples in the Gulf of Trieste, indicating the major rivers (Rižana, Dragonja) along the north-eastern coast. Pink and blue dots represent coastal and offshore sampling sites, respectively. All sampling sites are presented in Table 1.

depth of 22 m. The Gulf is surrounded by the coastal cities of Trieste and Monfalcone in Italy, and Koper, Izola, and Piran in Slovenia, as well as several smaller towns and villages. Four main rivers contribute to freshwater input to the Gulf, two rivers in Italy (Soča/Isonzo and Timavo), one in the proximity of Koper (Rižana), and the other further south near Seča (Dragonja). Despite freshwater inputs, local winds, tidal currents, and density currents also influence the circulation in the Gulf of Trieste (Malacic and Petelin, 2001). The north-eastern part of this gulf is ecologically important for its diverse marine life, including fish, sea turtles, and dolphins (Lazar et al., 2011; Borme and Voltolina, 2006; Lazar et al., 2008; Genov et al., 2021). It is also home to a variety of bird species that migrate through the area (Genov et al., 2021).

Due to its geomorphological and hydrological characteristics, the Gulf of Trieste is vulnerable to pollutant accumulation (Solis-Weiss et al., 2004; Cibic et al., 2008) which mainly enters the marine environment through anthropogenic activities. The bays of Koper and Piran have been considered sensitive areas since they can be affected by polluted waters of the Gulf of Trieste as well as by land-based sources of pollution along the coast. The inner part of the Bay of Koper receives effluents from the municipal wastewater treatment plant, individual industries, and freshwater discharge by the Rižana River (Cozzi et al., 2012), while the Bay of Piran receives agricultural discharges from the Dragonja River. Additional sources of possible plastic pollution are three shellfish harvesting areas located in Strunjan, in the Bay of Debeli Rtič, and in the Bay of Piran (Figure 1), intensive maritime traffic to the three ports in Trieste, Koper and Monfalcone, and tourism. The seawater of this area is also affected by urban runoff from coastal roads (Faganeli et al., 1997) and atmospheric deposition.

2.2 Sediment sampling

The present study was conducted in the autumn of 2020 in the Gulf of Trieste. Sampling sites at the coastal area were chosen based on potential different plastic sources: three marinas (S4, S13, S18), municipal harbors (S5, S14, S17, S20), shellfish farms (S1, S8, S22), freshwater inputs (S3, S9, S16), coastal wetland (S10, S11), touristic site (S12), previous industrial site (S15), and offshore (S2, S6, S7, S19, S21, S23, S24). To quantify MP abundance, samples were collected using a Van Veen grab at the south-eastern coast (Figure 1), within the coastal sampling sites and offshore (Table 1) at different depths. The superficial 2 cm layer of each sediment sample was placed in the previously cleaned glass jars. The sediment samples were stored at -20°C for further analysis.

2.3 Sediment analyses

MP particles from sediment samples were isolated following the procedure of a previous study (Thompson et al., 2004), using a saturated sodium chloride solution (1.2 g cm^{-3}) as the density separation solution. Briefly, the NaCl was dissolved in deionized water to form a saturated NaCl solution and filtered through 12 µm polycarbonate filters (Whatman, USA) using a vacuum pump to remove possible impurities. To determine the water content of the sediments, 200 g of wet sediment were accurately weighed in a glass beaker, placed in an oven at 105°C, and dried to constant weight.

Wet sediment sample of 200 g (accurately weighted) was placed in 800 mL glass jars, and 500 mL of filtered saturated NaCl solution was added. The resulting mixture was stirred with a glass rod for 2

TABLE 1 Sampling locations of sediment collection in the Gulf of Trieste (GoT).

Sampling location		Latitude	Longitude	Water Depth (m)
S1	Seča shellfish farm	45°29.471’	13°35.164’	9.3
S2	Bay of Piran	45°30.009’	13°34.326’	16.0
S3	Seča Jernej Channel	45°29.942’	13°35.334’	1.6
S4	Portorož Marina	45°30.324’	13°35.685’	10
S5	Piran Municipal Harbour	45°31.666’	13°34.067’	4.3
S6	Open sea off Piran	45°32.93’	13°33.03’	21.0
S7	Central part GoT 1	45°33.829’	13°23.777’	17.0
S8	Strunjan shellfish farm	45°31.757’	13°35.692’	16.0
S9	Roja Stream	45°52.541’	13°60.975’	1.5
S10	Strunjan lagoon entrance	45°52.651’	13°60.224’	1.5
S11	Stjuža Lagoon	45°52.699’	13°60.676’	1.5
S12	Bay of Bele Skale	45°32.160’	13°37.477’	6.5
S13	Marina Izola	45°32.105’	13°39.121’	5.6
S14	Municipal Harbour Izola	45°32.314’	13°39.396’	4.1
S15	Shipyard Izola	45°32.509’	13°39.814’	7.0
S16	Badaševica river outflow	45°32.588’	13°43.163’	1.9
S17	Municipal Harbour Koper	45°32.870’	13°43.500’	3.8
S18	Marina Koper	45°33.036’	13°43.598’	4.5
S19	Bay of Koper	45°33.579’	13°43.199’	16.0
S20	Municipal Harbour Ankaran	45°34.263’	13°44.531’	1.6
S21	Bay of Jernej (Ankaran)	45°35.511’	13°42.983’	2.6
S22	Debeli Rtič shellfish farm	45°35.812’	13°42.773’	17.3
S23	Bay of Debeli Rtič	45°35.962’	13°42.335’	17.0
S24	Central part GoT 2	45°35.962’	13°42.335’	24.0

min and left covered for sedimentation. After 18 h, the supernatant containing plastic particles was decanted. It was sieved through a 63 µm stainless steel sieve, and the retained solids were then rinsed into a beaker that had previously been rinsed three times with MilliQ water prepared with a water purification system (Millipore, USA). The procedure was repeated three times for each sediment sample. The samples were then filtered through polycarbonate filters with a diameter of 47 mm and pore size of 12 µm (Whatman, USA). The filters were transferred to Petri dishes, covered, and air-dried at room temperature.

2.4 Classification of microplastic particles

Microplastic particles were first classified under a stereomicroscope (Olympus SZX16, Japan) with a maximum magnification of 11.5. All isolated particles were photographed, counted, and categorized according to size, shape, and color. Regarding the size of the particles, the longest side was determined for the fragments and the length for the fibers. The particles were classified into four shape categories: fibers, films, fragments, and pellets.

2.5 Chemical composition of microplastic particles

Micro-Fourier transformed infrared (FT-IR) spectroscopy was used to assess the chemical composition of the extracted particles. A Spectrum Two FT-IR spectrometer equipped with Spotlight 200i microscope (Perkin Elmer, USA) was used for the analyses. Spectra were recorded in attenuated total reflectance (ATR) mode. The spectral range was set to 4000–700 cm^{-1}. Polymers were identified by comparison with plastic-specific libraries of standard spectra (Perkin Elmer FT-IR of Polymers library). Most polymers could be identified with sufficient match to spectra from the spectral libraries, while others with lower match (<1% of all extracted particles) were classified as unidentified. Fibers were separately identified since many of them are made from natural materials. Fibers larger than 200 µm were isolated and identified by ATR FT-IR, and fibers below

200 μm were identified by μFT-IR. The fibers identified and used for all analyses were 83% synthetic and 17% natural particles. Only plastic particles were considered in all performed analyses. Of all 519 extracted plastic particles, 88% were analyzed using FTIR.

2.6 SEM analysis

SEM analysis aimed to assess the ageing processes of MPs and possible fouling of the particles. Three MP fragments were coated with a 7 nm thick conductive Au-Pd layer using the Rotary Pumped Coater Q150R Plus (USA) and subjected to scanning electron microscopy (SEM) using the Tescan Mira LMU 4 (Brno, Czech Republic). The analysis was performed at various magnifications with an SEM acceleration voltage of 5 kV.

2.7 Contamination prevention

Sediment samples were collected in compliance with regulations to prevent MP contamination (Prata et al., 2021). All glass jars and the Van Veen grab were previously cleaned with MilliQ water. The collected material was immediately transferred into glass jars using clean equipment. All analyses were performed in a previously cleaned fume hood to avoid contamination (Scopetani et al., 2020). All equipment used was pre-rinsed with 0.2 μm filtered MilliQ water, and all clothing worn during laboratory work was made of cotton. During analyses, filters were stored in covered borosilicate Petri dishes and kept in a fume hood. To assess cross-contamination with airborne MPs, we left filters in opened Petri dish while preparing samples for analysis, while using an optical microscope and in the determination phase. Only two fibers were detected on filter which was placed next to the optical microscope. No particles were found in other two blank samples. In parallel with sample processing, blank samples were run with NaCl solution (n=3) without the sample. No potential MP particles were found in the solution (NaCl).

2.8 Statistical analysis

All statistical analyses and graphs were performed in R version 4.1.1 (Team et al., 2018). The packages used were ‘devtools’ (Wickham et al., 2019), ‘dplyr’ (Wickham et al., 2019), ‘magrittr’ (Mailund, 2022), ‘ggpubr’ (Kassambara and Kassambara, 2020), and ‘ggplot2’ (Wickham et al., 2016). Multidimensional scaling (MDS) was used to test the potential differences in MP’s quantity, shape, and polymer type between coastal and offshore sampling sites. Data were log-transformed (log$X$+1) before a Bray-Curtis similarity matrix was computed.

3 Results

3.1 Distribution and abundance of microplastics

MPs were detected in all surface sediment samples collected at the 24 stations along the north-eastern part of the Gulf of Trieste (Figure 2), showing how ubiquitous they are in the marine environment. The 24 samples yielded a total of 519 MPs (Table 2) with an average value of 22 ± 29 MPs per 100 g sediment (d.w.). Median MP density was higher in the coastal sampling sites than in the offshore sampling sites (Table 2). The coastal site Portorož Marina (S4)

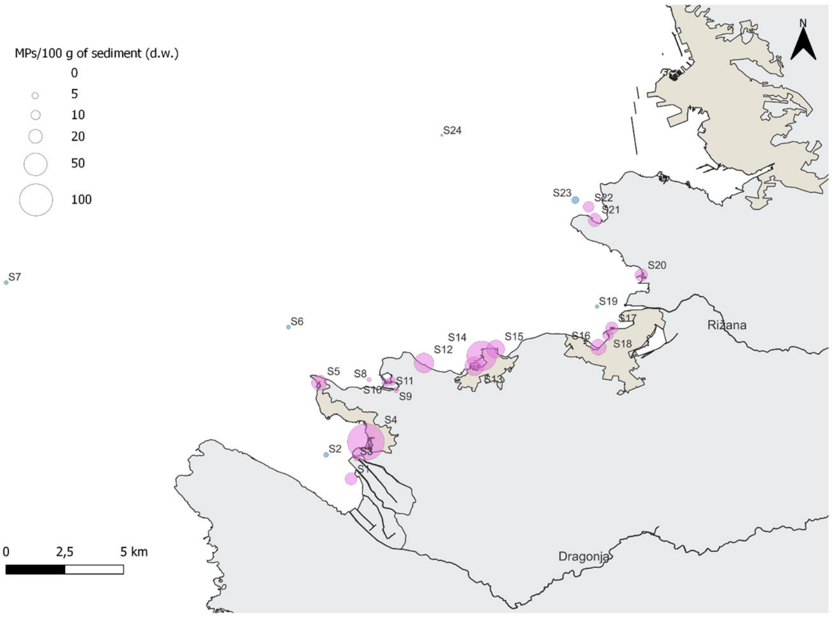


FIGURE 2
Map of the Gulf of Trieste showing the locations of all sampling sites and the distribution of microplastic concentrations expressed as microplastic particles per 100 g of sediment (d.w.). The size of the circles is proportional to the measured concentration values.

TABLE 2 Total amount of microplastic particles in investigated coastal and offshore sediment samples.

Sampling site	S4	S14	S12	S13	S15	S16	S5	S21	S20	S17	S1	S23	S22	S18	S11	S2	S10	S7	S3	S6	S19	S9	S8	S24	Total
MP particles/ 100 g sediment (d.w.)	125	85	40	37	33	26	25	19	17	16	16	14	13	12	8	6	6	4	4	4	3	3	2	1	**519**

had the highest concentration (125 MPs per 100 g), followed by Municipal Harbour Izola (S14) (85 MPs per 100 g). The coastal sampling sites of Roja Stream (S9) and Jernej Channel (S3) differed from other samples due to the lowest MP number. Of all offshore sampling sites, Debeli Rtič (S21) had the highest MP quantity (19 MPs per 100 g). The difference between the sites S4 and S24 clearly shows the large spatial variance of MP concentrations between coastal and offshore sampling sites of the Gulf of Trieste.

3.2 Size and shape

In terms of size, more than 75% of MPs were smaller than 500 µm (Figure 3). As observed on the distribution curve for all length fractions, MP length was skewed toward smaller particles, with a non-negligible quantity that measured less than 100 µm (Figure 3). The length fractions with the highest frequency were 100–300 µm (Figure 3). Median length varied among samples, from 269 µm in coastal sampling sites to 773 µm in offshore sampling sites. The longest MP fiber was 523 µm in length.

In terms of the characterization of MPs, there are four shapes of MPs extracted from the sediment of the different sampling sites – fiber, fragment, pellet, and film (Figures 4A, B). Fibers accounted for 63% of the extracted MPs in coastal sites followed by fragments (25%), films (10%), pellets (1%). Similarly, the four shapes of MPs were all present in the offshore sampling sites, the most abundant shape was fiber (83%), followed by film (11%), fragment (4%), pellet (2%) (Figure 5).

3.3 Color

Visual observation under a stereomicroscope revealed different MP colors (Figure 6), indicating the different material sources. Among the detected colors (colorless, blue, green, red, white, black, grey, and purple), colorless was by far the most common at the coast, accounting for 36% of samples, followed by blue and black, making up to 29% and 22% of particles, respectively. Polymers of other colors only made up a minor fraction of the particles. The offshore particles were mostly black (53%), followed by blue (27%), transparent (13%), and red (7%). Some particles in the sediment samples at coastal sites with semi-faded color indicate that the MPs detected had been in the environment for an extended time.

3.4 Polymer composition

Microplastic polymers were identified by FT-IR (Figures 4C, D). In coastal area, polypropylene (PP) was generally a dominant polymer within coastal sampling sites (55%) (Figure 4C). Low- and high-density polyethylene (PE) was the second most abundant polymer (34%) followed by polytetrafluoroethylene (PTFE), polyethylene terephthalate (PET), polystyrene (PS), and different copolymers, e.g., acrylate copolymers, styrene/isoprene copolymers (Figure 4C). The most abundant polymers found in offshore sites were PET (34%) and copolymers (25%) (Figure 4D). Other polymers found were PP (17%), PE (8%), polyvinyl chloride (PVC) (8%) and PTFE (8%).

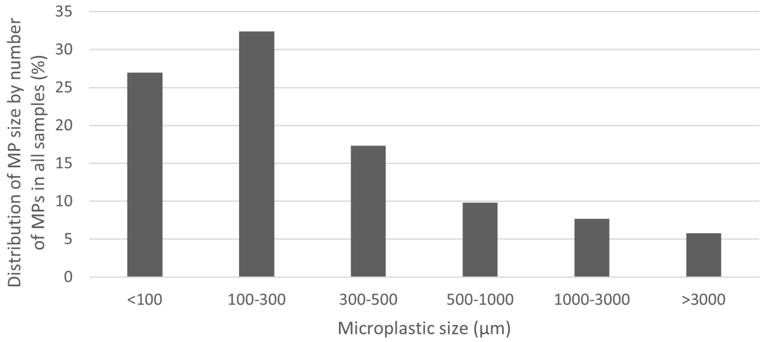


FIGURE 3
Distribution (%) of MPs by size for all samples from both coastal and offshore sediments in the Gulf of Trieste.

3.5 Comparison of microplastic quantity, shape, and polymer type among coastal and offshore sediment samples

Multidimensional scaling (MDS) (Figure 7) showed that the collected surface sediments at the coastal sites Municipal Harbour Izola (S14) and Portorož Marina (S4) differed from the other stations in terms of shape and polymer material with a high concentration of PP fibers. S12, S13, S15, S17, S18, S20, and S22 showed a preferential accumulation according to other sediments with the highest levels of PE fragments. Other sampling sites did not show a significant statistical difference in shape and polymer type and are in descending order regarding the amount of MP concentration.

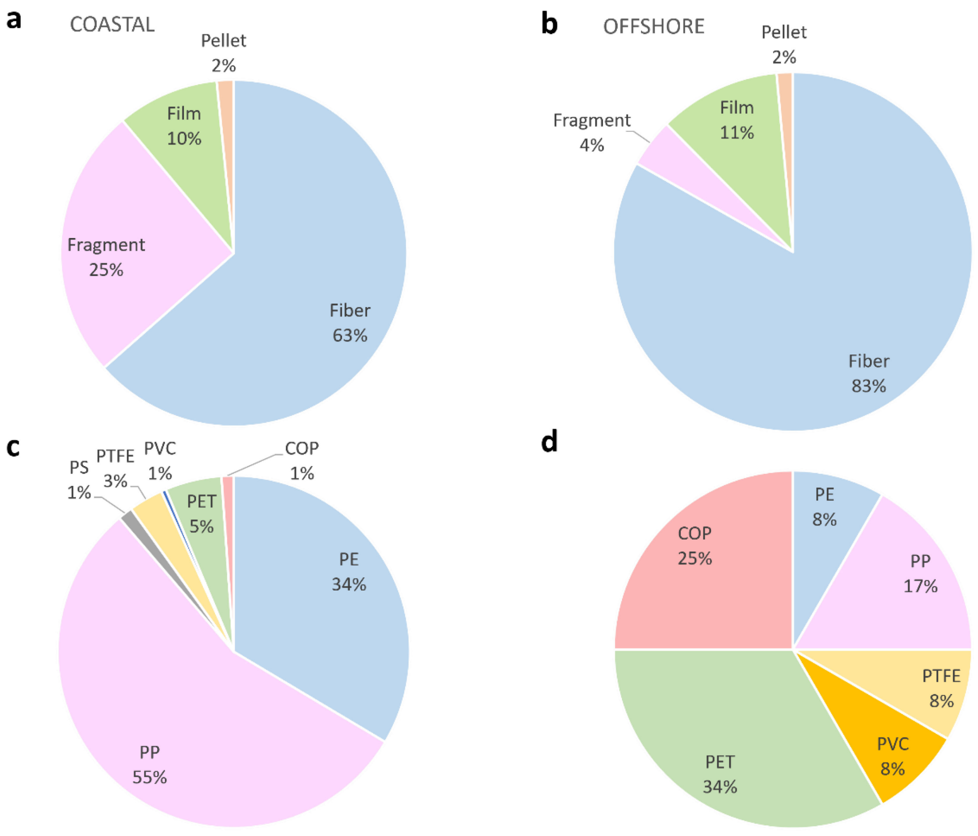


FIGURE 4
Proportion (%) of coastal **(A, C)** and offshore **(B, D)** sampling sites according to their shape and polymer type (PE, -polyethylene, PP, polypropylene; PS, polystyrene; PET, -polyethylene terephthalate; PVC, polyvinyl chloride; PTFE, polytetrafluoroethylene; COP, copolymers).

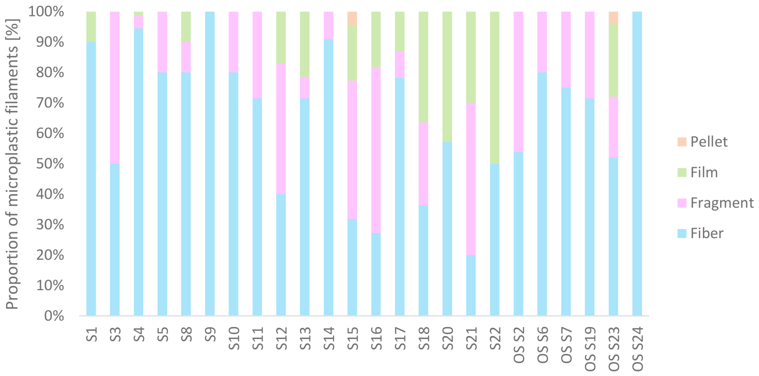


FIGURE 5
Proportion (%) of microplastics according to their shape at each coastal and offshore (OS) sampling site.

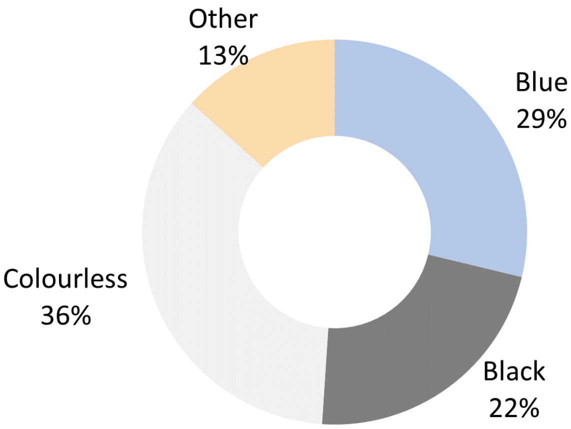


FIGURE 6
Colors of microplastics detected in sediments sampled in the south-eastern part of the Gulf of Trieste.

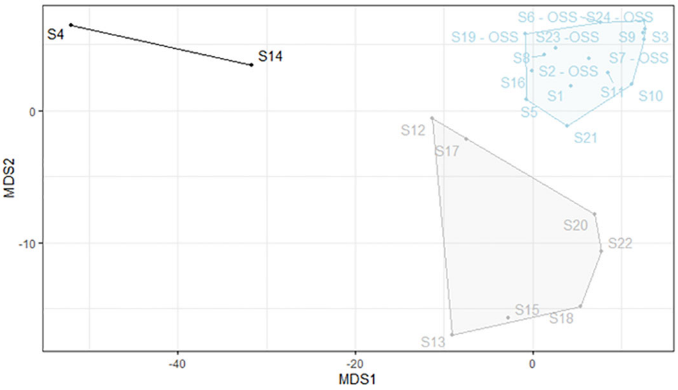


FIGURE 7
MDS plot of Bray-Curtis similarities of MP quantity (log-transformed particles per 100 g), MP shape, and MP type across coastal and offshore sampling sites in the Gulf of Trieste. MDS subsets of Bray-Curtis similarities are represented with linked clusters.

3.6 SEM examination and biofouling

The surface morphology of particles was analyzed to understand the change process of weathering and fragmentation of MPs and the possibility of adhesion of organisms to the surface of MPs in the marine environment. An MP fragment from the Stjuža Lagoon (S11) revealed a diatom of the genus *Cocconeis*. Observed structural changes in the form of pits and erosions at SEM indicate MP ageing. Our study confirmed that plastic fragments also provide long-term habitat for macroalgae (Figure 8) in marine ecosystems. This suggests that attachment of organisms increases sedimentation of MP particles due to increased density and size of the particles.

4 Discussion

This study examines MPs in seabed sediment along the south-eastern part of the Gulf of Trieste, comparing concentrations between coastal and offshore areas. Marine MPs are widespread in this region (Laglbauer et al., 2014). Plastic properties and natural processes break down large particles into MPs, which can accumulate at the coast and offshore, particularly under high human pressure.

Higher concentrations of microplastics along the coast may be linked to the claim that 80% of MPs come from land (Liubartseva et al., 2018). However, this is not certain as factors like currents and tides play a role. Microplastic presence may be influenced by local sources, sedimentation, and biofouling. Concentrations decrease toward offshore sites in the central Gulf of Trieste, with coastal areas averaging 25 particles per 100 g of dry sediment compared to 12 particles in offshore areas. Debeli Rtič (S23) had the highest MP numbers offshore, showing multiple MP shapes. Weaker currents at Debeli Rtič may limit outward transport, leading to accumulation. This was also observed by Laglbauer et al. (2014), suggesting that there are weaker currents at the Debeli Rtič site due to the protection afforded to the beach by constructions and their configurations, which may lead to limited outward transport of locally deposited plastic debris, resulting in accumulation (Galgani, 2015; Laglbauer et al., 2014). Offshore sites S2 (Piran Bay) and S19 (Koper Bay) contained similar numbers of fibers. The least plastic particles were present in the outermost parts, i.e. Open sea off Piran (S6) and Central parts of GoT (S7 and S24). Based on the provided context, it is evident that the composition of MPs at coastal sites in the south-eastern part of the Gulf of Trieste is influenced by various factors such as plastic inflow from freshwater sources like Rižana, Isonzo, and Dragonja rivers, as well as activities like agriculture, tourism, and fishing. In contrast, offshore sites are primarily influenced by shipping activities. Understanding these sources of MP pollution is crucial for developing targeted strategies to mitigate their impact on marine ecosystems.

The marinas and municipal harbours sampling sites had similar shapes and polymer types. These sediment samples (S4, S5, S13, S14, S17, S18, S20) dominated by PP fibers. S4 and S14 had the highest number of PP particles. The shellfish farm site Debeli Rtič (S22) had more PE fragments and films compared to other shellfish

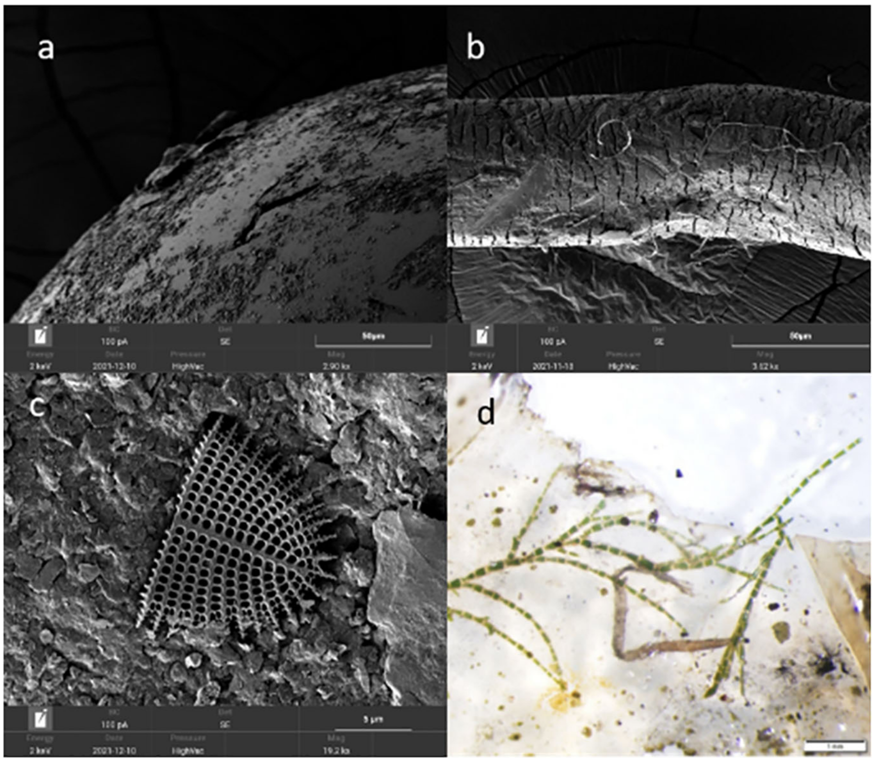


FIGURE 8
Microplastic particles observed by SEM: cracks, rough surface (**A**, sampling site S16; **B**, sampling site S4); diatom from genera *Cocconeis* (**C**, sampling site S12); colonization by macro-algae on PE (**D**, sampling site S15).

farm sites (S1 and S8) and was the only one with pellets. The coastal Jernej Channel in Seča (S3) had the lowest MP concentration, likely the least contaminated coastal site in the studied area. Comparable coastal sampling sites around Strunjan Lagoon (S9, S10, S11) had similar shapes and polymer types. The Bay of Bele Skale (S12) contained fragments, fibers, and films, with PE, PP, PTFE and PVC polymer types observed. PE fragments from the Bay of Bele Skale were similar to those in marinas and municipal harbours, possibly due to higher boat traffic and beach visits. Sampling site S5 (Izola shipyard) had the most diverse types of polymers, including PE, PP, PTFE, PVC, and PET in various forms. The Badaševica outflow area (S16) had three MP forms mainly from PE: fibers, fragments, and films. The Bay of Jernej (Ankaran) (S21) mainly contained PE films and PTFE fragments.

Fibers were the most common sediment shape on the coast (63%) and offshore (83%). In this study, it is important to point out that in addition to the primary origin, the secondary origin resulting from the degradation of larger pieces of plastic waste is also important. Primary MPs (spherical pellets) were only found in two samples (S23 and S15). MP films at certain sites (S14, S15, S18) suggest mechanical breakdown of PE packaging. Pellets could come from industrial and urban sources (Boucher and Friot, 2017). Shellfish farms have more fragments and films than other offshore areas, likely from fishing activities. The Bay of Debeli Rtič may have higher MP content due to currents (Malačič and Petelin, 2009) bringing in debris from other parts of the Gulf of Trieste, thus influencing MP accumulation in the Bay of Debeli Rtič (S23, S22, S21).

The composition of polymers at coastal and offshore sampling sites differs. The observation that municipal harbors and marinas have more irregular PE fragments, potentially resulting from larger plastic breakdown, is significant in understanding the sources and characteristics of MPs in the marine environment. This information underscores the need for targeted interventions and waste management practices to address the issue of plastic fragmentation and its contribution to MP pollution in coastal areas. PP fibers may come mostly from damaged fishing gear (Mistri et al., 2018; Palatinus et al., 2019). Our finding is consistent with Vianello et al. (2013), who revealed that PP and PE are the most frequently found polymers. Both are most commonly used and thus also discarded in marine environments around the Adriatic Sea. These two polymers have a wide range of applications and commonly used for fishing gear, packaging, ropes and other products. Coastal sites S12 and S15 and mariculture sites (S1, S8, S22) are sites that are second most polluted areas. PTFE was mainly found near industrial area (S12), indicating pollution from boats and shipyards. PTFE is used in various industries for its corrosion resistance and has a long environmental half-life (Dhanumalayan and Joshi, 2018). The susceptibility of shellfish farms to plastic pollution, particularly PP and PE originating from fishing gear, highlights the potential impact of MPs on aquaculture operations. In offshore sites most frequently found were PET and copolymers. The presence of PET, PE, PP at proximal site S19 suggests that this station has become an accumulation zone for a variety of degraded plastic materials due to proximity to a developed coastline, wastewater plants and the Rižana River. Offshore site S23 has surprisingly higher MP contents. We suspect that this could be due to touristic and fishing activities and water recirculation within Jernej Bay.

Previous studies in the Adriatic Basin area found that fibers were the main shape of polymer in sediments (Blašković et al., 2017 Blašković et al., 2018; Bošković et al., 2021; Renzi et al., 2018a; Renzi et al., 2020; Renzi et al., 2019), which is consistent with our results. All studies (Table 3) observed fibers as the most common

TABLE 3 The abundance of microplastics reported in the literature for coastal and seabed sediments sampled in the Adriatic Sea.

Sampling location	Sampling	MP concentration	Main polymer types	Main polymer shapes	Reference
Slovenia	Seabed sediments	170 items/kg d.w.	Not identified	Not identified	(Laglbauer et al., 2014)
Slovenia	Coastal sediments	178 items/kg d.w.	Not identified	Not identified	(Laglbauer et al., 2014)
Slovenia	Coastal sediments	3.1 ± 2.6 items/kg d.w.	PE, PP, PET, nylon	Fragments, fibers, films, and foams	(Korez et al., 2019)
Slovenia	Seabed sediments	Coastal: 2-125 items/100 g d.w. Offshore: 1-14 items/100 g d.w.	PP, PE, PTFE	Fibers, fragments	This study
Italy	Coastal sediments	62-1069 items/kg d.w.	Not identified	Fibers	(Cannas et al., 2017)
Italy	Coastal sediments	45-1069 items/kg d.w.	Not identified	Fibers, fragments	(Guerranti et al., 2017)
Italy	Seabed sediments	0-58 items/m^2	Nylon, PE	Fibers, fragments,	(Mistri et al., 2017)
Italy	Seabed sediments	672-2173 items/kg d.w.	PE, PP	Fragments, fibers,	(Vianello et al., 2013)

(Continued)

TABLE 3 Continued

Sampling location	Sampling	MP concentration	Main polymer types	Main polymer shapes	Reference
Italy	Seabed sediments	255 items/kg d.w.	Not identified	Not identified	(Renzi et al., 2018b)
Italy	Coastal sediments	72-1512 items/kg d.w.	PP, PE, polyester	Fibers	(Lots et al., 2017)
Italy	Coastal sediments	12 items/kg d.w.	PP, PE	Not identified	(Munari et al., 2016)
Italy	Coastal sediments	Up to 78 items/kg d.w.	PP, PE, PS	Not identified	(Atwood et al., 2019)
Italy	Coastal sediments	3 - 23 items/kg d.w. (1-5 mm)	PE, PP, PS	Not identified	(Piehl et al., 2019)
Croatia	Coastal sediments	178 items/kg d.w.	Not identified	Fibers, fragments	(Blašković et al., 2017)
Croatia	Seabed sediments	177.6 ± 112.7 items/kg d.w., (113.4–377.8)	Nylon, PVC, PE, PP, PET	Not identified	(Renzi and Blašković, 2020)
Croatia	Seabed sediments	137-703 items/kg d.w.	Not identified	Fibers	(Renzi et al., 2018b)
Croatia	Seabed sediments	180-360 items/kg d.w.	Not identified	Fibers	(Renzi et al., 2019)
Croatia	Seabed sediments	72-191 items/kg d.w.	Not identified	Fragments	(Blašković et al., 2018)
Croatia	Coastal sediments	24 ± 9 items/dm^3 (2-7 mm)	Not identified	Pellets	(Maršić-Lučić et al., 2018)
Montenegro	Seabed sediments	609 items/kg d.w.	PP, PE	Fibers granules, fragments, films	(Bošković et al., 2021)
Bosnia and Herzegovina	Coastal sediments	76 ± 13 items/kg d.w.	PP, PE, polyester	Fibers	(Lots et al., 2017)

shapemicroplastic particles, with slight variations in the eastern part (90% (Blašković et al., 2018)), while in the northern part, they were slightly more abundant in sediment samples (96% (Laglbauer et al., 2014)). Overall, marine surface sediments in the Gulf of Trieste are more contaminated by secondary MPs (98%) than virgin plastic pellets.

The average density of MPs (220 ± 29 items/kg d.w.) in the sediment samples was comparable to levels reported in other areas of the Adriatic Sea (Table 3). Specifically, our study showed similar numbers to Italy (255 items/kg d.w) and lower (609 particles/kg d.w.) amounts than the Montenegrin coast (Bošković et al., 2021). The Venice Lagoon had higher MP levels compared to studied coastal areas (Lots et al., 2017). The concentration detected in coastal areas was much higher than that observed for surface sediments in different coastal areas of the southern Adriatic Sea. Unfortunately, some studies conducted in marine sediments presented their results in other units (e.g. items/m^2), and therefore our results cannot be directly compared with other equivalent relevant research. The present findings are in line with those of Bošković et al. (2021) and Vianello et al. (2013), who found that PE and PP are the most abundant polymer types, accounting for more than 82% of MPs in sediments from the Venice Lagoon in Italy and the Montenegrin coastal area. These polymers, PE and PP, are widely used in various industries, contributing to their prevalence in marine environments, including the Adriatic Sea. These findings align with previous research on polymer distribution in marine sediments (Table 3).

To tackle the issue of marine litter and reduce waste at source, it is important to prioritize sustainable waste management practices. Local co-operation and action are necessary to effectively tackle the global problem of marine litter. This includes national and international action, reducing the release of plastics into wastewater treatment plants, educating and raising consumer awareness and improving life cycle and end-of-life management. Education and awareness campaigns play a key role in promoting long-term behavioral change. By emphasizing moral obligations and practical measures such as reducing the consumption of harmful products, minimizing littering and improving recycling rates, we can work toward a cleaner environment. It is clear that policy makers need to work together to find solutions if policy and regulatory measures are to be effective. The seemingly simple solution is to reduce the use of plastics, particularly wasteful practices such as multi-layer packaging, but this requires a rethink of both production processes and consumer standards.

5 Conclusion

The present study is the first study addressing the distribution and abundance of MP particles in the surface sediments of the Gulf of Trieste. MPs were present in all surface sediment samples, with an average concentration of 220 ± 29 particles/kg dry sediment, a moderate MP concentration compared to other regions of the Adriatic Sea. One of the main findings is that MPs are retained in the sediment and tend to accumulate in a narrow coastal area rather than offshore. The largest MP amounts were found in marinas and urban harbours. Most MPs detected in the surface sediments of the nearshore sampling sites were in general fibrous and the main polymer was PP. The offshore sediment samples consisted mainly of fibers from PET and other synthetic materials. Larger numbers of MP particles are being captured at coastal sites, possibly due to sewage runoff, waste disposal, and fishing. Proximity to the increasingly common anthropogenic stressors of coastal industrialization and population growth could also contribute to increased MP deposition at the sampled coastal sites. It cannot be excluded that some MP particles originated from other parts of the Adriatic Sea or entered the Gulf of Trieste via maritime transport.

Assessment of MPs in sediment samples in this relatively shallow gulf, which is prone to accumulation of pollutants, will provide useful scientific support for environmental management and risk assessment, as well as for future evaluation of the MP impacts in the Gulf of Trieste. Thus, a comprehensive approach is needed to address the problem, from research to the development of sustainable solutions. Understanding the sources and impacts of MP is critical to developing effective solutions. This includes identifying local sources of MPs, such as plastic waste from land and shipping, and understanding how they enter the marine environment. Our study will also help explain MP distribution in other semi-enclosed bays in the northern Adriatic. Finally, addressing the issue of MPs in marine sediments requires a comprehensive approach that also involves collaboration with local communities and governments. By acting in this area, we can help mitigate the impact of plastic pollution on the environment and human health.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

JJ: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. HP: Conceptualization, Investigation, Writing – review & editing. OB: Conceptualization, Data curation, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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