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

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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.

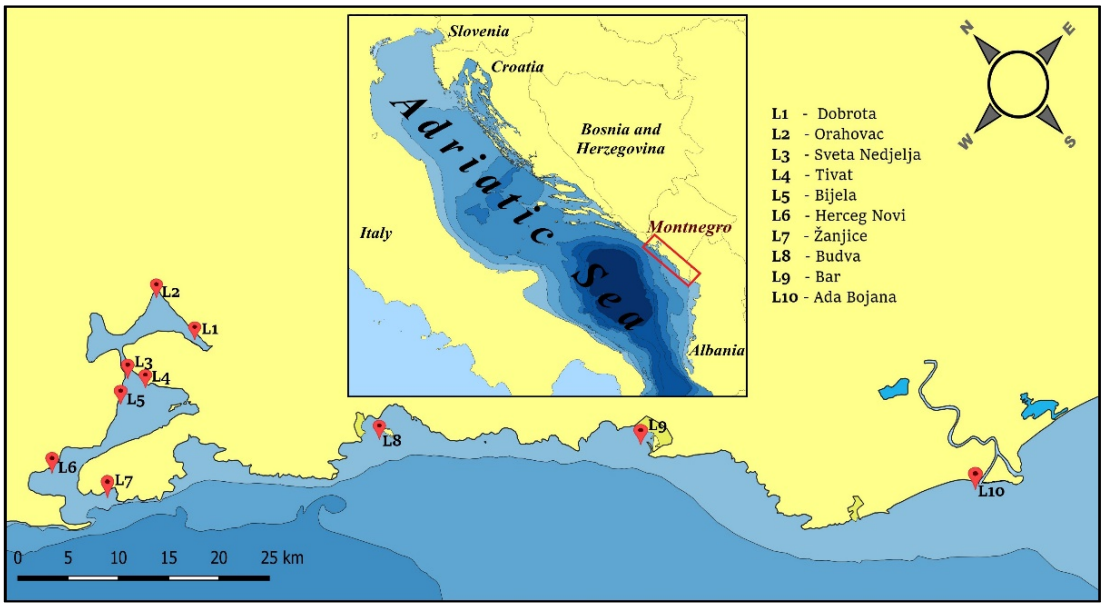

Figure 1. Study area and locations of sampling sites.

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.

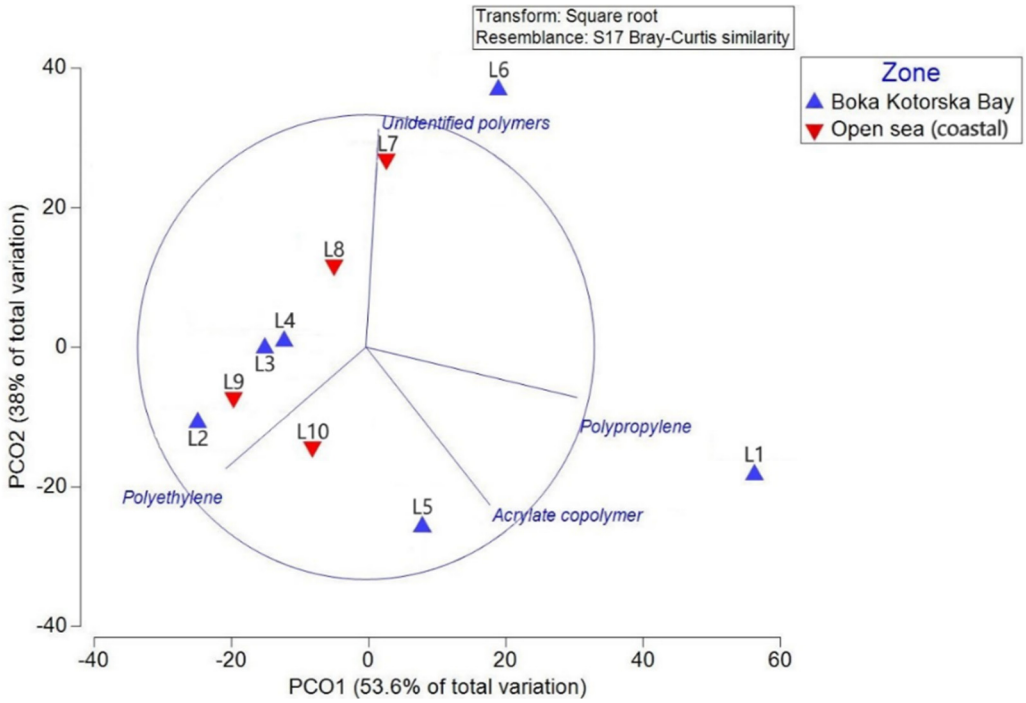

Figure 2. Polymer abundances evaluated at each sampling locations using principal coordinate analysis (PCO).

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

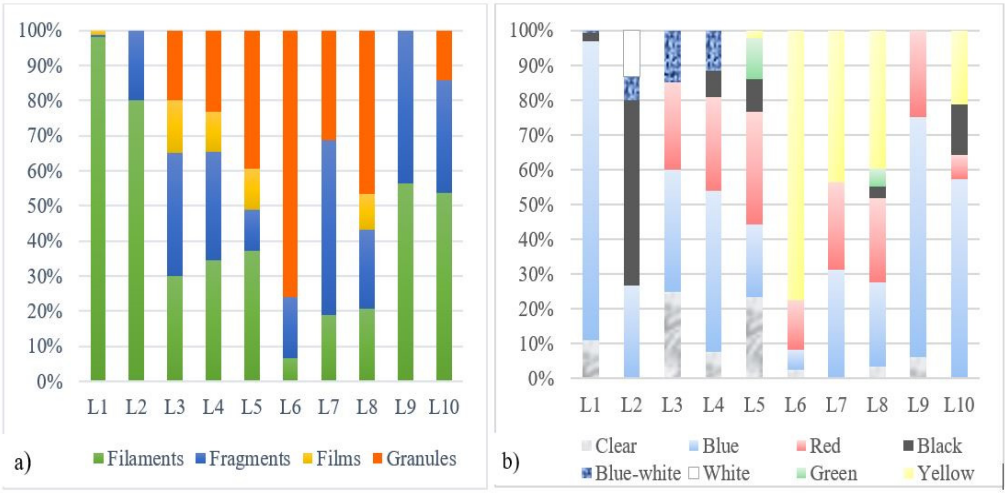

Figure 3. Classification of MPs (in %) according to (**a**) shape type and (**b**) color.

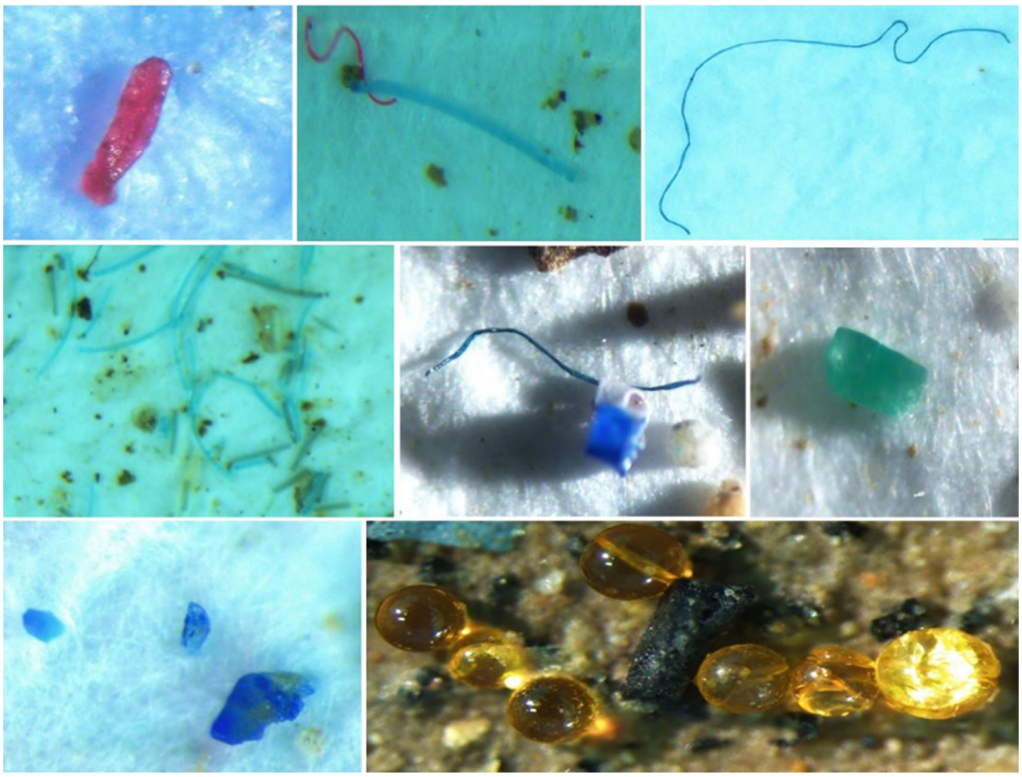

Figure 4. Examples of the collected MPs observed under a microscope. The images were obtained using ImageJ software (version 2.0.0).

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. Blăsković 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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