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Article

Microplastics in Surface Sediments along the Montenegrin Coast, Adriatic Sea: Types, Occurrence, and Distribution

Neda Bošković [1,*], Danijela Joksimović [1], Milica Peković [1], Ana Perošević-Bajčeta [1] and Oliver Bajt [2,3]

[1] Institute of Marine Biology, University of Montenegro, Put I Bokeljške Brigade 68, Kotor 85330, Montenegro; danijela.j@ucg.ac.me (D.J.); milica.pek@ucg.ac.me (M.P.); anap@ucg.ac.me (A.P.-B.)
[2] Faculty of Maritime Studies and Transport, University of Ljubljana, Pot pomorscakov 4, 6320 Portoroz, Slovenia; oliver.bajt@nib.si
[3] National Institute of Biology, Marine Biology Station, Fornače 41, 6330 Piran, Slovenia
* Correspondence: nedaboskovic93@gmail.com; Tel.: +38-268-722-532

Abstract: Considering that microplastics are widespread in the marine environment, in this study we evaluated the presence, identify distribution, abundance, shape type, and color of microplastics in surface sediment along the Montenegrin coast, on the Adriatic Sea. These preliminary results provide the first published record of microplastics found in the surface sediment of this area and highlight the importance of microplastics as a component of marine debris. We documented the presence of microplastics at all sampling locations. The identification of polymer types was performed using Fourier-transform infrared (FTIR) spectroscopy, whereby the presence of three polymer types became evident: polypropylene (54.5%), polyethylene (9.7%), and acrylate copolymer (2.0%). Another 22.2% of particles were unidentified polymers, and the remaining 11.5% were non-synthetic materials. The most common shape type of microplastics was filaments (55.5%), followed by granules (26.3%), fragments (14.9%), and films (3.3%). The dominant colors of microplastics followed the order: blue > yellow > red > clear > black > green > blue-white > white. The average abundance of microplastics in all sampling locations was 609 pieces of microplastic/kg of dry sediment. Compared with other studies, the surface sediment of the Montenegrin coast is moderately to highly polluted with microplastics, depending on the examined location.

Keywords: microplastics; sediment; FTIR-ATR; Montenegro; Adriatic Sea

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1. Introduction

Plastic production has increased around the world due to its useful properties; hence, there has been an increase in plastic waste and global plastic pollution [1]. According to Cole et al. [2], in the marine environment, plastic is considered the main "ingredient" of marine waste. For this reason, it is not surprising that plastic particles of different sizes and shapes are found in all segments of marine ecosystems around the world [3]. It has been estimated that 20% of plastic waste in the sea comes from sea-based sources (shipping, fisheries, fishing, and oil and gas platforms) [4,5], while as much as 80% comes from land-based sources (municipal waste, industrial activities, improper waste disposal, landfills, tourism, combined sewerage systems, etc.) [6]. The presence of marine plastic litter, which may contain harmful contaminants, poses a potential risk to marine ecosystems, biodiversity, and food availability [7]. Due to the marked growth in the production and use of plastics, there is a need for its identification and analysis in sediments, seawater, and living organisms.

Microplastics (MPs) are defined as plastic particles smaller than 5 mm [8]. MPs are a relatively new type of pollutant that is widely distributed in the marine environment, so understanding the distribution and accumulation of this form of pollution is crucial for environmental risk assessment [9,10].

The Mediterranean Sea, including the Adriatic Sea, is one of the most heavily polluted marine regions of the world (including microlitter) due to a high degree of urbanization, industrialization, and tourism [11–14]. The Adriatic Sea, shared by seven countries (Italy, Slovenia, Croatia, Bosnia and Herzegovina, Montenegro, Albania, and Greece), is a relatively small and semi-enclosed basin with a low water recirculation rate, making it particularly susceptible to pollution [15]. Recent studies have reported the presence of high concentrations of MPs in all parts of the Adriatic Sea, on beaches, at the sea surface, in sediments, and in biota [9,16–23], including polypropylene, polyethylene, polyvinyl chloride, polyethylene tetraphthalate and others. After accumulating in sediments, MPs become available to a wide range of benthic organisms, including some commercially important species of crustaceans, cephalopods, echinoderms, shellfish, fish and others. [24].

Taking into account that MPs are one of the descriptors of the Marine Strategy Framework Directive [25], with the present study we aimed to assess the quantity, distribution, and identification of MPs in the surface sediment along the Montenegrin coast (Adriatic Sea), collected from six locations in Boka Kotorska Bay and four locations from the coastal part of the open sea. We hypothesized the following: (1) MPs are found in all sampling locations; (2) the abundance of MPs is higher in locations in Boka Kotorska Bay, which are characterized by reduced contact with the coastal part of the open sea; and (3) polypropylene (PP) and polyethylene (PE) are the most abundant MPs because they represent polymers with the highest annual demand. The results from this study provide insight about MP pollution in surface sediments of the Montenegrin coast and will serve as a baseline for future comparisons, research, and monitoring of the state of the marine ecosystem and hopefully to protect it.

2. Materials and Methods

2.1. Sampling Area

Surface sediment samples were collected, during the autumn of 2019, along the Montenegrin coast from six locations in Boka Kotorska Bay—L1 (Dobrota), L2 (Orahovac), L3 (Sveta Nedjelja), L4 (Tivat), L5 (Bijela), and L6 (Herceg Novi)—and four locations from the coastal part of the open sea—L7 (Žanjice), L8 (Budva), L9 (Bar), and L10 (Ada Bojana). The study area and sampling locations are shown in Figure 1. The selection of these locations was based on the differences in tourist activities, population density, and harbors surrounding the locations.

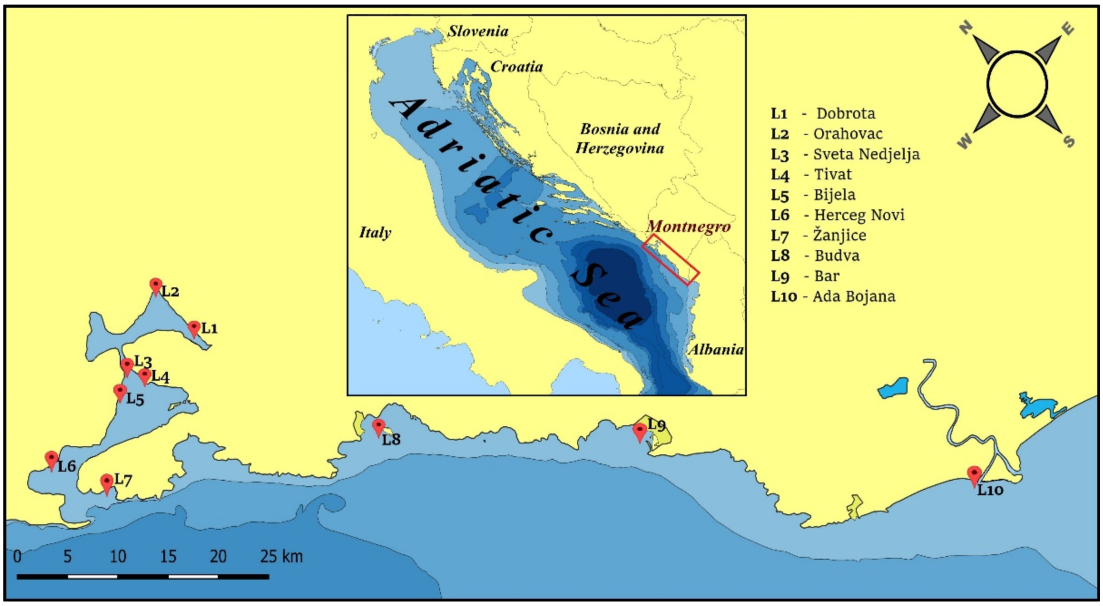

Figure 1. Study area and locations of sampling sites.

Dobrota, Tivat, Bijela, and Herceg Novi are the most populated places in the Boka Kotorska Bay; they are characterized by developed tourism, a large number of restaurants, hotels, beach bars, and intensive fishing activities. These locations are a waterway and a stopover for tourist boats and yachts that sail into the Boka Kotorska Bay throughout the year. By contrast, Orahovac and Sveta Nedjelja represent small, quiet, and sparsely populated fishing villages. Žanjice is an uninhabited area, but in the summer months it is a well-known tourist destination with a large number of restaurants and beach bars. Budva is also known as the "tourist metropolis of Montenegro", while Bar is mostly characterized by the presence of a port into which enter cargo container ships, bulk carriers, tankers, and passenger ships of various dimensions. Ada Bojana is a river island formed by the river of the same name at the estuary in the Adriatic Sea. The Bojana River flows through Montenegro and Albania and carries with it a great pollution potential.

Sediment samples (upper 5 cm) were collected using a Van Veen grab sampler and transferred to the laboratory. To prepare those sediment samples for analysis, after the homogenization which was carried out by conning and quartering, the samples (about 500g) were frozen at −18 °C in aluminum containers, after which they were freeze-dried at −40 °C for 48 h (Alpha 2-4 LD plus, CHRIST, Hagen, Germany) to prepare aliquots for MP extraction.

2.2. Separation of MPs Particles (MPPs)

After freeze-drying, samples were subjected to density separation. To isolate MPs from sediments, we used concentrated NaCl solution as proposed by Thompson et al. [26]. In a glass jar (1 L), 100 g of dry sediment and 0.5 L of concentrated NaCl solution (concentration 5.475 mol/L, density 1.2 g/cm^3, solubility 360 g in 1 L of water) were added. For 2 min, the sample was manually shaken vigorously and left to sediment for 24 h. Subsequently, the solution was decanted, and the supernatant, which contains the MPs, was sieved through a 63 μm steel sieve. With Mili-Q water, the material retained on the sieve was rinsed in a glass Petri dish. The procedure was repeated two times for each sample. The solutions were filtered using a vacuum pump on to Grade C glass fiber filters, stored in Petri dishes, and left to dry (ambient temperature) before the visual analysis. No MPs were identified under the 63 μm sieve. The MPPs in the samples ranged from 0.1 to 5 mm in size, which is within the definition of MPs [8], so there was no significant loss of MPs using a 63 μm sieve.

2.3. Visual Identification of MPPs

MPs in sediment samples were identified and counted based on their shape and color according to protocols developed and recommended by Frias et al. [27]. An Olympus SZX16 imaging microscope (with DP-Soft software) was used for visual identification. Images of the MPs were taken using ImageJ software (ver. 2.0.0). MPs can be of different colors: clear, white, blue, green, yellow, red, black, etc. [28]. According to the shape, MPs were categorized as granules, films, filaments, or fragments [16,28]. Granules have a regular round shape and usually a smaller size; these include pellets or resins. Films are thin, flexible, and usually transparent compared with fragments. Filaments are thread-shaped, oblong, and may look like strips. Fragments are irregularly shaped particles, rigid, thick with sharp curved edges [16,29,30]. To reduce errors, we followed the guidelines given by Hidalgo-Ruz et al. [31] during visual identification: no visible organic or cellular structure, the filaments should be of consistent thickness and color along their entire length, the particles should be clear and uniformly colored, and transparent and white particles should be observed under a high-magnification microscope [31]. MPs on the filters were counted three times, with the discrepancy not exceeding 5%. Abundances were calculated as the total number of MPs/kg of dry sediment.

2.4. Analysis of Polymer Types

Polymer composition of MPs in sediment samples was analyzed qualitatively using micro Fourier-transformer infrared (μ-FTIR) spectroscopy (Perkin Elmer Spotlight 200i, attenuated total reflectance (ATR)), making it possible to determine the chemical composition of natural and synthetic (polymer) materials. FTIR offers the possibility for precise identification of polymer particles according to their characteristic IR spectrum [17,32,33]. Polymers were identified by comparing each FTIR spectrum with spectra from a custom polymer library.

2.5. Quality Assurance and Quality Control

Contamination in work can cause significant overestimation of quantitative results [34]. Therefore, special attention was paid to preventing and minimizing contamination at all steps: All sampling tools (such as glass sampling containers, metal spatulas, tweezers) and analysis accessories (such as filters, aluminum foil, glass petri dishes) were washed and cleaned just before sampling and analysis, and all analyses were performed quickly to prevent contamination from the air. Samples were exposed to air for only a short amount of time. The entire procedure was performed in a fume hood, which had been cleaned before the work started. The work surfaces were cleaned with high-quality ethanol before each process/activity. Glassware and metal accessories used for each analytical step had been washed and rinsed with Mili-Q water. All utensils and dishes were covered with precleaned aluminum foil immediately after manipulation. After filtration, the filters were stored in glass Petri dishes. Pure cotton lab coats were used at all times, and special attention was paid to limiting synthetic clothing.

2.6. Statistical Analyses

We used the PRIMER 7 software to perform permutational multivariate analysis of variance (PERMANOVA) [35], in which data were square-root transformed before analysis on the basis of the Bray–Curtis similarity matrices. The design incorporated two factors: (1) location (L1, L2, L3, L4, L5, L6, L7, L8, L9, and L10) and (2) zone (Boka Kotorska Bay and the coastal part of the open sea). Principal coordinate analysis (PCO) was performed to describe the abundance of different types of plastic polymers among the sampling locations considered and to test our hypotheses about the amount of MP contamination in surface sediment samples along the Montenegrin coast.

3. Results

MPs were found in sediment samples from all examined locations, as expected from hypothesis 1. Because the potential MPPs looked similar in terms of morphology (e.g., color, texture, and shape), at least 15% of the collected MPPs from each sample (688 in total) were analyzed for their chemical composition to identify common polymers, representing the most common items in sediment samples from all locations.

Polymer identification by FTIR spectroscopy revealed that 54.5% of the analyzed particles were polypropylene (PP), 9.7% were polyethylene (PE), and 2.0% were acrylate copolymer (AC copol.), while the identity of 22.2% of particles could not be determined. The results showed the presence of polymeric material, different copolymers that are difficult to determine correctly, so we marked them as unidentified polymers. The remaining 11.5% of MPPs were non-synthetic materials, including 5.1% cellulose, 4.9% organic matter, and 1.5% inorganic matter (Table 1).

PP was present at all examined locations, with the largest proportion at L1. PE was present at seven locations, with the largest proportion at L8. AC copol. was present at only three examined locations. Unidentified polymers were observed at eight examined locations, with L6 containing the largest amount; that location also had the highest content of organic matter. Cellulose was identified at nine of the examined locations.

Based on results of chemical identification, which positively identified 88.5% of the analyzed MPPs as plastic, we determined that the corrected average abundance of MPs in all locations was 609 MPs/kg of dry sediment, with the highest MP concentration at L1 (2500 MPs/kg of dry sediment) and the lowest at L2 (150 MPs/kg of dry sediment). The mean concentrations of MPs in the surface sediments of the Montenegrin coast were in the descending order L1 > L6 > L8 > L5 > L7 > L10 > L4 > L3 > L9 > L2.

Table 1. The results of the polymer identification using attenuated total reflectance–Fourier-transform infrared spectroscopy, tested in 100 g of dry sediment for each location.

Location	Plastic Materials				Total
	PP	PE	AC Copol.	Unidentified	(MPs/100 g)
L1 *	246	0	4	0	250
L2 *	5	8	0	2	15
L3 *	11	5	0	4	20
L4 *	14	7	0	5	26
L5 *	21	14	8	0	43
L6	26	0	0	95	121
L7	15	0	0	17	32
L8	18	15	0	25	58
L9	8	6	0	2	16
L10	11	12	2	3	28

* [36].

In the study by Bošković et al. [36], preliminary results of visual identification of MPs in sediments at sites L1, L2, L3, L4 and L5 were published, while in this study the confirmed results of visual identification, abundance of different shape types and colors of MP particles and, most importantly, chemical identification of polymers are presented. Moreover, all data related to the other five locations (L6, L7, L8, L9 and L10) are presented for the first time in this paper.

The PCO performed on data collected in this study showed that two factors (PCO1 and PCO2) explained 91.6% of the total variance in the data matrix (Figure 2). PCO1 accounted for 53.6% of the variation while PCO2 accounted for 38.0% of the variation.

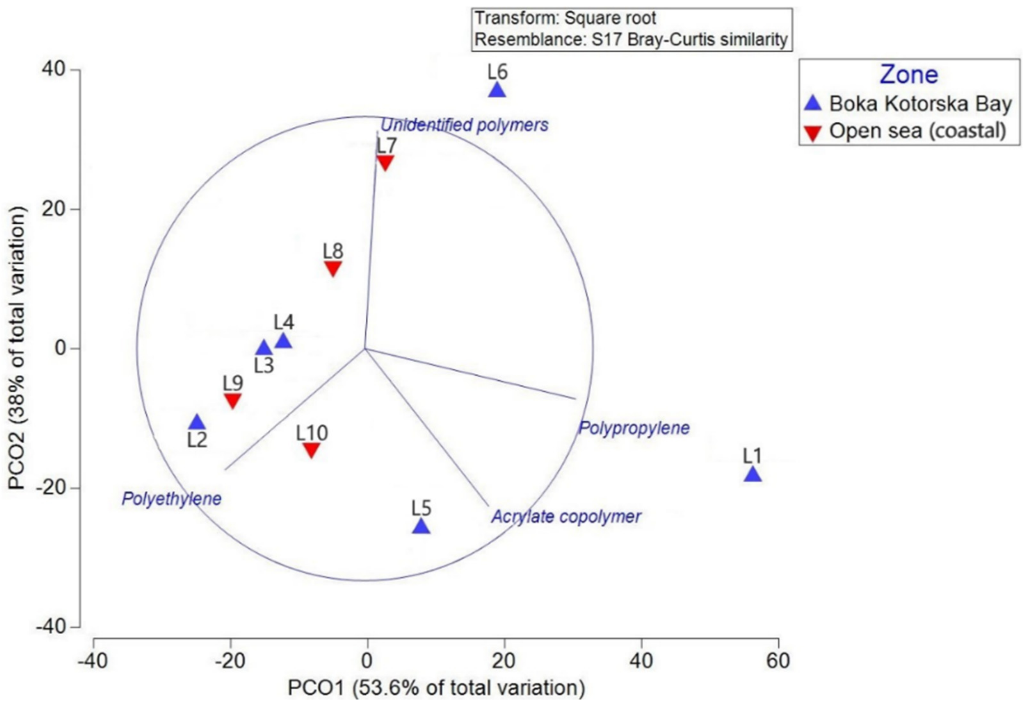

Figure 2. Polymer abundances evaluated at each sampling locations using principal coordinate analysis (PCO).

Based on Figure 2 and Table 1, we noticed that L1 was the most polluted location, with the highest concentration of PP and the presence of AC copol., while L6 was the second most polluted location, where unidentified polymers were dominant, and according to the position within the coordinates, the second dominant factor was PP. In L8, the abundance varied according to the three polymers, so the pollution at this location was higher than L7 due to the concentration of PE especially, which is presented in the lower part of the graph, in contrast to unidentified polymers. The relationship with PP classified this location in the positive quadrant of PCO2. The value observed in L5 showed that PE, PP, and AC copol. were dominant, while at L7 PP and unidentified polymers were the most abundant. Other locations that are close to the zero coordinates of the graphs move in descending order in terms of the amount of MP pollution: L10 > L4 > L3 > L9 > L2. There were no significant correlations ($p > 0.05$) between either of the attached communities, that is, the abundance of plastic polymers and the sampling locations. In future research, more sediment samples at the same location should be tested to increase statistical significance when examining potential relationships.

Considering the shape type, filaments (55.5%) were most common, followed by granules (26.3%), fragments (14.9%), and films (3.3%). Filaments and fragments were found at all examined locations, granules were identified at seven locations (L3, L4, L5, L6, L7, L8, and L10), and films were found at five sampling locations (L1, L3, L4, L5, and L8). Only four locations (L3, L4, L5, and L8) had all four shapes. Filaments were the most dominant shape at L1 (98%), followed by L2 (80%), L9 (56.3%), L10 (53.6%), and L4 (34.6%). The percentage of filaments in L1 was the highest compared with the other examined locations. Fragments were the most dominant shape type at L7 and L3, with 50% and 35%, respectively, while granules were the most dominant shape type at L6, L8, and L5, with 76%, 46.5%, and 39.5%, respectively. Table 2 and Figure 3 show the classification of MP particles according to (a) shape and (b) color.

The most frequent MP color in all studied locations was blue (50.1%), followed by yellow (22.7%), red (11.7%), clear (8.2%), black (4.3%), blue-white (1.5%), green (1.3%), and white (0.3%) (Table 2). The majority of filaments were blue, followed by clear, black, and red. Granules were dominated by yellow and red; fragments by red, blue, and yellow; and films by blue. Examples of collected MPs obtained under a microscope are present in Figure 4. Non-plastic particles were mostly transparent alongside red filaments, yellow fragments, and films.

Table 2. Shape type and colors of MPPs identified in all samples by visual inspection, tested in 100 g of dry sediment for each location.

Type of Shape	Color	Location									
		L1	L2	L3	L4	L5	L6	L7	L8	L9	L10
Filaments	Clear	27	0	3	2	6	3	0	2	1	0
	Blue	212	4	2	7	7	5	6	8	5	11
	Red	0	0	1	0	3	0	0	0	3	0
	Black	6	8	0	0	0	0	0	2	0	4
Fragments	Blue	0	0	2	2	0	2	4	3	6	5
	Red	0	0	2	3	2	12	8	10	1	0
	Blue-white	2	1	3	3	0	0	0	0	0	0
	White	0	2	0	0	0	0	0	0	0	0
	Green	0	0	0	0	2	0	0	0	0	0
	Yellow	0	0	0	0	1	7	4	0	0	4
Films	Blue	3	0	3	3	2	0	0	3	0	0
	Green	0	0	0	0	3	0	0	3	0	0
Granules	Clear	0	0	2	0	4	0	0	0	0	0
	Red	0	0	2	4	9	5	0	4	0	2
	Black	0	0	0	2	4	0	0	0	0	0
	Yellow	0	0	0	0	0	87	10	23	0	2
Total (MPs/100 g)		250	15	20	26	43	121	32	58	16	28

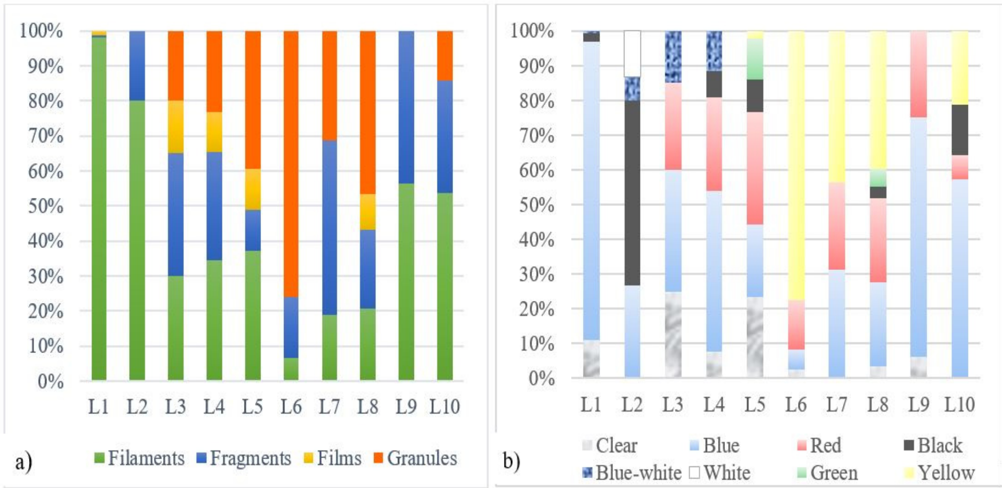

Figure 3. Classification of MPs (in %) according to (**a**) shape type and (**b**) color.

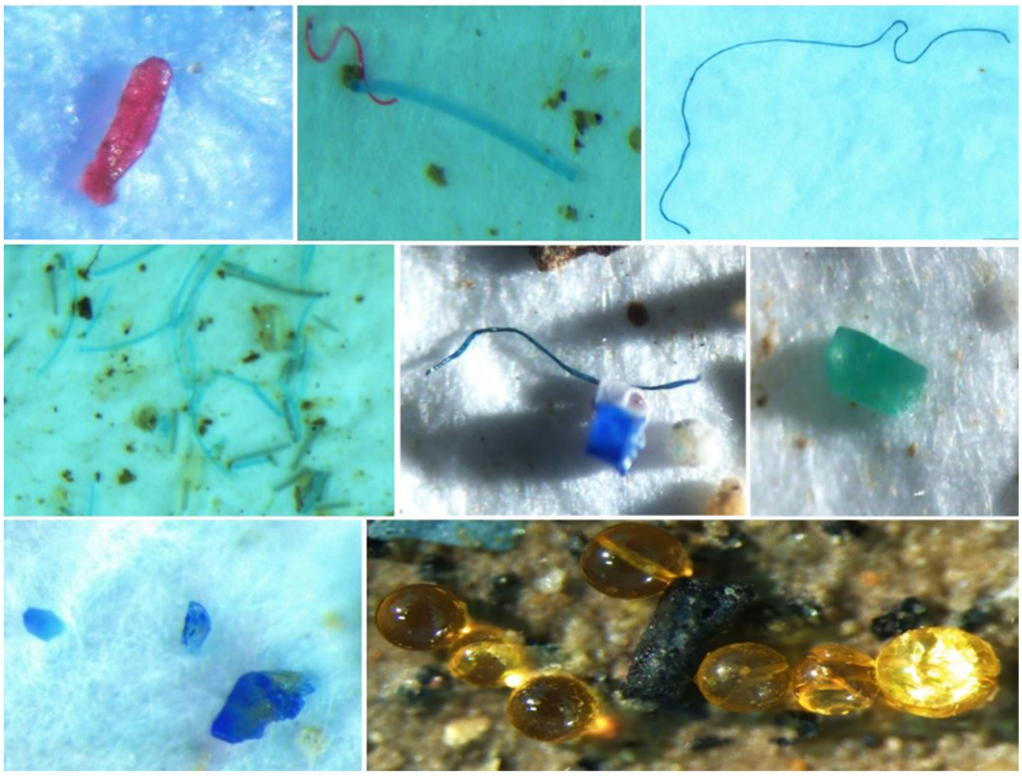

Figure 4. Examples of the collected MPs observed under a microscope. The images were obtained using ImageJ software (version 2.0.0).

4. Discussion

The relative contribution of different shapes of MP recovered from sediment samples at each location on the Montenegrin coast showed that filaments were most common (55.5%), followed by granules (26.3%), fragments (14.9%), and films (3.3%). Filaments are mainly derived from the breakage of fishing lines, wastewater, domestic outflows, and from fabric and textile industrial production [14,37]. The source of granules could be certain types of hand cleaners, cosmetic preparations, and some cleaning media [16]. The high number of fragments is related to the breakdown of larger plastic debris. The presence of films indicates that these locations are contaminated with plastic coming from packaging, bags, or wrappers [10].

In the present study, 73.7% of MPs (filaments, fragments, and films) were secondary MP products derived from the degradation and fragmentation of larger plastics through biodegradation processes, photolysis, thermal oxidation, thermal degradation, and mechanical forces. A smaller percentage (26.3%) was identified as primary MPs (granules). Arthur et al. [38] emphasized that for management purposes, it is crucial to have information about the potential sources of MPs given that control strategies differ according to the source and origin.

Previous studies have reported that filaments were the dominant type of MP in sediments [16,26], which is consistent with our results. For example, in sediment samples from the Central Adriatic Sea, Mistri et al. [12,37] revealed that the dominant shape of MP was filaments. Blǎsković et al. [9] made similar observations, stating that filaments were the principal form of MP pollution (90%) in sediment samples from the Eastern Adriatic Sea. In the North Adriatic Sea, 96% of the primary MPs in samples of infralittoral sediment were filaments [18].

The collected MPs presented different colors, and colored particles were found in all locations. The detected colors of MPs were in the following order: blue > yellow > red > clear > black > green > blue-white > white, findings that are consistent with other studies on MPs [39–42]. Colored particles of MPs are very attractive to marine biota and similar to natural prey, and are, therefore, very often replaced with food [43]. We conclude that MPPs, based on the presence of different shapes and colors, may have originated from different sources and have different origins, as indicated by Munari et al. [21].

FTIR analysis showed the presence of three polymer types: PP (54.5%), PE (9.7%), and AC copol. (2%). The higher abundance of PP and PE supported hypothesis 3. Overall, 22.2% of particles were marked as unidentified and the remaining 11.5% were non-synthetic materials. Our findings are consistent with Vianello et al. [17], who revealed that PE and PP are the most frequently found polymers, accounting for more than 82% of MPs in sediment from the Venetian Lagoon in Italy. Duis and Coors, Frère et al., and Abidli et al. [10,44,45] also revealed that PE and PP are the most frequently found polymers. PP and PE are two polymers with very high annual demand; hence, it is not surprising that they are the most common polymers found in marine environments around the world, as well as in the Adriatic Sea. These polymers have a wide range of applications (domestic and industrial), most commonly used for packaging that is used once and then discarded, for textile production, disposable bags, ropes, fishing gear, automotive components, production of furniture parts, computer parts, electronic components, household goods, and other products [14,16,37,46]. AC copol. provides excellent water resistance and is widely used in the cosmetic industry for sunscreen, skin care products, hair care products, shaving creams, body wash, and moisturizers [47].

Compared with literature data for the Adriatic Sea and around the world, the average abundance of MPs found in all sediment samples of this study (609 MPs/kg of dry sediment) was lower than that reported for the Adriatic Sea, Italy [17]; the Pacific Ocean, Japan [48]; and the Mediterranean Sea, Tunisia [41]. By contrast, we found similar values to those reported in the North Sea, Belgium [49]. The concentrations of MPs in this study were higher than measured for sediment samples from the Adriatic Sea, Croatia, Slovenia, and Italy [9,14,18,50–52] as well as the Mediterranean Sea, Spain, Tunisia, and Italy [10,30,53,54]. Moreover, the average abundance of MPs in this study was higher than that observed in the North Sea, Belgium, the Netherlands, England and France [16,49]; the Baltic Sea, Russia [55]; the Atlantic Ocean, Argentina [42]; and the Indian Ocean, Iran [56] (Table 3).

The abundance of MPs we measured along the Montenegrin coast confirmed hypothesis 2. We expected higher concentrations of MPs in the sediment at locations in Boka Kotorska Bay (L1, L4, L5, and L6), which are characterized by reduced contact with the open sea, in relation to locations from the coastal part of the open sea (L7, L8, L9, and L10). In our study, L1, which is situated in Boka Kotorska Bay, was the most contaminated location (2500 MPs/kg of dry sediment). Higher concentrations of MPs in sediment were attributed to areas with higher population densities, enclosed harbor areas (Port of Kotor), tourist locations, and a high density of restaurants and fishing activities; these features characterize L1. This location is a waterway and a stopover for a large number of cruisers and yachts that enter throughout the year, and this all can significantly affect the quality of marine sediment and contribute to pollution [57]. Many authors suggest these factors are some of the main sources of MPs in the marine environment [10,16,39,41,58,59].

Table 3. Comparison of MPs concentrations in marine sediments found in this study and from previous studies in the literature.

Location	Water Body	Habitat	No. of Surveyed Stations	Mean Concentration (MPs/kg of Dry Sediment)	Reference
Montenegro	Adriatic Sea	Surface sediment	10	609	Present study
Croatia	Adriatic Sea	Surface sediment	10	177.61	[9]
Croatia	Adriatic Sea	Surface sediment	7	310	[51]
Croatia	Adriatic Sea	Seabed	20	360	[14]
Croatia	Adriatic Sea	Surface sediment	17	245.6	[52]
Slovenia	Adriatic Sea	Infralittoral	6	170.4	[18]
Italy	Adriatic Sea	Lagoon	10	1445.2	[17]
Italy	Adriatic Sea	Surface sediment	7	254.57	[50]
Italy	Mediterranean Sea	Coastal sediment	9	272.8	[54]
Italy	Mediterranean Sea	Seafloor	29	1.7	[53]
Tunisia	Mediterranean Sea	Surface sediment	4	7960	[41]
Tunisia	Mediterranean Sea	Surface sediment	2	242	[10]
Spain	Mediterranean Sea	Shallow sediments	6	499.065	[30]
Belgium	North Sea	Harbor	11	166.7	[16]
Belgium	North Sea	Surface sediment	7	585.29	[49]
Netherlands	North Sea	Surface sediment	11	224.5	[49]
England	North Sea	Surface sediment	4	306	[49]
France	North Sea	Surface sediment	5	481.2	[49]
Russia	Baltic Sea	Bottom sediment	7	34	[55]
Argentina	Atlantic Ocean	Seafloor	7	182.85	[42]
Japan	Pacific Ocean	Surface sediment	2	1800	[48]
Iran	Indian Ocean	Surface sediment	5	61	[56]

The lower abundance of MPs in the sediment from L4 (260 MPs/kg of dry sediment), Boka Kotorska Bay, was surprising because it is a tourist destination located in the luxury marina Porto Montenegro. There were similar lower abundances of MPs at L9 (160 MPs/kg of dry sediment) and L10 (280 MPs/kg of dry sediment), the coastal part of the open sea. At L7 (320 MPs/kg of dry sediment), also the coastal part of the open sea, the presence of MPs in the analyzed sediment was higher than expected. The results could be related to strong sea currents, waves, and winds, all of which might translocate MPs in surface sediment far away from its source, leading to a reduction or accumulation of MPs in certain locations [10,13,14,18,30,41,60]. The low concentrations of MPs in the sediments from L2 (150 MPs/kg of dry sediment) and L3 (200 MPs/kg of dry sediment) might be related to the low population density in this part of the coast compared with the other locations. In addition, L2 receives input of fresh water from the Ljuta River, which might transport MPs to other parts of Boka Kotorska Bay and into the Montenegrin coast. In this context, Laglbauer et al. [18] and Zeri et al. [61] suggested that the input of fresh water could be a crucial factor affecting the distribution of MPs in marine environments. The occurrence of MPs at L5, L6, and L8—with 430, 1210, and 580 MPs/kg of dry sediment, respectively—is in line with the expected results, considering that they represent tourist centers, are characterized by high population density and intensive fishing activity, and have notable wastewater discharges.

MPs can be discharged into the sea indirectly via wastewater [21,41,59]. We emphasize that the issue of wastewater treatment has not been completely solved on the Montenegrin coast. Furthermore, Montenegro has a problem with the management and storage of municipal waste, which can significantly affect the quality of marine sediment and contribute to pollution. Six Montenegrin municipalities are geographically located along the south Adriatic coastline (Kotor, Tivat, Herceg Novi, Budva, Bar, and Ulcinj). In these municipalities, apart from the permanent population, there is dynamic tourism, which causes a higher inflow of wastewater [62]. There are eight sea outfalls in the municipality of Kotor, three each in the municipalities of Budva and Bar, two in the municipality of Ulcinj and one each in the municipalities of Tivat and Herceg Novi. In addition to major sea outfalls, there are many uncontrolled local discharges. More of the outfalls in the coastal region of Montenegro are old and in poor operational condition, deficient, and have been earmarked for replacement or termination. In addition to wastewater from the coastal region, a portion of wastewater from the central region of Montenegro flows into the Adriatic Sea [62].

L1, which was the most polluted location in terms of the occurrence of MPs in the surface sediment, receives the largest number of wastewater discharges. In such a context, Browne et al. [59] concluded that up to 80% of MPs in sediment originate from the discharge of wastewater into marine environments.

Compared with the literature data, the MP concentrations in surface sediment of the 10 sampling locations of the present study, with the exception of L1, where extreme MPs values were recorded in the sediment, were medium to moderately contaminated with MPs. The occurrence and distribution of MP contamination in the sediments at our sampling locations can be related to several factors: dense populations, tourist and fishing activities, wastewater discharges, passenger ships, harbors, freshwater inflows, strong currents, winds, and waves. Many authors have reached similar conclusions [8,10,16,41,56,59].

5. Conclusions

We have provided evidence of the presence of MP contamination in surface sediments along the Montenegrin coast, contributing to the knowledge of MPs' distribution and abundance. MPs were present in all samples of surface sediment, with an average concentration of 609 MPs/kg of dry sediment, which is a relatively high MP concentration compared with what has been reported for other parts of the Mediterranean Sea. The most abundant shape of MP in the present study was filaments, a finding that is consistent with the literature, while blue was the most common color. Considering the polymer type, PP was present at all sampling locations, while PE was present at seven of ten sampling locations. Our results showed the highest concentrations of MPs were in locations in the vicinity of highly populated centers, municipal effluent discharge restaurants, fishing and tourist activities, and a large number of cruisers that pass throughout the year. We have provided a useful basis for further research to improve waste management policies, wastewater control, transport control, and other potential effects to reduce plastic waste emissions into the marine ecosystem.

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SEDIMENT CHALLENGES AND OPPORTUNITIES

Distribution and characterization of microplastics in marine sediments from the Montenegrin coast

Neda Bošković[1] · Danijela Joksimović[1] · Ana Perošević-Bajčeta[1] · Milica Peković[1] · Oliver Bajt[2,3]

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Abstract

Purpose Plastic pollution in the world has led to an abundance of microplastics (MPs) and has been identified as a potential factor that can lead to serious environmental problems, especially in oceans and seas. Information on the current status of MPs pollution along the Montenegrin coast is insufficiently investigated. This study monitors the abundance, distribution, and sources of MPs, and identifies present polymers in the surface sediment of the Montenegrin coast, as well as comparison with previous research.

Materials and methods Ten sampling sites along the Montenegrin coast were selected to collect surface sediment samples. The upper layer of sediment (0–5 cm) was collected by a Petite ponar grab. The samples were dried, and density separation was performed using a NaCl solution. The abundance and morphological characteristics of MPs were determined using an optical microscope (DP-Soft software), while FT-IR analysis was done to identify the polymer type.

Results and discussion Microplastics were identified in all sediment samples with an average abundance of 307 ± 133 (SD) MPs/kg in dry sediment. The highest abundance of MPs was found in locations in the vicinity of highly populated areas, near wastewater discharges, and areas with high fishing and tourist activities. The most dominant shape types of MPs in all samples were filaments and fragments. The most common colors of MPs were blue and red, while the dominant MPs sizes were 0.1–0.5 mm and 0.5–1.0 mm. Of the eight identified polymers, PP, PE, and PET were the most common.

Conclusion This study reveals MPs characteristics (abundance, distribution, shape type, colors, size, polymers type) in surface sediment along the Montenegrin coast, as well as the most significant sources of MPs pollution, and provides important data for further research on MPs to identify the effects of MPs pollution on the quality, health, and functionality of the marine environment.

Keywords Microplastics · Marine sediment · FT-IR · Montenegro · Adriatic Sea

1 Introduction

The term microplastics (MPs) describes any synthetic solid particle or polymeric matrix, with regular or irregular shape, with size ranging from 1 μm to 5 mm, primary or secondary manufacturing origin and which are insoluble in water (Frias and Nash 2019). Primary MPs are intentionally produced MPs of synthetic polymers that have a wide range of applications including micro-beads incorporated into cosmetic products, resin pellets, and beads used for abrasive blasting (Ryan et al. 2009; Hintersteiner et al. 2015; Wang et al. 2020). Also, primary MPs can originate from the abrasion of synthetic textiles during washing or abrasion of large plastic objects during manufacturing, use, or maintenance such as the erosion of tyres (Sundt et al. 2014). Secondary MPs are formed by the fragmentation of larger pieces of plastic due to the action of various environmental factors (physical, chemical, and biological), which results in the decomposition of plastic into smaller fragments, meaning that macroplastics will fragment into microplastics (Thompson et al. 2004; Arthur et al. 2009; Cole et al. 2011; Yu et al. 2020).

Responsible editor: Elena Romano

✉ Neda Bošković
nedaboskovic93@gmail.com

[1] Institute of Marine Biology, University of Montenegro, Put I Bokeljške brigade 68, Kotor 85330, Montenegro

[2] Marine Biology Station, National Institute of Biology, Fornače 41, Piran 6330, Slovenia

[3] Faculty of Maritime Studies and Transport, University of Ljubljana, Pot pomorscakov 4, Portoroz 6320, Slovenia

Side effects of MPs on marine organisms can be physical and chemical. Physical effects are most often related to the size and shape of MPs, while the chemical effects are related to the fact that plastic carries a "cocktail of chemicals" with it (Browne et al. 2011). Among the chemicals present in MPs are those incorporated into plastic polymers during their production (various additives) and those present in water that are adsorbed on the surface of MPs, such as various organic and inorganic pollutants (Godoy et al. 2019).

A large number of studies indicate the presence of plastic as a pollutant in the Adriatic Sea and predict that the Adriatic region will be one of the main areas of plastic accumulation in the Mediterranean, both due to its oceanographic conditions and the high degree of different anthropogenic pressures present in the small area (Liubartseva et al. 2016; Carlson et al. 2017). In the Adriatic Sea, MPs have been found in abiotic and biotic areas, including beaches (Munari et al. 2017), surface waters (Gajšt et al. 2016; Suaria et al. 2016; Vianello et al. 2018), sediment (Vianello et al. 2013; Laglbauer et al. 2014; Renzi and Blašković 2020; Bošković et al. 2021), fish (Avio et al. 2015; Anastasopoulou et al. 2018; Giani et al. 2019), and shellfish (Gomiero et al. 2019; De Simone et al. 2021).

Increased awareness of the growing production and subsequent accumulation of plastic pollution in the environments worldwide has identified MPs as a potential factor contributing to the biodiversity loss in the oceans and seas (Gall and Thompson 2015), which has encouraged the inclusion of various international legislation and projects in the field of marine environment protection. The Marine Strategy Framework Directive (MSFD) states that member states are obliged to take action to achieve and maintain good environmental status and emphasizes the need to obtain as accurate data as possible on the identification, quantification, distribution, and monitoring of environmental MPs, as defined in priority descriptor 10.1.3 (MSFD 2008/56/EC 2008).

The aim of this study is to give additional and more precise information on sources, abundance, and distribution of MPs in surface sediment on the Montenegrin coast. This is important for undertaking available measures to reduce MPs levels in the marine environment, as well as further investigations and monitoring in this field contributing to the efforts of the MSFD.

2 Materials and methods

Sediment sampling was performed during the spring of 2021. The study areas for sediment analysis included six locations in Boka Kotorska Bay (Dobrota, Orahovac, Sveta Nedjelja, Tivat, Bijela, and Herceg Novi) and four locations on the coastal area of the open sea (Žanjice, Budva, Bar, and Ada Bojana) (Fig. 1). Sampling locations selected for the research had different geographical positions, morphological and hydrological characteristics, and were influenced by different anthropogenic factors. In Table 1, the basic sampling data are presented.

Surface sediment (upper 5 cm) was sampled using a Petite ponar grab, Wildco (composite sample of two samples from one location). Sediment samples after the homogenization which was carried out by conning and quartering (about 500 g) were then frozen at −18 °C and subjected to a cold drying procedure in a freeze-dryer (CHRIST, Alpha 2–4 LD plus) under a vacuum at −40 °C for 48 h. In order to

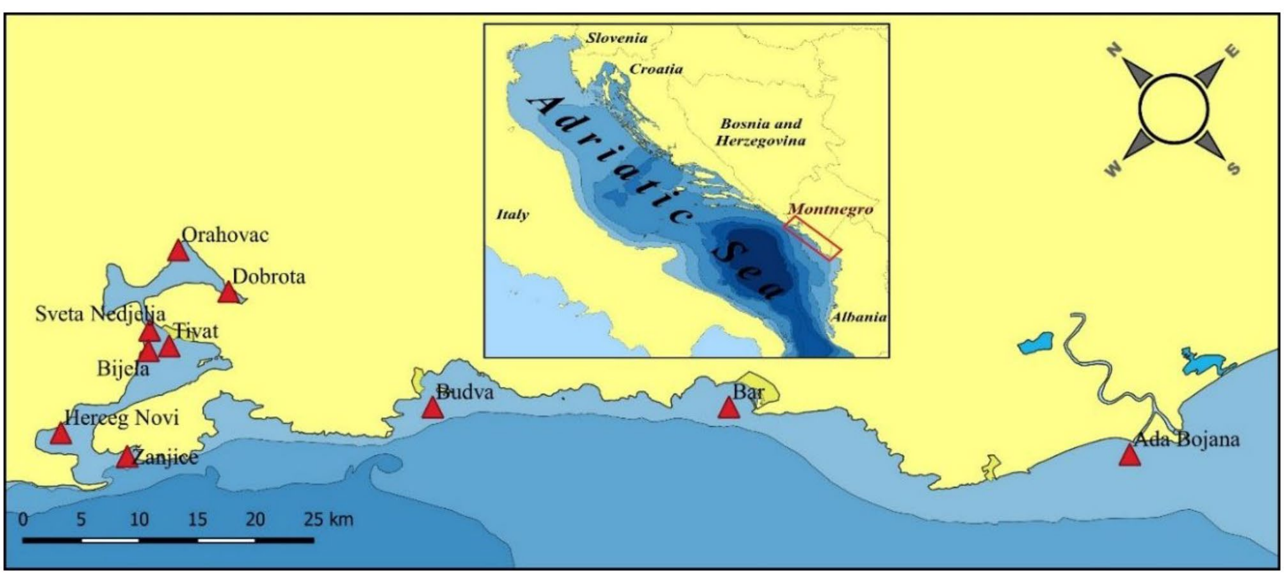

Fig. 1 Sampling locations of surface sediments along the Montenegrin coast

Table 1 The basic sampling data

Sampling locations	Coordinates		Depth of sampling (m)	Date of sampling	Type of sediment*
Dobrota	42.436738	18.762041	10	12.04.2021	Slightly gravelly muddy sand
Orahovac	42.486974	18.753844	20	12.04.2021	Slightly gravelly muddy sand
Sveta Nedjelja	42.457092	18.674193	19	12.04.2021	Gravelly muddy sand
Tivat	42.437744	18.677641	38	12.04.2021	Slightly gravelly muddy sand
Bijela	42.446168	18.658379	24	12.04.2021	Slightly gravelly muddy sand
Herceg Novi	42.446485	18.532894	42	12.04.2021	Slightly gravelly muddy sand
Žanjice	42.397888	18.566368	9	12.04.2021	Slightly gravelly muddy sand
Budva	42.262911	18.833523	31	16.04.2021	Slightly gravelly sand
Bar	42.104562	19.057053	32	16.04.2021	Slightly gravelly muddy sand
Ada Bojana	41.863054	19.323559	12	16.04.2021	Slightly gravelly sand

*According to classification by Folk (1954)

extract MPs from the sediment, a density separation process was applied according to the method proposed by Thompson et al. (2004), using supersaturated NaCl solution (1.202 g cm^{-3}). In a glass jar (1 L), 100 g of dry sediment and 0.5 L of concentrated NaCl solution were added. The sample was manually vigorously shaken for 2 min. After 24 h, the supernatant was decanted through a 63 µm steel sieve. The residue (precipitate) for each sample was again subjected to a density separation process. After sieving, the samples were filtered on glass fiber filters of Grade C using a vacuum pump, and then transferred to glass Petri dishes.

In order to visually identify and count the number, determine the shape, color, size, and texture of MPs present in the samples, the samples were analyzed under a microscope. Microplastics are usually divided into four size categories: < 0.1 mm, 0.1–0.5 mm, 0.5–1.0 mm, and 1.0–5.0 mm and four types of shapes: fragments, filaments, films, and granules (Galgani et al. 2013). Fragments represent irregularly shaped particles, such as crystals, powder and flakes, rigid, thick, with sharp curved edges. The filaments or fibres are thread-shaped, oblong, may look like strips or have a cylindrical shape. Films are irregularly shaped, thin, flexible and usually transparent compared to fragments. Granules are spherical particles, such as pellets of common resins, spherical microbeads and microspheres (Claessens et al. 2011; Frias and Nash 2019). Even though color is not considered to be crucial to defining MPs, because color differentiation is subjective (Frias and Nash 2019), categorizing MPs according to color is useful to identify potential sources as well as potential contaminations (Hartmann et al. 2019). Visual analysis of MPs was performed using an Olympus SZX16 optical microscope (DP-Soft software). During visual identification, we followed the guidelines proposed by Hidalgo-Ruz et al. (2012) to reduce errors. The MPs on the filters were counted three times, with a discrepancy that did not exceed 5%. Chemical identification of MPs was performed using FT-IR microspectroscopy (Perkin Elmer Spotlight 200i FT-IR spectroscopy), which allows accurate identification of polymer particles according to their IR spectrum (Thompson et al. 2004; Ng and Obbard 2006; Reddy et al. 2006; Frias et al. 2010; Harrison et al. 2012; Löder and Gerdts 2015). Special care was taken to analyze all types of particles (different colors, shapes, sizes, and structures) using FT−IR spectroscopy. Approximately 30% of the particles were recorded on FT-IR in each sample individually. Each MPs particle was recorded on FT-IR which was previously photographed and their spectra were preserved. Procedural blanks were performed and collected during all analyses. All results were corrected according to the level of contamination measured during sample processing and analysis, to compensate for external contamination. Abundances of MPs were calculated as the total number of MPs/kg of dry sediment.

2.1 Quality assurance and quality control

As contamination in the work can cause significant overestimation of quantitative results (Foekema et al. 2013), in all phases (sampling, transport, drying, density separation, visual, and chemical identification), special care was taken to prevent contamination or cross-contamination of samples. In other words, plastic accessories were avoided during the analysis. Glass and metal utensils/glasswear, washed and rinsed with Milli-Q water, were used during each analysis. We paid special attention to ensure the cleanliness of the laboratory space, especially in regards to dust or other particles. The samples were exposed to air for a minimum time and the analysis procedures were performed in a clean laboratory (fume hood). Work surfaces were cleaned with high-quality ethanol before each process/activity. After filtration, the filters were stored in glass Petri dishes. Pure cotton lab coats were used all the time and synthetic clothing was limited.

2.2 Statistical analyses

Statistical analysis was carried out using principal coordinate analysis (PCO) and cluster analyses with the Premanova Monte Carlo test to verify the significant difference between MPs abundance at different sampling locations ($p < 0.05$). Data were square-root transformed before analysis based on the Bray–Curtis similarity matrices. All data analyses were carried out in PRIMER v7 with PERMANOVA+ software.

3 Results and discussion

From the total 348 particles of MPs visually detected in the surface sediments at all locations, 29.31% of them were analyzed for chemical identification of polymer types using FT−IR spectroscopy. Polymer identification by FT-IR spectroscopy identified eight polymer types: polypropylene (PP, 33.3%), polyethylene (PE, 15.7%), polyethylene terephthalate (PET, 14.7%), polyamide (PA, 4.9%), polystyrene (PS, 3.9%), and acrylate copolymer (AC cop., 2.9%). Some MPs particles (12.7%) were identified as polymers, but due to their decomposition during years (aged plastic), it was difficult to determine which polymer category it fell into (because of the high number of different copolymers, which have emerged during years), so we marked them as unidentified polymers (Unid. poly.). The remaining 11.8% of MPs were non-synthetic materials, cellulose. Cellulose was identified in the surface sediments at 6 of the 10 sampling locations, and these were usually filaments.

Results of chemical identification positively identified 88.2% of the analyzed MPs as plastic, so the corrected average abundance of MPs in surface sediment from 10 locations along the Montenegrin coast sampled during the spring of 2021 was 307 ± 133 (SD) MPs/kg of dry sediment. Figure 2a shows the percentage of polymers in the sediments samples from the Montenegrin coast, and Fig. 2b shows examples of the identified spectra by FT-IR of the most common polymers in the analyzed sediments All sediment samples contained a minimum of three and a maximum of seven different polymer types. Polypropylene and PE were detected in surface sediments at all 10 sampling locations.

Polypropylene and PE were the most common types of polymers in the study done by Bošković et al. (2021). However, in this study, polymers such as PET, PS, and PA were not identified in sediment sampled during the autumn of 2019 (Bošković et al. 2021). Statistical significance ($p < 0.05$) was observed in the presence of different polymers in this study from spring 2021 and the study Bošković et al. (2021) from autumn 2019 (Permanova, Monte Carlo test). Polypropylene and PE are two polymers with very high annual demand and many authors revealed that these polymers are the most frequently found polymers in marine environments around the world (Vianello et al. 2013; Frère et al. 2017; Abidli et al. 2017, 2018; Bošković et al. 2021). They are widely distributed in household appliances, such as packaging, durable textiles, pipes, but are also used for fishing nets, strapping ropes, bottles, packaging bags, etc. (Mistri et al. 2017; Vianello et al. 2018; Fan et al. 2021). Polystyrene, in addition to PP and PE, is one of the most

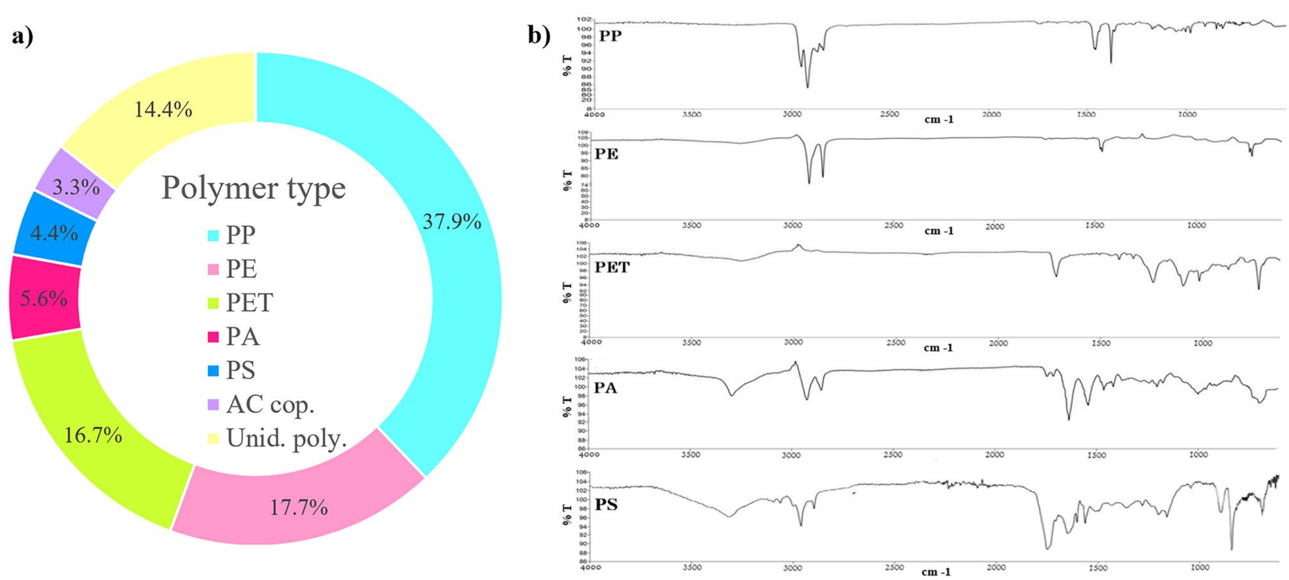

Fig. 2 **a** Distribution of polymers in surface sediments at all sampling locations and **b** FT-IR spectroscopy spectra of the most common polymers collected in this study

commonly used plastics. The use of PS includes protective packaging, containers, lids, bottles, trays, baking cups, and disposable utensils (Maul et al. 2007). Polyethylene terephthalate is used in clothing fibers, for the production of bags, sacks and wrappers, packaging, containers, and also in combination with glass fibers for engineering resins (Oliveira et al. 2020; Fan et al. 2021). Polyamide has commercial application in the production of fabrics, fibers, nets, and films (mainly for food packaging) (Ndiaye and Forster 2007), while the AC cop. is widely used in the cosmetics industry for the production of sunscreens, skin and hair care products, shaving creams, body washes, and moisturizers (Yayayürük 2017).

The mutual PCO and cluster analysis of the distribution of identified polymers with respect to sampling sites and sampling zones are shown in Fig. 3. The results of the PCO show that factors 1 and 2 explain 85.8% of the total variance in the data matrix, where factor 1 explains 54.3% of the total variance, and factor 2 explains 31.4% of the total variance. PCO showed significant correlations between different sampling zones in relation to the polymer distribution ($p < 0.05$). The cluster analysis showed two separate clusters whose mutual similarity and connection is 40%, while within the clusters, individually, it is from 60 to 80%. The first cluster includes sediment samples from the locations Sveta Nedjelja and Žanjice which are connected by a similar presence of the PE as the dominant polymer, followed by AC cop., Unid. poly., and PP. The second cluster includes sediment samples from the locations Ada Bojana, Budva, Herceg Novi, Bijela, Tivat, Orahovac, Dobrota, and Bar and reveals several different types of polymers. Only at the locations of Bijela and Tivat, had PS identified in addition to all other polymers, which is why they are in the subcluster, while Orahovac, Bar, and Dobrota in the subcluster are linked by a similar presence of PA and Unid. poly. in addition to other present being polymers (Fig. 3).

Microplastics were identified at all 10 locations. The average concentrations of MPs in the surface sediments of the Montenegrin coast were in the descending order Bijela > Dobrota > Tivat > Budva > Herceg Novi > Orahovac > Bar > Ada Bojana > Sveta Nedjelja > Žanjice. The overall abundance of MPs at all sampling locations of the Montenegrin coast is shown in Fig. 4.

The abundance of MPs greatly varied with sampling location. The locations characterized by the highest population density, and therefore the greatest anthropogenic influences, the highest concentrations of MPs (Dobrota, Tivat, Bijela, Herceg Novi, and Budva) were recorded. As expected, locations Orahovac, Sveta Nedjelja, and Žanjice, had lower concentrations of MPs, since these locations are not densely populated, except during the summer months when they are tourist hotspots. Lower prevalence of MPs were recorded at Bar and Ada Bojana. This can be explained by the greater scattering of MPs in the areas influenced by the open sea due to greater and stronger actions of currents and waves in comparison to the Bay. Similar observations were made previously by Alomar et al. (2016), Abidli et al. (2018), Korez et al. (2019), Palatinus et al. (2019), and Bošković et al. (2021). Comparing the zones, Boka Kotorska Bay and the coastal part of the open sea, it is concluded that the average

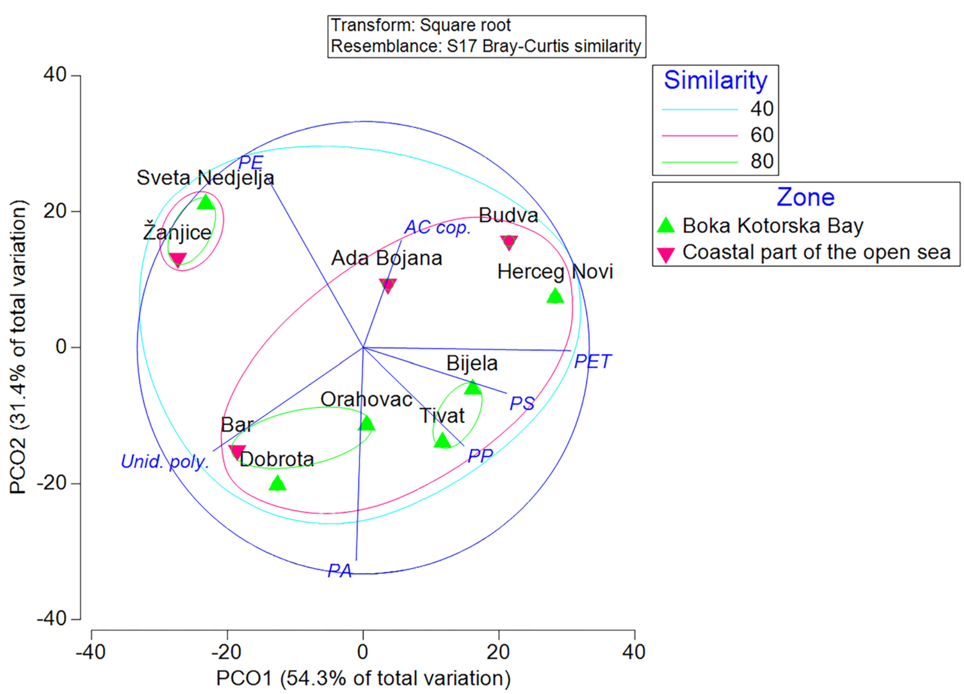

Fig. 3 Graphical representation of the distribution of polymers in the sampled sediments in relation to the locations and sampling zones, PCO + cluster analysis (PRIMER v7 with PERMANOVA+)

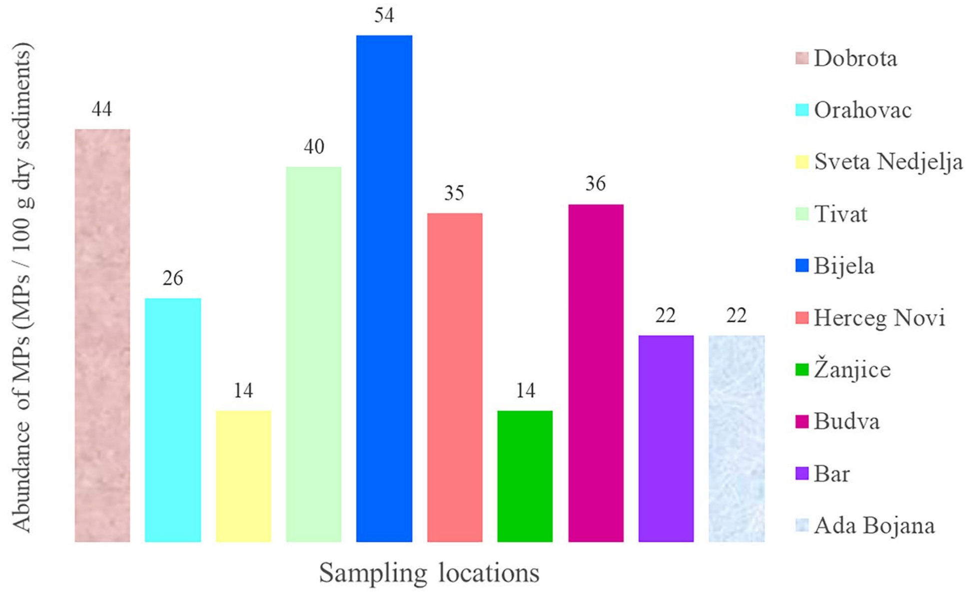

Fig. 4 The abundance of microplastics in surface sediments at 10 sampling locations along the Montenegrin coast

presence of MPs was significantly higher in surface sediments at the locations from the Bay than at the locations on the coastal part of the open sea.

The average number of MPs found in all sediment samples collected in the spring of 2021 was twice as low than that reported for the Montenegrin coast at the same locations during the autumn period of 2019 (Bošković et al. 2021). More precisely, at the locations of Dobrota, Sveta Nedjelja, Herceg Novi, Žanjice, Budva, and Ada Bojana, there were significantly higher concentrations of MPs in the sediment sampled during autumn 2019 compared to sediment sampled in this study (Bošković et al. 2021). It is important to note that in 2019, it was recorded as the best tourist season in Montenegro (Government of Montenegro 2019). The impact of epidemiological measures caused by COVID-19 in 2020 had a noticable effect. During this time, activities such as tourism and fishing lessened. Locations representing port centers such as Tivat, Bijela, and Bar carried out all their usual activities during the pandemic caused by COVID-19. At these locations, higher concentrations of MPs were recorded in this study compared to the study by Bošković et al. (2021). The largest difference in the number of MPs in the sediment from the Montenegrin coast sampled during the autumn period 2019 compared to the spring period 2021 may be a consequence of anthropogenic impact due to increased tourist activity and accumulation of MPs during summer (Claessens et al. 2011; Browne et al. 2011; Abidli et al. 2018). Compared with literature data from the Adriatic and the Mediterranean Sea, the average abundance of MPs found in all sediment samples of this study was lower than that reported for Croatia, Italy, and Spain (Vianello et al. 2013; Alomar et al. 2016; Palatinus et al. 2019; Renzi et al. 2019), and higher than MPs abundance found for sediment samples from Slovenia, Croatia, Italy, and Tunisia (Laglbauer et al. 2014; Blašković et al. 2017; Abidli et al. 2018; Renzi et al. 2018, 2019; Renzi and Blašković 2020). In this study, several factors were observed that can be related to the occurrence and distribution of the MPs contamination in the surface sediments: (1) natural factors, such as plastic properties, meteorological, and hydrodynamic conditions, and (2) anthropogenic factors such as dense populations, tourist, fishing activities, wastewater discharges, solid waste, passenger ships, and harbors. Similar observations were made by Barnes et al. (2009), Browne et al. (2011), Wagner et al. (2014), Abidli et al. (2017), Naji et al. (2017), and Fan et al. (2021).

Microplastics appear in different shape, size, and color. The images of collected MPs in surface sediments from the Montenegrin coast are shown in Fig. 5. The highest proportion of shapes was recorded for filaments (52.8%), followed by fragments (35.5%), films (6.5%), and granules (5.2%) (Fig. 6a). Filaments and fragments were found at all examined locations, while films and granules were identified at five sampling locations (Dobrota, Sveta Nedjelja, Bijela, Žanjice, and Ada Bojana for films, and Dobrota, Žanjice, Budva, Bar, and Ada Bojana for granules). Sediments from Orahovac, Tivat, and Herceg Novi had all four shape types. Filaments accounted for over 50% of the total MPs at seven of the 10 sampling locations. Filaments in surface sediments can originate from a wide range of sources, such as peeling of plastic fishing gear, domestic sewage (laundry wastewater), and the industrial production of fabrics and textiles (Mistri et al. 2018; Fan et al. 2021). Abundance of filaments was similar in sediment samples in this study and at the same locations sampled during 2019 (Bošković et al. 2021). Abundance of fragments and films was twice as high in sediment samples in this study compared to the study conducted in 2019, while the abundance of granules was four times higher in the

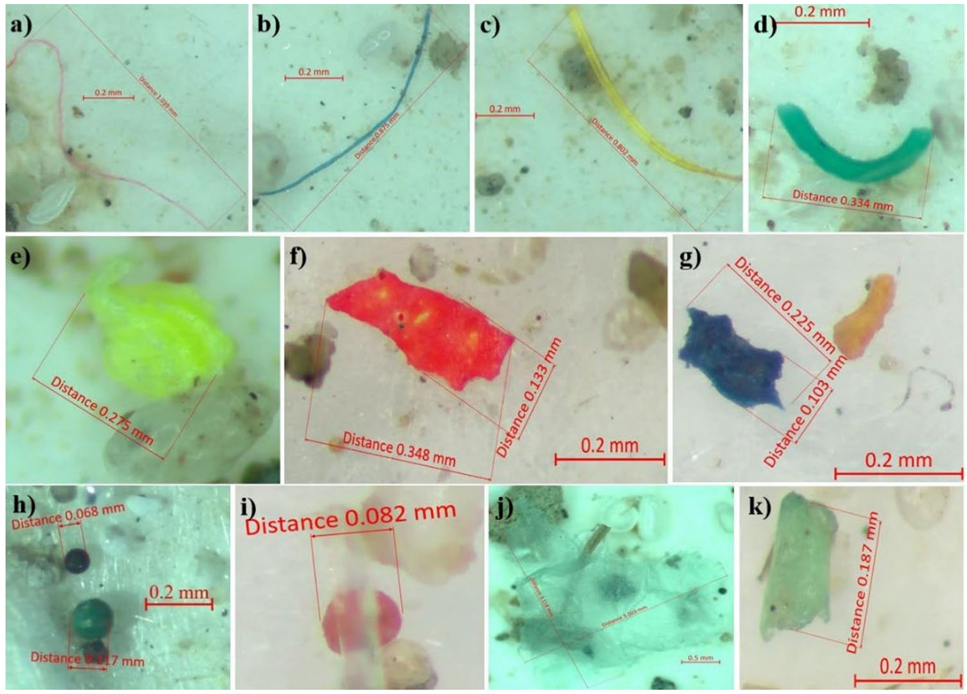

Fig. 5 Images of microplastic particles identified by using an Olympus SZX16 optical microscope: filaments (**a**–**d**), fragments (**e**–**g**), granules (**h**, **i**), and films (**j**, **k**)

study from 2019 compared to this study (Bošković et al. 2021). Statistical significance ($p < 0.05$) was observed between different sampling years (2021 and 2019) and different zones (Boka Kototska Bay and coastal part of the open sea) in relation to the presence of different shape types of MPs (Permanova, Monte Carlo test). Previous studies reported that filaments were the dominant shape type of MPs in sediments (Thompson et al. 2004; Vianello et al. 2013; Blašković et al. 2017; Mistri et al. 2017, 2018; Bošković et al. 2021). The source of fragments is related to the breakdown of larger plastic debris, films mainly originate from the weathering and cracking of packaging/bags or plastic wrappers, while granules could originate from various cosmetic products (Claessens et al. 2011; Abidli et al. 2017, 2018; Fan et al. 2021).

In terms of color, there were clear differences in abundance: blue (37.8%) > red (25.1%) > green (11.1%) > black (10.1%) > yellow (7.8%) > clear (6.14%) (Fig. 6b). The majority of filaments were blue (46.9%), followed by red (16%), black (15.4%), clear (14.8%), yellow (4.94%), and green (1.85%). Fragments were dominated by red (39.4%), blue (33.9%), green (21.1%), yellow (4.6%), and black (0.9%) color. Films by green (40%), yellow (30%), red (20%), black (5%), and clear (5%). Lastly, granules by black (31.3%), yellow (31.3%), red (25%), and blue (12.5%) color.

The size distribution of MPs in the studied samples is presented in Fig. 6c. Microplastics were divided into four size categories: < 0.1 mm, 0.1–0.5 mm, 0.5–1.0 mm, and 1.0–5.0 mm. Small-sized MPs usually have a high abundance because large particles can be split into small ones

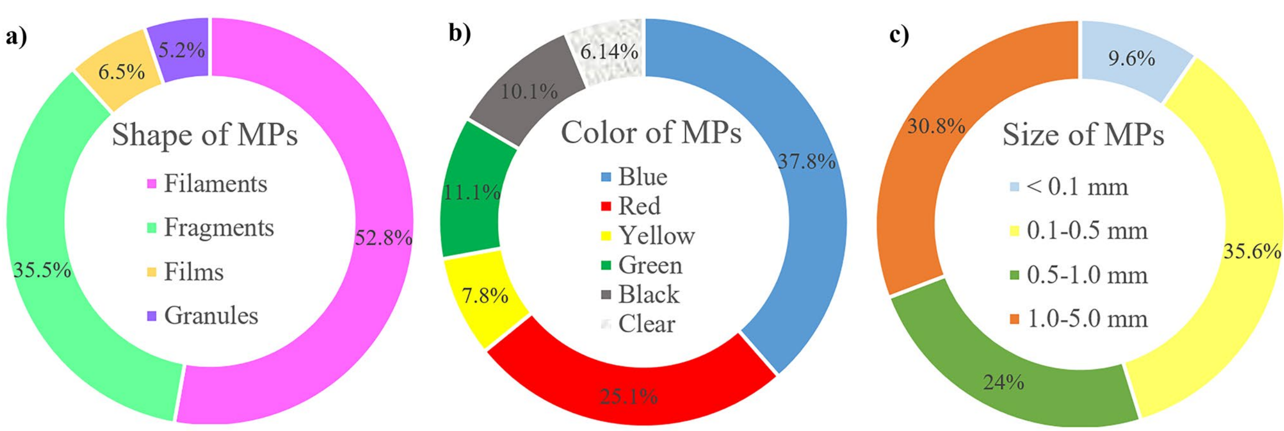

Fig. 6 Distribution of microplastics in surface sediments regarding **a** shape, **b** color, and **c** size at all sampling locations

(Browne et al. 2010; Zhang et al. 2020; Fan et al. 2021). Microplastics in the size category of 0.1–0.5 mm (35.6%) were the most abundant in the sediment samples at all sampling locations, following by sizes 1.0–5.0 mm (30.8%), 0.5–1.0 mm (24%), and < 0.1 mm (9.6%). Differences in the size, shape, and color of MPs could indicate the different origin of the plastics but also the different degrees of accumulation and degradation (Hidalgo-Ruz et al. 2012; Choi et al. 2021).

This study confirms the influence of anthropogenic factors, which is enhanced by tourism. This statement can be approved by the fact that the presence of MPs decreased twice compared to the previous measurement period, during the autumn of 2019, after the best summer tourist season (Bošković et al. 2021). Similarly, Piazzolla et al. (2020) indicated that repeated long-term investigations and seasonal surveys of MPs pollution in sediments give more precise information important for further investigations and monitoring. Additionally, in this study, approximately 30% of MPs particles were analyzed on FT-IR and compared with the study from autumn of 2019, in which 15% of MPs particles were analyzed of the total number of identified MPs (Bošković et al. 2021). Therefore, the results from this study give a more precise insight into the presence of different polymer types in the analyzed sediments and are crucial for undertaking prevention measures to reduce MPs levels in the marine environment. Nevertheless, further studies are needed to better evaluate risks for marine biota associated with MPs pollution.

4 Conclusions

Microplastics were detected in the surface sediments at all sampling locations along the Montenegrin coast. The average abundance of the MPs was 307 ± 133 (SD) MPs/kg of dry sediment. The highest abundance of MPs in surface sediments was detected at the locations in the vicinity of highly populated centers. This result indicates that different human activities might play an important role in MPs pollution around the study area. Additionally, the distribution of MPs depends on meteorological and hydrological factors that can lead to the dispersal or accumulation of MPs in sediments. Filaments and fragments were the dominant shape type of MPs, blue and red were the most common colors, while dominated MPs sizes in all the samples were 0.1–0.5 mm and 0.5–1.0 mm. Eight different polymers were identified in sediments from the examined locations, the most dominant of which were PP, PE, and PET. Polypropylene and PE were present at all sampling locations. In the future, in order to prevent and control plastic pollution, additional studies should be conducted on the analysis of pollution sources as well as on environmental risks arising from the increased presence of MPs in the marine environment.

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Declarations

Conflict of interest The authors declare no competing interests.

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