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ORIGINAL ARTICLE

Assessment of seafloor marine litter along the Montenegrin coast through Fishing for Litter initiatives

Ines Kokić[1*], Ilija Ćetković[1], Ana Pešić[1], Slađana Nikolić[1] and Milica Mandić[1]

[1]*Institute of Marine Biology, University of Montenegro, Kotor, Montenegro*

Abstract: This paper presents an assessment of the amount, composition and spatial distribution of seafloor marine litter in the southern part of the Adriatic Sea (GSA 18). Surveys were performed during a six-year period (2019-2024) from 24 hauls. Sampling was carried out using a bottom trawl during regular fishing activities (Fishing for Litter - FFL). Seafloor marine litter was classified into nine main categories (plastic, metal, rubber, cardboard/paper, textile/natural fibres, glass/ceramics, processed wood, and two categories of unclassified waste) in the laboratory of the Institute of Marine Biology, Kotor. The total average density of collected litter was 260.89 items/km^2. The highest concentration of marine litter was determined in the Boka Kotorska Bay area, near the shoreline, at a depth range of 35-40 metres with an average density of 597.39 items/km^2. The lowest value was recorded in the open part of the Montenegrin coast at depths of between 60 and 120 metres (148.74 items/km^2). The highest concentration of marine litter near the coast is a consequence of increasingly intensive urbanisation, river inflows and the hydrological characteristics of the area. Plastic represents the dominant category in terms of the number of items, followed by metal and textiles/natural fibres. Marine litter related to fishing activities accounted for 3.34 % of the total litter collected on the seafloor.
Keywords: marine litter; bottom trawl; seafloor; pollution; plastic; Adriatic Sea

Sažetak: PROCJENA MORSKOG OTPADA NA MORSKOM DNU DUŽ CRNOGORSKE OBALE KROZ INICIJATIVE FISHING FOR LITTER. Ovaj rad predstavlja procjenu količine, sastava i prostorne raspodjele morskog otpada na morskom dnu u južnom dijelu Jadranskog mora (GSA 18). Istraživanja su obavljena tijekom šestogodišnjeg razdoblja (2019.-2024.) na podacima prikupljenim iz 24 koćarska potega. Uzorkovanje je obavljeno pridnenom koćom tijekom redovitih ribolovnih aktivnosti (Fishing for Litter - FFL). Otpad s morskog dna razvrstan je u devet osnovnih kategorija (plastika, metal, guma, karton/papir, tekstil/prirodna vlakna, staklo/keramika, prerađeno drvo i dvije kategorije nerazvrstanog otpada) u laboratoriju Instituta za biologiju mora u Kotoru. Ukupna prosječna količina sakupljenog otpada iznosila je 260,89 komada/km^2. Najveća količina morskog otpada utvrđena je u području Boke Kotorske, u blizini obale, na dubini od 35-40 metara s prosječnom gustoćom od 597,39 komada/km^2. Najniža vrijednost zabilježena je na otvorenom dijelu Crnogorskog primorja na dubinama od 60 do 120 metara (148,74 komada/km^2). Najveća koncentracija morskog otpada uz obalu posljedica je sve intenzivnije urbanizacije, riječnih dotoka i hidroloških karakteristika područja. Plastika predstavlja dominantnu kategoriju po broju komada, a slijede je metal i tekstil/prirodna vlakna. Morski otpad povezan s ribolovnim aktivnostima činio je 3,34 % ukupnog otpada sakupljenog na morskom dnu.
Ključne riječi: morski otpad; pridnena koća; morsko dno; onečišćenje; plastika; Jadransko more

INTRODUCTION

Marine litter greatly affects not only the lives of marine organisms, but also those of humans. It can be found in all segments of the marine environment: on beaches, on the sea surface, in the water column, on the seabed, as well as on/in the marine organisms themselves (Palatinus *et al*., 2019; Renzi *et al*., 2019). Once on the seafloor, marine litter (e.g., fishing nets, bags and plastic sheets) can smother and abrade the substratum and cause hypoxia in sediments and in benthic organisms (Mordecai *et al*., 2011; Consoli *et al*., 2018). Abandoned fishing gear negatively affects sedentary benthic organisms and bottom-dwelling fish species, and causes irreparable damage to rare communities such as corals (Bo *et al*., 2014; Angiolillo *et al*., 2015; Consoli *et al*., 2018; Gvozdenović *et al*., 2021).

Compared to litter located on the sea surface and beaches, the assessment of the amount, composition, distribution, and accumulation of marine litter on the seafloor has been investigated less, mainly due to sampling difficulties and associated costs (Galgani, 2015; Schneider *et al*., 2018; Schwarz *et al*., 2019; Strafella *et al*., 2019). The origin of the marine litter found in the sea can be divided into two groups: land-based and sea-based. Sea-based sources of marine litter are landfills and waste on beaches and coastal areas (tourism), rivers and floodwaters, industrial wastewater, discharge from storm drains and untreated municipal sewage (UNEP, 2009). According to STAP (2011) and Crocetta *et al*. (2020), approximately 80% of marine litter originates from land-based sources, with the remaining 20% attributed to sea-based activities such as transport, navigation, and fishing. Marine litter originating from the sea

**Corresponding author:* ines@ucg.ac.me
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includes: transport of cargo and passengers, recreational navigation, military navigation, facilities for fishing and aquaculture, the energy industry, as well as legal and illegal dumping (Čulin and Bielić, 2016).

Large amounts of litter, including an estimated eight million tonnes of plastic from the land alone (Jambeck *et al*., 2015), enter the oceans each year. The amount of plastic coming from the mainland on an annual basis is growing at an accelerated pace, as pointed out by Borrelle *et al*. (2020), whose results reported an increase in plastic litter up to 19-23 million tonnes for all aquatic ecosystems in 2016. Global annual waste production continues to grow and is predicted to double from the 2 billion tonnes recorded in 2016 to around 3.4 billion tonnes in the next 30 years (Kaza *et al*., 2018).

The type and amount of marine litter vary significantly across different marine regions due to varying hydrodynamic, geomorphological, and anthropogenic factors. Enclosed seas, such as the Mediterranean Sea, are recognized as some of the most affected areas in the world (Cózar *et al*., 2015; UNEP/MAP, 2015; Suaria *et al*., 2016). The spatial distribution and accumulation of litter in the ocean are influenced by hydrography, geomorphological factors (Galgani *et al*., 2000; Barnes *et al*., 2009), prevailing winds, waves, tides, sea currents, and human activities (Ramirez-Llodra *et al*., 2013; UNEP, 2021). Marine litter tends to accumulate in areas under high anthropogenic pressure, such as cities, tourism hotspots, and shipping routes. The distribution of litter is also influenced by water depth (Gerigny *et al*., 2019). The Mediterranean Sea is strongly impacted by marine litter (Galgani *et al*., 2013) and is considered one of the most severely affected basins in Europe (Garcia-Rivera *et al*., 2017). This litter originates mainly from land-based sources such as tourism, recreational activities, poor waste management practices, discharges of untreated municipal waste, and industrial outfalls (Galgani *et al*., 2013). Rivers are a significant pathway through which a considerable amount of marine litter enters the coastal and marine environment. Additionally, sea-based activities such as maritime transport, fisheries, and aquaculture contribute to litter inputs, particularly through the direct discharge of waste and abandoned, lost, or otherwise discarded fishing gear (ALDFG) (Ziveri *et al*., 2023).

The Adriatic Sea is a semi-enclosed basin with poor seawater circulation and long water retention, making it vulnerable and very sensitive to persistent pollution, especially when it comes to plastic waste (Williams and Tudor, 2011). The Adriatic-Ionian macro-region has numerous potential waste sources (Vlachogianni *et al*., 2017), making marine solid waste pollution a growing environmental problem in the Adriatic Sea (Pasquini *et al*., 2016; Melli *et al*., 2017; Arcangeli *et al*., 2018; Zeri *et al*., 2018). It is estimated that 40% of waste enters the Adriatic Sea *via* rivers, 40% *via* coastal urban populations, and 20% *via* shipping and fishing activities (Liubartseva *et al*., 2016). It is also estimated that 70% of the litter that enters the sea ends up on the seafloor (UNEP, 2005; OSPAR, 2014; Faussone *et al*., 2021). However, marine litter on the seafloor is the least researched fraction, as most of the litter lies in deep-sea areas. Although marine litter is recognized as a major threat to the oceans, monitoring frameworks are still being developed (Canals *et al*., 2021). There are different methods of estimating litter on the seafloor: ROVs (remotely operated vehicles) (Angiolillo *et al*., 2015; Melli *et al*., 2017), trawling (Strafella *et al*., 2015; Pasquini *et al*., 2016; Fortibuoni *et al*., 2019; Strafella *et al*., 2019) and scuba diving (Mačić *et al*., 2017; Vlachogianni *et al*., 2018; Gvozdenović *et al*., 2021), with trawling being one of the most common and widely used methods. Trawling is mainly used in the area of deep waters with a soft bottom, and is not allowed in shallow waters.

The aim of this work is to provide information on the composition, weight and spatial distribution of marine litter from the seafloor along the Montenegrin coast during a six-year period. Furthermore, the present study provides baseline information on seafloor marine litter for future spatio-temporal comparisons.

MATERIAL AND METHODS

Study area

The study area was located along the Montenegrin coast, which belongs to the geographical sub-area GSA 18 - southern Adriatic (according to the classification established by the Food and Agriculture Organization of the United Nations - FAO). The southern Adriatic is characterised by the presence of the deep South Adriatic Pit, a depression approximately 1,200 metres deep, which is delimited by the sill of the Otranto Strait to the south (Fortibuoni *et al*., 2019). Montenegro has 293 km of coastline along the Adriatic Sea, while its waters extend up to 12 nautical miles from the coast, covering an area of about 2,500 km^2, with a maximum depth of 1,233 metres. The width of the continental shelf (up to 200 metres deep) varies along the coast of Montenegro, extending from 9.5 nautical miles at the entrance to the Boka Kotorska Bay to 34 nautical miles at the mouth of the River Buna-Bojana (UNEP/MAP-PAP/RAC and MESPU, 2021). The River Buna-Bojana is the main river in Montenegro in terms of water discharge (Fortibuoni *et al*., 2019). It originates from the confluence of the Drin River and Lake Skadar's outflow, and has a substantial annual discharge. Before the construction of dams on the Drin River, the average annual discharge at the delta was about 680 m^3/s. The river's flow typically peaks in the spring, especially in April and May, due to snowmelt from nearby mountains and increased rainfall. However, the exact discharge levels can vary each year depending on climatic factors (Petković and Sekulić, 2019).

There are two main coastal entities along the Montenegrin coast: the open sea and the Boka Kotorska Bay. The main type of sediment in the open part of the sea is clay, silt and sand (Del Bianco *et al*., 2014), while the bottom type of the Boka Kotorska Bay is characterised by silt and sand, except for a narrow area along the shoreline.

Bottom-trawl surveys

Seafloor marine litter was collected by bottom trawling during usual fishing activities in the period from May 2019 to February 2024. Monitoring was carried out in line with the methodology provided in Decision IG.22/10 Implementing the Marine Litter Regional Plan in the Mediterranean (Fishing for Litter Guidelines) (UNEP(DEPI)/MED IG.22/28, 2016) with the aim of intensifying the activity of Fishing for Litter practice with the help of professional fishermen. Although according to the protocol, it is necessary to have more intensive sampling dynamics, due to the inability of fishermen to collect litter more regularly (lack of manpower and space on board), the analyses were done during two seasons of each year, covering the periods spring-summer and autumn-winter.

Trawl surveys were performed along 24 hauls (transects) (Figs. 1 and 2; Table 1) at depths from 35 to 120 metres, on sandy/silty/muddy bottoms. The mean length of the vessels was 14.21 ± 3.1 metres. The mean length of the hauls was 13.7 ± 7 km, and the mean towing time was 169.8 ± 84.2 minutes at a mean towing speed of 4.8 ± 0.43 km/h.

The collected marine litter was classified according to the type of material into nine main categories: plastic, rubber, metal, glass/ceramic, textile/natural fibres, processed wood, paper and cardboard, other waste, and non-specific waste. After that, a detailed sub-categorisation of the marine litter was made within the mentioned main groups. Marine litter categorisation was done based on the MED POL protocol (MED POL Survey Form for seafloor marine litter) (UNEP/MAP MEDPOL, 2014). Each litter item > 2.5 cm was counted and weighed (wet weight).

The marine litter density was expressed as the number of items per square km (N/km²), as well as the weight per square km (kg/km²), based on the "swept" methodology. The swept area (a) was estimated according to Sparre and Venema (1998):

$$a = D \times h \times X,$$

$$D = V \times t$$

where D is haul length, V is velocity of the vessel during trawling, t is time spent trawling, h is length of the head-rope, and X is 0.5 as suggested by Pauly (1980).

Statistical analysis

The marine litter quantity and composition were compared between the two main areas – the open sea and Boka Kotorska Bay. Non-parametric Kruskal-Wallis followed by *post-hoc* Mann-Whitney test were used to determine the differences (significant if $p < 0.05$) in ma-

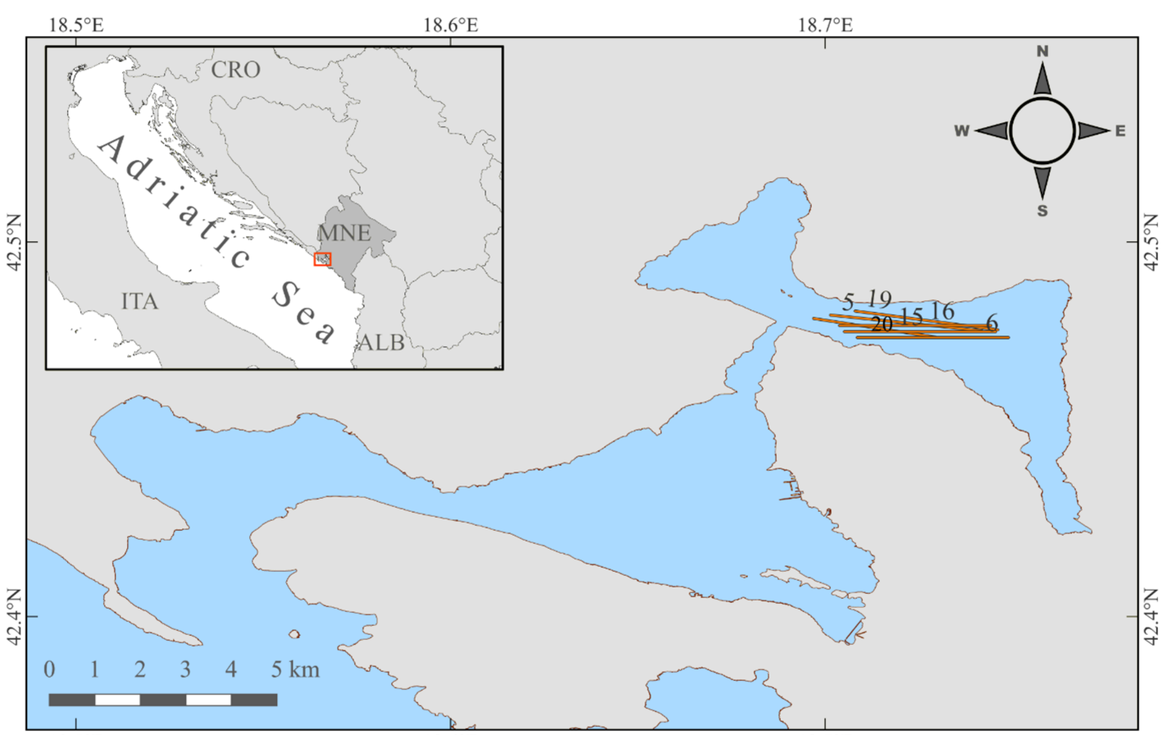

Fig. 1. Map of the study sites (transects) where trawl surveys were performed in the Boka Kotorska Bay (Adriatic Sea) (see Table 1 for details).

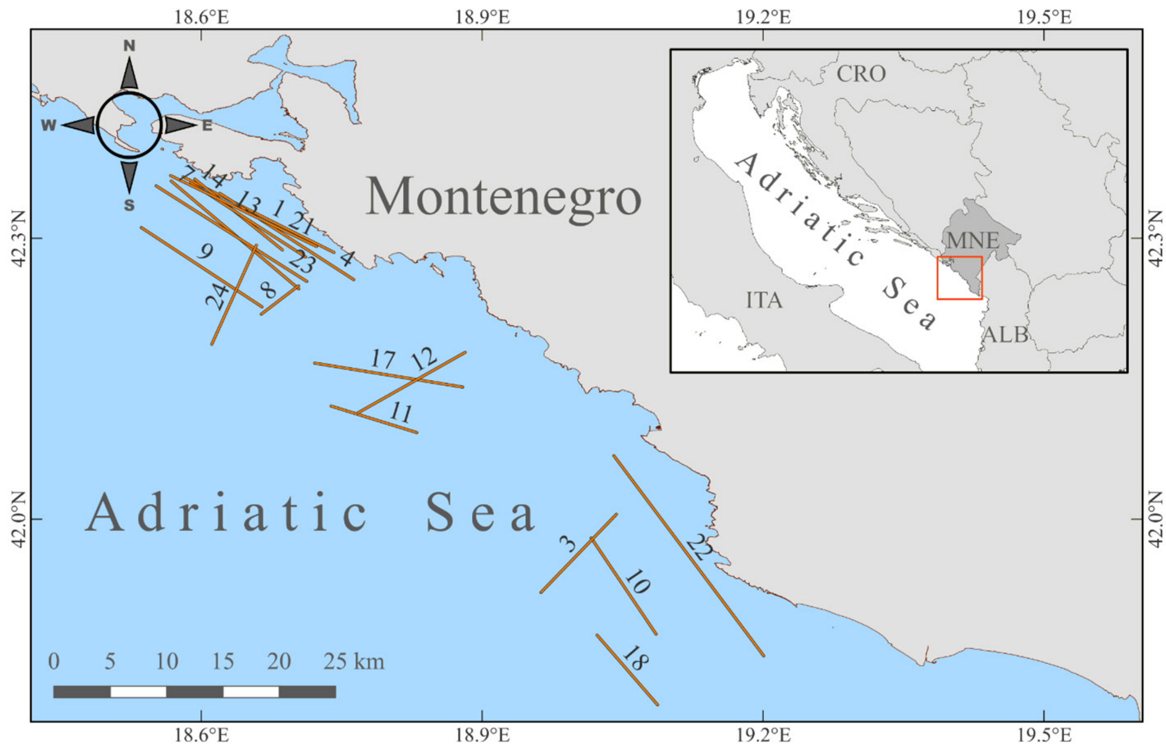

Fig. 2. Map of the study sites (transects) where trawl surveys were performed along the open sea of Montenegro (Adriatic Sea) (see Table 1 for details).

rine litter density between the areas, transects, and years of sampling. Non-parametric ANOSIM (using PAST software) based on the Bray-Curtis dissimilarity index (9,999 permutations) was used to analyse differences in the marine litter composition between the areas and transects, where an R-value of 1 indicates that the marine litter composition differs across areas/transects, while a value close to 0 indicates that the composition of marine litter at different areas/transects is identical. R toolbox SIMPER was applied to identify the most abundant litter categories that contribute to similarities/differences between areas.

RESULTS

In the period from May 2019 to February 2024, a total of 903 items of marine litter with a total weight of 176.48 kg were collected from 24 transects in an area of 5.53 square kilometres. The number of items per transect ranged from 7 to 197, while the weight of marine litter ranged from 0.07 to 30.82 kg. The average marine litter density was 260.89 items/km^2, the highest density of 1,308.23 items/km^2 was recorded in the Boka Kotorska Bay, while the lowest density of 24.29 items/km^2 was recorded in the area of the open sea.

A mean weight of 210.39 kg/km^2 was recorded in the area of the Boka Kotorska Bay (30-40 m depth), while for transects in the open sea (60-120 m) a mean weight of 22.77 kg/km^2 was recorded. The average value of items per square kilometer for the Boka Kotorska Bay was 597.38 items/km^2, and for the open-sea transects was 148.73 items/km^2.

Based on the overall results, in terms of the number of items, plastic litter was dominant, accounting for 81.95% of the total marine litter, followed by metal with 6.98% and textiles/natural fibres with 6.42%. Plastic constituted the largest portion of marine litter by weight (40.92%), followed by unclassified waste (objects that are difficult to classify into one specific category because of their complex composition) (20.59%) and metal (12.39%) (Fig. 3). On the investigated transects, almost all marine litter subcategories were represented (22 out of 27).

The top 10 most numerous litter items accounted for 91.36% of the total litter. Among plastic items, plastic bags were the most common (29.01%), followed by plastic bottles (19.71%).

The obtained results showed that the higher density of marine litter in the Boka Kotorska Bay, compared to the open sea, is statistically significant ($z = 3.23$, $p < 0.05$), while no significant difference in litter density between the transects was shown ($KW\text{-}H(22;24) = 23$, $p > 0.05$). The SIMPER analysis identified the main marine litter categories that contribute to the differences between sampling areas (Table 2). Plastic (66.79%) and metal (12.92%) (Table 2) contribute the most to the diversity of the areas. Plastic (71.27%) and metal (10.76%) are also the most responsible for the difference between

Table 1. Geographical coordinates and estimated swept area of the analysed transects.

Area	Transect		Start coordinates	End coordinates	Swept area (km^2)
Platamuni	1	N	42.365577	42.284708	0.3970
		E	18.58049	18.741767	
Platamuni	2	N	42.38148	42.28433	0.2836
		E	18.56265	18.73723	
Bar	3	N	42.00516	41.92158	0.1667
		E	19.04343	18.96277	
Platamuni	4	N	42.347944	42.255722	0.3334
		E	18.619783	18.762778	
Boka Kotorska Bay	5	N	42.480117	42.475933	0.0405
		E	18.70065	18.74105	
Boka Kotorska Bay	6	N	42.475933	42.475933	0.0405
		E	18.74105	18.70065	
Platamuni	7	N	42.361039	42.245794	0.3704
		E	18.567828	18.704108	
Platamuni	8	N	42.249156	43222.856	0.3704
		E	18.703744	18.671869	
Platamuni	9	N	42.311281	42.226596	0.2836
		E	18.535961	18.664899	
Bar-Ulcinj	10	N	41.979883	41.877044	0.2836
		E	19.016363	19.085722	
Budva-Bar	11	N	42.092341	42.120683	0.3241
		E	18.830202	18.738566	
Budva-Bar	12	N	42.11325	42.178066	0.3241
		E	18.766983	18.881816	
Platamuni	13	N	42.359149	42.279910	0.2431
		E	18.588866	18.711395	
Platamuni	14	N	42.287340	42.363199	0.2633
		E	18.686704	18.592877	
Boka Kotorska Bay	15	N	42.475933	42.480117	0.0338
		E	18.74105	18.70065	
Boka Kotorska Bay	16	N	42.475933	42.475933	0.0438
		E	18.74105	18.70065	
Budva	17	N	42.166542	42.140972	0.2836
		E	18.721044	18.879192	
Bar	18	N	41.801522	41.875967	0.1733
		E	19.087308	19.022664	
Boka Kotorska Bay	19	N	42.48071	42.475700	0.0540
		E	18.705865	18.743955	
Boka Kotorska Bay	20	N	42.475703	42.480687	0.0473
		E	18.735233	18.702667	
Platamuni	21	N	42.291186	42.366936	0.3241
		E	18.722978	18.567061	
Bar-Ulcinj	22	N	41.853809	42.067619	0.1200
		E	19.200675	19.040614	
Platamuni	23	N	42.253805	42.355904	0.3630
		E	18.712617	18.551692	
Platamuni	24	N	42.292558	42.186685	0.3630
		E	18.658800	18.611135	

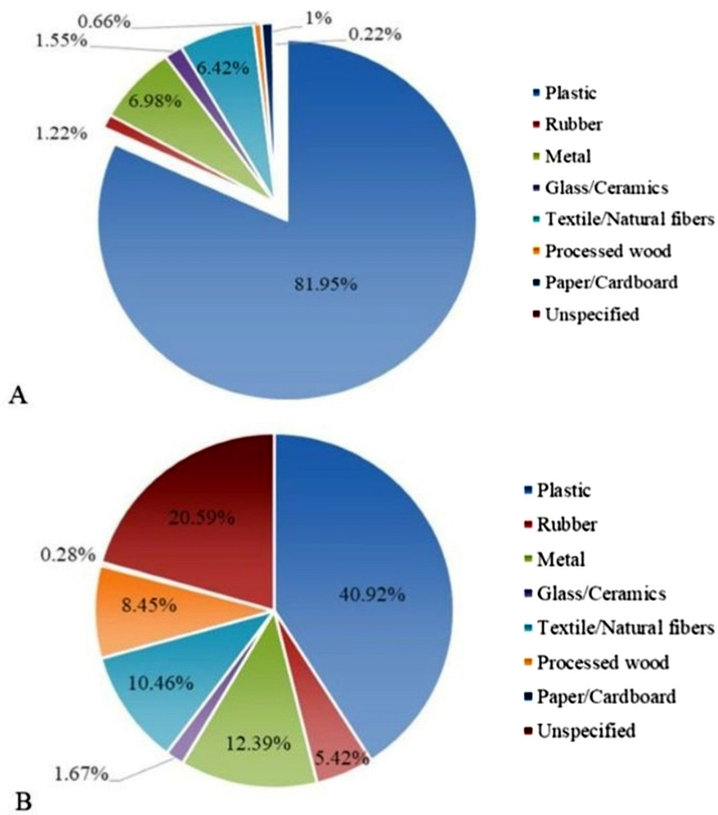

Fig. 3. Percentage composition of litter categories by number **(A)** and weight **(B).**

transects (Table 2). Changes in the amount of litter (KW-H = 3.52, $p > 0.05$) and the number of different categories ($p > 0.05$) over the years do not show a statistically significant difference during the studied period.

Thirty-one items of recorded marine litter were related to fishing and aquaculture activities, which make up 3.43% of the total amount of marine litter. The mentioned subcategory was more present in the open sea (26 items), compared to the Boka Kotorska Bay (16 items in total).

DISCUSSION

The Mediterranean Sea is strongly impacted by marine litter (Galgani *et al*., 2013) and is considered probably the most affected basin in Europe (García-Rivera *et al*., 2017). The amount and distribution of marine litter can vary greatly depending on the area, being initially driven by human activities and later influenced by biological (e.g., biofouling) and physical (e.g., hydrodynamics, geomorphology) drivers (Moriarty *et al*., 2016). Bottom-trawl surveys provide an excellent tool for surveying large areas of the seafloor efficiently, in a short time and at a lower cost. Most of the existing information on litter on the seafloor in the Mediterranean basin has been obtained using soft-bottom trawls, although new methodologies such as the use of remotely operated vehicles (ROVs) have proven to be very effective for these purposes (Consoli *et al*., 2018).

We found a large amount of marine litter along the transects located in the Boka Kotorska Bay, which was expected, considering that the bay is characterised by densely populated coasts and a weak exchange of water masses. Even in earlier research works, the area of the Boka Kotorska Bay was recognised as an area where the accumulation of marine litter is larger than in the open sea (see Mačić *et al*., 2017; Krstulović, 2020). A larger amount of marine litter is also recorded in the Gulf of Venice, as well as in similar bays, due to their location, proximity to the coasts, reduced movement of water masses and large sediment accumulation (Ioakeimidis *et al*., 2014; Liubartseva *et al*., 2016).

The relatively low amount of seafloor marine litter in the open part of the Montenegrin coast can be explained by water circulation patterns. Water mass movement in the Adriatic Sea is primarily influenced by geomorphological, meteorological, and hydrographic factors. These include the shape of the coastline, weather patterns (such as wind and temperature changes), and variations in seawater temperature, salinity, and density. The surface layer circulation in the Adriatic is predominantly cyclonic, meaning it flows counter-clockwise. Water enters the basin along the eastern coast, moving northwestward, and exits along the western coast, moving

Table 2. Litter categories contributing to similarity between areas (open sea and Boka Kotorska Bay) and transects.

Litter category	Contribution (%)	
	Area	Transects
Plastic	66.79	71.27
Metal	12.92	10.76
Textile/natural fibres	8.08	7.87
Glass/ceramics	4.30	3.33
Rubber	3.63	2.90
Paper/cardboard	2.12	1.72
Processed wood	1.45	1.50
Unspecified	0.67	0.53

northeastward. This movement is driven by a combination of factors, shaping the distinctive circulation patterns of the Adriatic. In addition to the general cyclonic circulation, the Adriatic also hosts several gyres, with the most prominent being the southern Adriatic cyclonic gyre. These currents and gyres significantly impact the overall water movement in the region.

Research by Carlson *et al*. (2017) and Liubartseva *et al*. (2016) has provided valuable insights into the movement and accumulation of marine debris in the Adriatic Sea. Marine debris in this region is primarily influenced by the cyclonic surface circulation, which transports debris along the surface of the sea. The debris may either accumulate on the southwest coast, exit the Adriatic, or get trapped in the southern gyre, where it may recirculate. This cyclical movement highlights the important role of sea currents in transporting and redistributing marine litter within the region (Carlson *et al*., 2017).

Liubartseva *et al*. (2016) further expand on this by noting that the Adriatic Sea is a highly dissipative basin. This means that the physical characteristics of the sea, such as its water depth and coastline shape, cause debris to be deposited along the shore. The geomorphology of the shoreline, including the shape of the coast, wave action, and currents, leads to the accumulation and concentration of plastic litter on the beaches. In this sense, the Adriatic's shoreline acts as the "main sink" for plastic pollution, serving as the primary location where debris ultimately settles. These findings underscore the combined influence of oceanographic factors (like circulation patterns and gyres) and coastal morphology in determining where and how marine litter accumulates in the Adriatic Sea.

Interestingly, the relatively small amount of marine litter recorded in this study can be linked to the specific circulation patterns of the Adriatic. The dynamics of the cyclonic gyres and currents may limit the movement of debris in certain areas, leading to lower accumulation or dispersal of litter in some regions. The winter and spring periods, characterized by higher precipitation and increased river outflow, especially from the Buna-Bojana watershed (Marini *et al*., 2010), also play a role. In addition, the long period of strong southern winds contributes to the increased accumulation of transboundary litter washed onto the southern shores or sinking in front of them. This suggests that the circulation patterns may either direct marine litter away from the studied area or prevent significant accumulation in that specific location.

The overall mean value of marine litter density on the investigated transects was 260.89 items/km^2. Compared to other studies carried out in the Mediterranean Sea (Ioakeimidis *et al*., 2014; Alvito *et al*., 2018; Crocetta *et al*., 2020), the density of litter records similar values, e.g., the Aegean Sea (416-1,211 items/km^2) (Ioakeimidis *et al*., 2014); the Black Sea (291 ± 237 items/km^2) (Ioakeimidis *et al*., 2014); the Tyrrhenian Sea (299.2 items/km^2) (Crocetta *et al*., 2020). However, higher mean values of marine litter density compared to our results have been recorded in the northern Adriatic-Croatia (679 items/km^2) (Fortibuoni *et al*., 2019), the Ionian Sea-Greece (847 items/km^2) (Fortibuoni *et al*., 2019), then the northern and central Adriatic (913 items/km^2) (Pasquini *et al*., 2016). Fortibuoni *et al*. (2019) discovered that Slovenia and Montenegro belong to cleaner areas compared to the other countries of the Adriatic-Ionian region, with an average density of 200 items/km^2 recorded along the Montenegrin coast.

Plastic litter was recognized as a major environmental issue in the late 1980s due to its dominance as a category of marine litter and its persistence in the environment (Derraik, 2002; Barnes *et al*., 2009; Avio *et al*., 2017). Plastics can be extremely harmful to the marine ecosystem, serving as a potential source of toxic chemicals such as PCBs and dioxins (Engler, 2012). In recent years, microplastics have become a significant concern due to their widespread presence and their tendency to be easily ingested by marine organisms, eventually reaching humans through the trophic chain (Andrady, 2011). The dominance of plastics (Galgani, 2015) is not surprising, given its widespread use and poor degradability (Katsanevakis and Katsarou, 2004; Fortibuoni *et al*., 2019).

Our study found that plastics was the most abundant category of marine litter, accounting for 65.33% of the total. These results are consistent with earlier research on seafloor marine litter in the Boka Kotorska Bay and the open part of the Montenegrin coast (Mačić *et al*., 2017; Krstulović, 2020; Gvozdenović *et al*., 2021). Gvozdenović *et al*. (2021) reported plastics as the dominant category of seafloor marine litter, with a percentage of 46.91%. The dominance of plastics in seafloor marine litter is also noted by Mačić *et al*. (2017), who found an unusually high percentage of rubber and metal litter.

The composition of seafloor marine litter in the open sea also shows dominance of plastics, with a percentage share of 85.25%, slightly higher than the previously published value of 79% (Mačić *et al*., 2017). The dominance of plastic is not limited to the southern Adriatic; it is also found throughout the Mediterranean Sea (Mifsud *et al*., 2013; Pasquini *et al*., 2016; Fortibuoni *et al*., 2019; Spedicato *et al*., 2019; Strafella *et al*., 2019; Alomar *et al*., 2020). Strafella *et al*. (2015, 2019) found plastic litter to be the most abundant category in the North and Central Adriatic Sea, followed by metal. Similarly, Pasanisi *et al*. (2023), in their research in the Chioggia and Civitanova Marche ports (Adriatic Sea), reported plastic litter as the dominant category, followed by metal and rubber. The presence of metal and rubber categories can be related to our findings of their high percentage in the Boka Kotorska Bay.

A similar pattern of plastics dominance, followed by metal and cloth/textile, was observed by Stagličić *et al*. (2021) in the Central Adriatic Sea, which aligns with our results for the open sea. Fortibuoni *et al*. (2019) stated that single-use plastics, especially bags, represent the most numerous subcategory in the area of Montenegro, which is consistent with our findings. We also observed that plastic bottles made a significant contribution (see Fig. 3). The prevalence of plastic bags in the Boka Kotorska Bay (Sopot and Dražin vrt) was also noted by Gvozdenović *et al*. (2021). The dominance of plastic bottles and bags has also been recorded in the central and northern Adriatic (Pasquini *et al*., 2016; Fortibuoni *et al*., 2019; Strafella *et al*., 2019; Pasanisi *et al*., 2023). Additionally, the dominance of these subcategories is not confined to the Adriatic Sea but has also been recorded in the central Mediterranean Sea around the island of Malta (Mifsud *et al*., 2013).

No significant statistical difference in the change in litter quantity was observed during the study period, although a significant decreasing trend was found specifically for the “plastic” litter category. In contrast to our results, Strafella *et al*. (2019) recorded a change in the average values of total litter in the central and northern Adriatic area, with a significant decreasing trend observed in the “other” litter category.

The anthropogenic (human-caused) influence on marine litter in the Montenegrin Sea is significant, resulting from a variety of activities that contribute to litter accumulation in the marine environment. These influences primarily stem from tourism, shipping, fishing, and land-based pollution. A large proportion of plastic items, such as bags, bottles, and other plastics, can be attributed to poor waste management practices, tourism, and recreational activities. In particular, Boka Kotorska Bay, which attracts a high number of visitors, especially during the summer months, faces an increased risk of marine litter generation. Common items include food wrappers, plastic bottles, and other single-use plastics. Additionally, shipping and maritime traffic during the summer months contribute significantly to marine litter, with single-use plastics being a major component. Similarly to findings reported in other European waters (Galgani *et al*., 2000; Katsanevakis and Katsarou, 2004; Strafella *et al*., 2015, 2019), the highest density of litter was found near the coast rather than offshore. This can be attributed to high urbanization and the numerous human activities that take place in coastal areas.

Land-based activities have historically been a major source of litter. Various materials have been illegally dumped along the coast, particularly near roads, and later discarded into the sea by irresponsible individuals. Due to inadequate recycling systems and the slow breakdown of certain materials, items like plastic, glass (such as bottles), and rubber (like tires) have led to their accumulation on the seafloor. Furthermore, the absence of public awareness and the lack of strict penalties for improper waste disposal have exacerbated the marine litter issue (Mačić *et al*., 2017). According to Mačić *et al*. (2017), plastic and metal debris, such as bottles and cans, are commonly found in areas where tourist facilities or settlements are located along the coast. The dominance of plastic bottles, glass bottles, and beverage containers has also been reported in the central-eastern Adriatic Sea (Stagličić *et al*., 2021), while along the Italian and eastern Adriatic coast, plastic bottles are found to be in the top three (Vlachogianni *et al*., 2017). For the area of Bay, Gvozdenović *et al*. (2021) also emphasize the dominance of the aforementioned categories. The category of textile is typically found near tourist complexes and settlements, but a certain percentage of it can also reach the open sea through river inputs (Mačić *et al*., 2017).

Fishing has a long-standing tradition along the Montenegrin coast, both commercially and recreationally. However, fishing activities also contribute to marine litter, mainly due to illegal or abandoned fishing gear. In the study area, litter was represented mostly by fishing nets and other synthetic fishing related items. Earlier studies along the Montenegrin coast reported similar results (Vlachogianni *et al*., 2017, 2018). Fisheries-related litter was present in greater quantities along the open-sea transects compared to the Boka Kotorska Bay. However, in earlier studies, a higher percentage of fisheries-related litter and aquaculture-related litter was recorded in the Boka Kotorska Bay (Mačić *et al*., 2017). Numerous studies have linked the appearance of fishing tools (nets, buoys, lines) to losses incurred due to bad weather conditions (Melli *et al*., 2017), however the presence of many net fragments may suggest that these nets were abandoned during collection and cleaning at sea and were not lost due to bad weather conditions, as was previously thought (Pasanisi *et al*., 2023). Pieces of fishing nets and ropes often arise when parts of damaged nets are cut out of the net and thrown into the sea (intentionally or accidentally) during maintenance and repair work on fishing gear (Pasanisi *et al*., 2023). The large quantities of fishing-related items found during the numerous surveys are becoming a growing global concern, as fishing gear is slowly becoming an additional source of marine pollution. Recent global estimates indicate an average annual fishing gear loss rate of 1.82%, which increases to 3.57% if only trawls are considered, which means that one trawler potentially loses about 5,000 square metres of gear per year (Richardson *et al*., 2022).

Marine litter management is a critical aspect of environmental protection, and it involves several key activities such as collection, sorting, transport, storage, and disposal of waste. These activities are typically guided by the Law on Waste Management, which sets the framework for how waste should be handled and managed, including marine litter. Montenegro, as a candidate country for European Union (EU) membership, is actively working towards aligning its marine environmental policies with EU standards, notably through the implementation of the Marine Strategy Framework Directive (MSFD). The MSFD, established in 2008, aims to protect the marine environment across Europe and to achieve Good Environmental Status (GES) of the EU's marine waters by 2020.

Efforts to reduce marine litter on the seafloor and raise awareness can be carried out through a variety of clean-up initiatives. These initiatives help tackle pollution, promote environmental responsibility, and engage communities in protecting marine ecosystems. Such efforts can include programs like "Fishing for Litter" (Fortibuoni *et al*., 2019; Ronchi *et al.*, 2019; Madricardo *et al*., 2020), which involves fishermen collecting marine litter during their activities, and SCUBA diving volunteer campaigns, where divers actively remove marine litter from shallower waters. These initiatives not only help reduce marine litter but also raise awareness about the environmental impact of pollution on our oceans. These approaches are recognized as important for tackling the marine litter issue that the legislation supports explicitly (Madricardo *et al*., 2020).

CONCLUSION

Marine litter on the Adriatic seafloor in Montenegro remains a significant environmental challenge. Studies indicate that various types of marine litter, including plastics and other pollutants, accumulate on the seafloor, affecting marine ecosystems and biodiversity. The insights from this study can also help promote initiatives aimed at actively reducing marine litter. Engaging key stakeholders, such as fishermen (e.g., through the Fishing for Litter initiatives), is essential to these efforts. Moreover, the findings can encourage governments to amend certain laws, such as by providing port reception facilities where fishermen can land the marine debris they encounter during fishing activities. These legal adjustments would promote more sustainable practices and significantly reduce marine waste. Increasing public awareness of the issue is another vital aspect. The success of these initiatives depends on the effective dissemination of scientific knowledge and the availability of accurate, consistent, and comparable data. This will facilitate the implementation of coordinated, region-wide plans to reduce marine litter effectively.

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