Studia Marina 2026, 39(1): 22-40
Review
UDC 551.462:504.5(497.8)
DOI 10.5281/zenodo.20377701

Microplastic pollution in the Adriatic Sea with an emphasis on Montenegro: Distribution, sources, methods, biota, policy, and implications

Antonija AVDALOVIĆ[1*], Mirko ĐUROVIĆ[1], Milica MANDIĆ[1], Ines KOKIĆ[1]

[1]Institute of Marine Biology, University of Montenegro, Put I bokeljske brigade 68, Kotor, Montenegro, [*]e-mail: antonijaa@edu.ucg.ac.me

ABSTRACT

The Adriatic Sea is recognized as a preferential accumulation zone for plastic debris within the Mediterranean. Microplastics have been detected in surface waters, sediments, and biota, with pronounced spatial and temporal variability linked to hydrodynamics, riverine inputs, and seasonality. This review synthesizes current evidence on microplastic distribution, composition, sources, and drivers across the Adriatic Sea, with particular emphasis on Montenegro, where sediment and mussel studies reveal widespread contamination dominated by polyethylene and polypropylene. Montenegrin coastal sediments contain on average 300–600 microplastic particles kg^{-1} dry sediment, with highest concentrations in enclosed areas such as Boka Kotorska Bay. While the Marine Strategy Framework Directive provides the policy scaffold for monitoring and management, methodological heterogeneity across studies and critical data gaps, particularly the scarcity of seasonal sea-surface microplastic data along the Eastern Adriatic, currently limit regional comparability and long-term trend assessment. Priority needs for Montenegro and the wider Adriatic include harmonized surface-water monitoring, integration of hydrodynamic context, and stakeholder-relevant assessments linking ecological indicators to aquaculture, tourism, and seafood safety.

Keywords: microplastics, Adriatic Sea, Montenegro, marine pollution, Mediterranean

INTRODUCTION

Microplastic pollution has emerged as a pervasive environmental challenge, with particles <5 mm detected across virtually all marine environments (Eriksen *et al.*, 2014). Although the Mediterranean Sea represents less than 1% of global ocean volume, it receives approximately 7% of global microplastic inputs and exhibits some of the highest reported concentrations worldwide (Suaria *et al.*, 2016; Cózar *et al.*, 2015). Within this context, the Adriatic Sea constitutes a critical sub-basin due to its semi-enclosed nature, dense coastal populations, substantial riverine inputs, particularly from the Po River, and intensive maritime traffic (Liubartseva *et al.*, 2016; Campanale *et al.*, 2020).

The Adriatic's oceanographic setting further promotes microplastic accumulation. Cyclonic circulation and limited water exchange through the Otranto Strait create

retention zones that favor the concentration of floating debris and the sedimentation of denser particles (Artegiani *et al.*, 1997; Poulain *et al.*, 2001). Montenegro's 293 km coastline reflects these broader Adriatic dynamics, encompassing enclosed areas such as Boka Kotorska Bay, open coastal areas, and productive fishing grounds (Kovačić *et al.*, 2024). Intense seasonal tourism, with visitor numbers exceeding 2 million annually relative to a population of ~620,000, further contributes to multiple and temporally variable microplastic sources (MONSTAT, 2023).

A scopus-based literature screening highlights pronounced regional imbalances in research effort, with most Adriatic microplastic studies affiliated with Italy (54 records), followed by Croatia (16), Slovenia (15), Montenegro (7), and Albania (3), underscoring persistent geographic asymmetries in data availability (Fig. 1).

This review synthesizes current knowledge on microplastic pollution in the Adriatic Sea, with particular emphasis on Montenegro, addressing distribution patterns, polymer composition, sources, analytical methodologies, ecological impacts, and key knowledge gaps relevant to the Eastern Adriatic.



Figure 1. Literature-based overview of microplastic evidence across the Adriatic Sea, illustrating spatial patterns in reported occurrence that are strongly influenced by differences in research intensity

DISTRIBUTION AND CONCENTRATIONS

Basin-wide patterns

The Adriatic Sea exhibits widespread microplastic contamination across all environmental compartments. Surface waters in the northwestern Adriatic, strongly influenced by Po River discharge, show concentrations ranging from 0.3 to 43 × 10^5 particles km^{-2}, with marked spatial and temporal variability (Vianello *et al*., 2018; Campanale *et al*., 2020). Near the Venice Lagoon, reported areal densities of 0.25–2.29 × 10^5 particles km^{-2} further illustrate the dynamic nature of surface distributions (Marchetto *et al*., 2022).

Spatial patterns are patchy and closely linked to river plumes, coastal retention, the southward Western Adriatic Coastal Current, and basin-scale cyclonic gyres that structure accumulation zones (Vianello *et al*., 2013; Avio *et al*., 2017). A consistent near shore gradient has been identified, with substantially higher abundances within 4 km of coastlines, emphasizing the role of terrestrial inputs and coastal processes (Zeri *et al*., 2018).

Sediments

Sediment surveys confirm pervasive microplastic contamination throughout the Adriatic. Along a 140 km central Adriatic transect, plastics were detected at 69% of stations, with the 1–5 mm size class accounting for 65.1% of debris by number (Mistri *et al*., 2017). In Special Areas of Conservation within the Gulf of Venice, concentrations ranged from 28.4 to 2,250 items kg^{-1} dry sediment, highlighting pronounced spatial heterogeneity even within protected areas (Mistri *et al*., 2021).

Across the basin, filaments typically dominate sedimentary microplastics, often exceeding two-thirds of particle counts, followed by fragments and films (Gajšt *et al*., 2016; Mistri *et al*., 2017). Polymer analyses consistently identify polyethylene (PE) and polypropylene (PP) as dominant, alongside denser polymers such as polyamide, polyethylene terephthalate (PET), and polyvinyl chloride (PVC), reflecting biofouling processes and density-driven redistribution to the seabed (Avio *et al*., 2015; Koelmans *et al*., 2017).

Along the Montenegrin coast, sediment contamination is ubiquitous. Mean concentrations of 609 items kg^{-1} dry sediment were reported across multiple sites, with highest abundances in enclosed areas such as Boka Kotorska Bay (Bošković *et al*., 2021). Subsequent surveys documented mean concentrations of 307 ± 133 items kg^{-1} dry sediment across 10 sites, with peaks near population centers, tourism hotspots, fishing areas, and municipal discharge points (Bošković *et al*., 2022a). Filaments dominate shape distributions, consistent with fishing activity and wastewater-derived fibers, while size fractions cluster mainly between 0.1–1.0 mm (Bošković *et al*., 2021; 2022a). Polymer identification confirms PP (~33.3%) and PE (~15.7%) as dominant, with additional contributions from PET, polyamide, and polystyrene (Bošković *et al*., 2021; 2022a).

Biota

A basin-wide assessment detected microplastics in 21 of 24 marine species, with higher ingestion frequencies in the central and southern Adriatic (Avio *et al*., 2020). Benthopelagic species showed the highest ingestion rates, followed by pelagic, demersal, and benthic taxa, with ingested particles predominantly small (<300 μm) and approximately one-third <100 μm (Avio *et al*., 2020).

The Mediterranean mussel *Mytilus galloprovincialis* is widely used as a

bioindicator. Studies from the northern and central Adriatic report concentrations of 0.62–1.33 items g^{-1} wet weight for fragments and 0.24–0.63 items g^{-1} wet weight for fibers, with elevated burdens in coastal compared to offshore populations (Gomiero *et al*., 2019). Seasonal monitoring recorded concentrations up to 1.11 items g^{-1} wet weight during periods of high river discharge and adverse weather (Pizzurro *et al*., 2022).

In Montenegro, microplastics were found in 53.3% of mussels from Boka Kotorska Bay, with a mean burden of 2.53 items per mussel (Bošković *et al*., 2023). Microplastics were also detected in two species of fish, 58.6% for *Mullus barbatus* and 54% for *Merluccius merluccius* (Bošković *et al*., 2022b). Fibers predominated, with polymer types including PE, PP, and PET. Comparable polymer profiles and accumulation patterns observed in sediments and biota suggest direct environmental-to-organism transfer along the Montenegrin coast (Bošković *et al*., 2023).

SOURCES AND TRANSPORT PATHWAYS

Riverine inputs

The Po River constitutes the dominant freshwater and pollutant source to the Adriatic Sea, discharging approximately 46 km^3 annually (Montanari, 2012). Its influence on microplastic distribution is reflected in pronounced spatial gradients, with the highest surface-water and sediment concentrations observed near the Po Delta (Vianello *et al*., 2013; Blašković *et al*., 2017). Polymer assemblages in Po-affected areas are dominated by low-density polyolefins (PE and PP), consistent with inputs from consumer packaging and agricultural plastics (Blašković *et al*., 2017).

Seasonal discharge variability further modulates microplastic transport, with elevated concentrations during spring snowmelt and autumn rainfall events (Vianello *et al*., 2013; Pizzurro *et al*., 2022). Although the Po River dominates northern inputs, numerous smaller rivers contribute microplastics along both Adriatic coasts, though their relative contributions remain insufficiently quantified (Kraus & Supić, 2011).

Coastal urban sources

Wastewater treatment plants (WWTPs) represent major pathways for microplastics, particularly microfibers from textile laundering and fragmented particles from personal care products (Browne *et al*., 2011; Murphy *et al*., 2016). Even advanced treatment systems typically remove 90–99% of microplastics, allowing substantial residual loads to reach receiving waters (Talvitie *et al*., 2017).

Along the Montenegrin coast, aging wastewater infrastructure and incomplete treatment coverage likely enhance microplastic emissions, particularly during peak tourist seasons when population pressures intensify (Bošković *et al*., 2022a; 2023). Elevated sediment concentrations near discharge points and urban centers support the role of municipal effluents as important local sources (Bošković *et al*., 2021; 2022a).

Maritime activities

The Adriatic Sea supports intensive maritime traffic, with major commercial ports handling millions of tons of cargo annually (UNCTAD, 2021). Port areas and shipping lanes function as both sources and accumulation zones for microplastics, with contributions arising from cargo handling, vessel maintenance, and operational losses (Fastelli *et al*., 2016).

Fishing activities contribute microplastics primarily through the loss and degradation of gear such as nets, lines, and floats, resulting in frequent detection of nylon fragments and filaments in sediments and biota near fishing ports (Strafella *et al*., 2015; Aytan *et al*., 2016). Aquaculture operations similarly introduce microplastics through the degradation of netting and farming equipment, with elevated nylon concentrations reported in mussels collected near aquaculture sites (Gomiero *et al*., 2019; Bošković *et al*., 2023).

Hydrodynamic controls

In addition to source inputs, microplastic distribution in the Adriatic is strongly shaped by circulation and hydrodynamic processes (Liubartseva *et al*., 2018; Mansui *et al*., 2020). Basin-scale cyclonic circulation, characterized by northward flow along the eastern coast and southward flow along the western coast, defines preferential transport pathways and accumulation zones (Carlson *et al*., 2017).

In semi-enclosed systems such as Boka Kotorska Bay, restricted water exchange and prolonged residence times promote the accumulation of locally sourced microplastics (Vilibić & Orlić, 2001; Bošković *et al*., 2021). Seasonal variability in winds, currents, and river discharge further modulates microplastic distribution on timescales ranging from days to months (Vianello *et al*., 2013; Pizzurro *et al*., 2022).

SAMPLING AND ANALYTICAL METHODS

Sample collection

Sea-surface microplastic data in the Adriatic Sea are predominantly derived from manta and neuston net sampling, with most studies employing mesh sizes between 200 and 333 μm (Vianello *et al*., 2013; Suaria & Aliani, 2014). These nets are typically towed at the sea surface over standardized distances or time intervals to ensure comparable sampling effort and facilitate inter-study comparison (Lippiatt *et al*., 2013). However, the widespread use of 200–333 μm mesh sizes constitutes a major methodological constraint, as smaller microplastic particles are not retained and are therefore systematically underestimated (Poulain *et al*., 2019; Lindeque *et al*., 2020).

Microplastics in intertidal sediments are most commonly assessed using surface sediment samples collected from the upper 0–5 cm layer, often with metal tools to reduce contamination risk (Hanke *et al*., 2013; Bošković *et al*., 2022a). Subtidal sediment studies generally rely on grab samplers, with subsequent analysis focused on the surface fraction of the collected material (Woodall *et al*., 2014; Mistri *et al*., 2017). In biota-based studies, bivalves are frequently used as bioindicators, with whole organisms collected and soft tissues processed to quantify and characterize ingested microplastics (Gomiero *et al*., 2019; Bošković *et al*., 2023).

Sample preparation

Across Adriatic microplastic studies, density separation is the most commonly applied approach for isolating plastic particles from sediment matrices (Thompson *et al*., 2004). Flotation media frequently used include sodium chloride (NaCl; density ~1.2 g cm^{-3}), zinc chloride ($ZnCl_2$; ~1.5–1.8 g cm^{-3}), and sodium iodide (NaI; ~1.6–1.8 g cm^{-3}), with the choice of solution influencing recovery efficiency for polymers of different densities (Quinn *et al*., 2017). In studies conducted along the Montenegrin coast, NaCl-based separation has been predominantly applied; however, this approach selectively recovers low-density polymers and may underestimate the presence of denser materials such as PVC and PET (Bošković *et al*., 2021; 2022a).

For biota-based investigations, removal of organic matter is a necessary preparatory step prior to microplastic identification. Oxidative digestion using hydrogen peroxide (H_2O_2) is widely employed due to its effectiveness and relative simplicity, whereas enzymatic digestion protocols are increasingly adopted to better preserve polymer integrity, albeit at the cost of longer processing times (Cole *et al*., 2014; Dehaut *et al*., 2016; Courtene-Jones *et al*., 2017).

Contamination control has emerged as a critical methodological consideration in microplastic analysis. Recent studies emphasize the importance of standardized preventative measures, including the use of natural-fiber laboratory clothing, filtration of all solutions, reliance on glass or metal equipment, and the routine inclusion of procedural blanks to assess background contamination (Wesch *et al*., 2016; Hermsen *et al*., 2018).

Polymer identification

Polymer identification in Adriatic microplastic studies is most commonly conducted using Fourier-transform infrared spectroscopy (FT-IR), with micro-FT-IR and attenuated total reflectance (ATR) configurations widely applied for particles across a range of sizes (Jung *et al*., 2018; Primpke *et al*., 2018). FT-IR enables polymer classification through the acquisition of characteristic absorption spectra, which are matched against reference libraries to determine polymer type (Käppler *et al*., 2016). Studies from the Montenegrin coast have predominantly relied on FT-IR for polymer confirmation, reporting common polymers such as polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and related materials (Bošković *et al*., 2021; 2022a; 2023).

Raman spectroscopy is frequently employed as a complementary technique, offering higher spatial resolution (approximately 1 μm) and improved performance for dark, pigmented, or weathered particles that may be challenging to analyze using FT-IR alone (Frère *et al*., 2017; Araujo *et al*., 2018). Increasingly, multi-method analytical workflows combining FT-IR and Raman spectroscopy are adopted to enhance identification confidence and reduce polymer misclassification, particularly in heterogeneous environmental samples (Renner *et al*., 2018).

Methodological challenges

Methodological heterogeneity continues to represent a major constraint for cross-study synthesis in microplastic research (Koelmans *et al*., 2019; Rochman *et al*., 2019). Across Adriatic studies, key sources of variability include differences in sampling gear and mesh sizes, extraction and digestion procedures, particle size thresholds, polymer identification techniques, and reporting units, all of which influence reported concentrations and composition (Lusher *et al*., 2017; Cowger *et al*., 2021). As a result, direct comparison of datasets within the Adriatic basin, as well as with other Mediterranean regions, remains challenging (Šaravanja *et al*., 2022).

Recognition of these limitations has driven progressive standardization efforts at the European level. Early guidance developed in support of MSFD implementation laid the foundation for harmonized marine litter monitoring (Galgani *et al*., 2013; Addamo *et al*., 2017), while more recent initiatives emphasize the adoption of standardized, comparable methodologies across environmental compartments. Wider implementation of these frameworks within Adriatic monitoring programs would substantially improve data comparability and

facilitate regional-scale assessments (Galgani *et al*., 2018).

ECOLOGICAL AND HUMAN HEALTH IMPLICATIONS

Ecological impacts

Microplastic ingestion can cause physical and physiological harm to marine organisms through multiple mechanisms (Wright *et al*., 2013). In filter feeders such as mussels, accumulated microplastics may reduce feeding efficiency, impair nutrient absorption, and induce false satiation (Von Moos *et al*., 2012; Wegner *et al*., 2012). Experimental studies on Mediterranean mussels have demonstrated reduced filtration rates and depleted energy reserves following exposure (Avio *et al*., 2015).

Microplastics also act as vectors for hydrophobic organic contaminants, including polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs), as well as plastic additives such as phthalates and bisphenol A (BPA), which may leach from ingested particles (Teuten *et al*., 2009; Rochman *et al*., 2013; Hermabessiere *et al*., 2017). Studies on Adriatic mussels indicate co-occurrence of microplastics with trace metals, suggesting potential for combined contaminant exposure (Fajković *et al*., 2022; Bošković *et al*., 2023).

In addition, microplastics provide substrates for microbial colonization, forming distinct "plastisphere" communities that may include opportunistic pathogens (Zettler *et al*., 2013; Oberbeckmann *et al*., 2015). Laboratory experiments have documented sublethal effects such as oxidative stress, inflammation, and reproductive impairment, although evidence for population- or ecosystem-level impacts in marine environments remains limited (Sussarellu *et al*., 2016; Lu *et al*., 2016; Galloway *et al*., 2017).

Human health implications

Human exposure to microplastics occurs primarily through dietary intake, particularly via consumption of contaminated seafood (Cox *et al*., 2019; Prata *et al*., 2020). Bivalves represent a direct exposure pathway due to their feeding mode and whole-organism consumption (Van Cauwenberghe & Janssen, 2014). Estimated dietary exposure based on Montenegrin mussel consumption suggests annual ingestion of thousands to tens of thousands of particles by regular consumers, although such estimates remain highly uncertain (Barboza *et al*., 2018; Bošković *et al*., 2023).

Microplastics have also been detected in table salt, bottled water, and processed foods, indicating multiple exposure routes beyond seafood (Kosuth *et al*., 2018; Schymanski *et al*., 2018). The health consequences of chronic exposure are not yet well understood, but potential risks include physical irritation, chemical toxicity from additives and sorbed pollutants, inflammatory responses, and microbiome disruption (Wright & Kelly, 2017; Prata, 2018; Jin *et al*., 2019). Detection of microplastics in human stool, blood, and lung tissue suggests the potential for systemic exposure (Schwabl *et al*., 2019; Leslie *et al*., 2022).

Socioeconomic impacts

Microplastic contamination poses risks to Adriatic fisheries and aquaculture by affecting product quality, consumer confidence, and market value (Whitmarsh & Palmieri, 2009; Barboza *et al*., 2020). In mussel aquaculture, documented contamination raises concerns regarding food safety and economic sustainability (Mathalon & Hill, 2014).

Coastal tourism, a key economic sector in Montenegro, is particularly sensitive to visible plastic pollution. Studies from Mediterranean destinations show that beach litter negatively influences tourist perceptions and destination attractiveness, while municipalities incur substantial costs for beach cleaning and waste management (Mouat *et al*., 2010; Krelling *et al*., 2017; Brouwer *et al*., 2017).

POLICY FRAMEWORK AND RESEARCH PRIORITIES

Marine Strategy Framework Directive – MSFD

The European Union's Marine Strategy Framework Directive (European Commission, 2008) provides the principal legislative framework for addressing marine litter, including microplastics (European Commission, 2008). The MSFD requires member states to achieve "Good Environmental Status" (GES) of marine waters, with marine litter addressed under Descriptor 10 (European Commission, 2017).

For Montenegro, as an EU candidate country, alignment with MSFD requirements represents both an obligation and an opportunity to establish systematic monitoring frameworks (European Commission, 2021). Descriptor 10 criteria include trends in microplastic particles in the water column (D10C2), litter in seafloor sediments (D10C3), and litter ingested by marine animals (D10C4) (Werner *et al*., 2016).

MSFD implementation requires coordinated monitoring programs with standardized methods to enable trend detection (Zampoukas *et al*., 2014). The Technical Group on Marine Litter has developed monitoring guidance including recommended sampling frequencies, standardized protocols, quality assurance requirements, and reporting formats (Galgani *et al*., 2013; Gago *et al*., 2016).

More recent updates to MSFD-related monitoring guidance further emphasize harmonized approaches to assessing marine macro- and micro-litter across environmental compartments, including surface waters, sediments, and biota, in order to improve data comparability and long-term trend analysis (European Commission JRC, 2023).

Regional cooperation

The Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean (Barcelona Convention) provides a regional framework, with all Adriatic countries as contracting parties (UNEP/MAP, 1995). The 2013 Regional Plan on Marine Litter Management specifically addresses plastic pollution (UNEP/MAP, 2013). More recent Mediterranean Action Plan initiatives and ongoing updates to the Mediterranean Quality Status Report reflect continued regional efforts to improve marine litter monitoring, data harmonization, and policy coordination across the basin (UNEP/MAP, 2023). At the EU level, the Zero Pollution Action Plan further reinforces commitments to reduce marine pollution, including plastics, by setting long-term targets and tracking progress through indicators such as coastline litter trends, thereby complementing MSFD implementation and regional Mediterranean frameworks (EEA, 2024). However, implementation has been uneven, with northern Adriatic countries generally more advanced than eastern Mediterranean states (Vlachogianni *et al*., 2017).

Montenegro's context

Montenegro has made progress in aligning national legislation with EU environmental directives as part of the accession process

(Government of Montenegro, 2016). While legislative alignment with the MSFD has largely been achieved, operational microplastic monitoring remains limited and not yet fully implemented, particularly for sea-surface waters (UNEP/MAP-PAP/RAC-SPA/RAC & MESPU, 2021).

Key capacity gaps include limited analytical infrastructure, small number of trained personnel, insufficient funding for sustained monitoring, and lack of coordination between institutions (Mandić, 2021). Addressing these gaps will require investment in equipment and training, establishment of dedicated monitoring programs, and integration of microplastic monitoring into broader marine environmental surveillance in line with emerging EU and regional guidance (UNEP/MAP, 2020; European Commission JRC, 2023).

Critical knowledge gaps

The most critical data gap for the Adriatic basin is the scarcity of systematic surface water monitoring along the eastern coast, including Montenegro (Galgani *et al*., 2018; Šaravanja *et al*., 2022). While northern Italian waters have been relatively well studied, the Croatian, Montenegrin and Albanian coasts lack comparable datasets (Panti *et al*., 2015).

Addressing current knowledge gaps in Montenegro requires coordinated efforts focused on standardized surface-water monitoring, long-term trend detection, and source identification. Seasonal sea-surface surveys using harmonized manta-net protocols are needed to capture spatial and temporal variability, alongside sustained monitoring at fixed stations to enable trend analysis over multi-year periods (Galgani *et al*., 2013; Kershaw *et al*., 2019). Given the role of rivers as major pathways of plastic transport, systematic monitoring of riverine fluxes is essential to quantify inputs and identify dominant sources (Lebreton *et al*., 2017). Emerging priorities include the development of methods for nanoplastic detection (<1 μm) and targeted studies on trophic transfer to assess ecological consequences (Setälä *et al*., 2014; Gigault *et al*., 2018). Consistent application of existing standardized protocols aligned with MSFD and UNEP frameworks remains critical for data comparability (Galgani *et al*., 2013; 2018), while advances in source apportionment and stakeholder engagement are needed to support effective mitigation and policy implementation (Hartley *et al*., 2015; Dümichen *et al*., 2017).

CONCLUSIONS AND RECOMMENDATIONS

Microplastic pollution is pervasive throughout the Adriatic Sea, affecting surface waters, sediments, and biota. Surface-water concentrations show pronounced spatial and temporal variability driven by riverine inputs, coastal activities, and circulation patterns. Along the Montenegrin coast, sediment contamination averages 300–600 items kg^{-1}, with higher values in enclosed areas, while biota contamination is widespread, with mussels containing approximately 2.5 items per individual.

Polymer compositions are highly consistent across the basin, dominated by polyethylene and polypropylene (often >70%), followed by PET, polystyrene, and polyamides, reflecting mixed land-based and maritime sources including rivers, urban areas, wastewater treatment plants, ports, and fishing activities. Despite increasing data availability, methodological heterogeneity remains a major limitation, as differences in sampling, extraction, analysis, and reporting continue to constrain cross-study comparability.

Ecological impacts are primarily documented at the individual organism level and include physical effects of ingestion and potential chemical exposure. While human health implications remain uncertain, dietary exposure through seafood represents a plausible pathway of concern. Existing policy frameworks, particularly the Marine Strategy Framework Directive, provide a regulatory basis for action, but implementation remains uneven across the Adriatic.

For Montenegro, priority actions include establishing systematic MSFD-aligned surface-water monitoring, extending observations to multi-year timescales for trend detection, and quantifying riverine microplastic inputs. These efforts should be supported by investment in analytical infrastructure, targeted training, source-control measures, and stakeholder engagement to ensure effective translation of scientific knowledge into mitigation.

At the regional scale, progress will depend on basin-wide adoption of standardized protocols, improved spatial coverage along the eastern Adriatic, coordinated river monitoring, and the integration of modelling approaches to assess transboundary transport and mitigation effectiveness. The Adriatic experience highlights the need for sustained monitoring coupled with broader changes in plastic production, use, and waste management. For Montenegro, advancing monitoring capacity and stakeholder involvement represents an immediate opportunity to strengthen marine environmental protection in the Eastern Adriatic.

ACKNOWLEDGMENTS

This review was supported by the Institute of Marine Biology, University of Montenegro. The author thanks colleagues who contributed data and insights on Montenegrin coastal contamination.

REFERENCES

Addamo, A. M., P. Laroche & G. Hanke (2017): Top marine beach litter items in Europe. EUR 29249 EN. Publications Office of the European Union, Luxembourg, 39 pp.

Araujo, C. F., M. M. Nolasco, A. M. P. Ribeiro & P. J. A. Ribeiro-Claro (2018): Identification of microplastics using Raman spectroscopy: Latest developments and future prospects. Water. Res., 142: 426–440.

Artegiani, A., D. Bregant, E. Paschini, N. Pinardi, F. Raicich., A. Russo & P. Simodetti (1997): The Adriatic Sea general circulation. Part I: Air-sea interactions and water mass structure. J. Phys. Oceanogr., 27: 1492–1514.

Avio, C. G., S. Gorbi & F. Regoli (2015): Experimental development of a new protocol for extraction and characterization of microplastics in fish tissues: First observations in commercial species from Adriatic Sea. Mar. Environ. Res., 111: 18–26.

Avio, C. G., S. Gorbi & F. Regoli (2017): Plastics and microplastics in the oceans: From emerging pollutants to emerged threat. Mar. Environ. Res., 128: 2–11.

Avio, C. G., L. Pittura, G. d'Errico, S. Abel, S. Amorello, G. Marino, S. Gorbi & F. Regoli (2020): Distribution and characterization of microplastic particles and textile microfibers in Adriatic food webs: General insights for biomonitoring strategies. Environ. Pollut., 258: 113766.

Aytan, U., A. Valente, Y. Senturk, R. Usta, F. B. Esensoy Sahin, R. E. Mazlum & E. Agirbas (2016): First evaluation of

neustonic microplastics in Black Sea waters. Mar. Environ. Res., 119: 22–30.

Barboza, L. G. A., A. D. Vethaak, B. R. B. O. Lavorante, A. K. Lundebye, L. Guilhermino (2018): Marine microplastic debris: An emerging issue for food security, food safety and human health. Mar. Pollut. Bull., 133: 336–348.

Barboza, L. G. A., C. Lopes, P. Oliveira, F. Bessa, V. Otero, B. Henriques, J. Raimundo, M. Caetano, C. Vale & L. Guilhermino (2020): Microplastics in wild fish from the North East Atlantic Ocean and its potential for causing neurotoxic effects, lipid oxidative damage, and human health risks associated with ingestion exposure. Sci. Total. Environ., 717: 134625.

Blašković, A., P. Fastelli, H. Čižmek, C. Guerranti & M. Renzi (2017): Plastic litter in sediments from the Croatian marine protected area of the natural park of Telaščica Bay (Adriatic Sea). Mar. Pollut. Bull., 114: 583–586.

Bošković, N., D. Joksimović, M. Peković, O. Bajt & A. Joksimović (2021): Microplastics in surface sediments along the Montenegrin coast, Adriatic Sea: Types, occurrence, and distribution. J. Mar. Sci. Eng., 9: 841.

Bošković, N., D. Joksimović, A. Perošević-Bajčeta, M. Peković & O. Bajt (2022a): Distribution and characterization of microplastics in marine sediments from the Montenegrin coast. J. Soils. Sediments, 22(11): 2958–2967.

Bošković, N., D. Joksimović & O. Bajt (2022b): Microplastics in fish and sediments from the Montenegrin coast (Adriatic Sea): Similarities in accumulation. Sci. Total. Environ., 850: 158074.

Bošković, N., D. Joksimović & O. Bajt (2023): Microplastics in mussels from the Boka Kotorska Bay (Adriatic Sea) and impact on human health. Food Chem. Toxicol., 173: 113641.

Brouwer, R., D. Hadzhiyska, C. Ioakeimidis & H. Ouderdorp (2017): The social costs of marine litter along European coasts. Ocean Coast. Manag., 138: 38–49.

Browne, M. A., P. Crump, S. J. Niven, E. Teuten, A. Tonkin, T. Galloway & R. C. Thompson (2011): Accumulation of microplastic on shorelines worldwide: Sources and sinks. Environ. Sci. Technol., 45: 9175–9179.

Campanale, C., F. Stock, C. Massarelli, C. Kochleus, G. Bagnuolo, G. Reifferscheid & V. F. Uricchio (2020): Microplastics and their possible sources: The example of Ofanto River in southeast Italy. Environ. Pollut., 258: 113284.

Carlson, D. F., G. Suaria, S. Aliani, E. Fredj, T. Fortibuoni, A. Griffa, A. Russo & E. Zambianchi (2017): Combining litter observations with a regional ocean model to identify sources and sinks of floating debris in a semi-enclosed basin: The Adriatic Sea. Front. Mar. Sci., 3: 78.

Cole, M., H. Webb, P. K. Lindeque, E. S. Fileman, C. Halsband & T. S. Galloway (2014): Isolation of microplastics in biota-rich seawater samples and marine organisms. Sci. Rep., 4: 4528.

Courtene-Jones, W., B. Quinn, S. F. Gary, A. O. M. Mogg & B. E. Narayanaswamy (2017): Optimisation of enzymatic digestion and validation of specimen preservation methods for the analysis of ingested microplastics. Anal. Methods, 9: 1437–1445.

Cowger, W., Z. Steinmetz, A. Gray, K. Munno, J. Lynch, H. Hapich, S. Primpke, H. De Frond, C. Rochman & O. Herodotou (2021): Microplastic spectral classification needs an open source

community: Open Specy to the rescue! Anal. Chem., 93(21): 7543–7548.

Cox, K. D., G. A. Covernton, H. L. Davies, J. F. Dower, F. Juanes & S. E. Dudas (2019): Human consumption of microplastics. Environ. Sci. Technol., 53: 7068–7074.

Cózar, A., M. Sanz-Martín, E. Martí, J. I. González-Gordillo, B. Ubeda, J. Á. Gálvez, X. Irigoien & C. M. Duarte (2015): Plastic accumulation in the Mediterranean Sea. PLOS ONE, 10: e0121762.

Dehaut, A., A. L. Cassone, L. Frère, L. Hermabessiere, C. Himber, E. Rinnert, G. Rivière, C. Lambert, P. Soudant, A. Huvet, G. Duflos & I. Paul-Pont (2016): Microplastics in seafood: Benchmark protocol for their extraction and characterization. Environ. Pollut., 215: 223–233.

Dümichen, E., P. Eisentraut, C. G. Bannick, A. K. Barthel, R. Senz & U. Braun (2017): Fast identification of microplastics in complex environmental samples by a thermal degradation method. Chemosphere, 174: 572–584.

Eriksen, M., L. C. M. Lebreton, H. S. Carson, M. Thiel, C. J. Moore, J. C. Borerro, F. Galgani, P. G. Ryan & J. Reisser (2014): Plastic pollution in the world's oceans: More than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PLOS ONE, 9: e111913.

EEA (2024): EU coastline macro litter trends. (Available at: https://www.eea.europa.eu/en/european-zero-pollution-dashboards/indicators/eu-coastline-macro-litter-trends).

European Commission (2008): Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). Off. J. Eur. Union L., 164: 19–40.

European Commission (2017): Commission Decision (EU) 2017/848 of 17 May 2017 laying down criteria and methodological standards on good environmental status of marine waters. Off. J. Eur. Union L., 125: 43–74.

European Commission (2021): Montenegro 2021 Report. 121 pp. (Available at: https://www.eeas.europa.eu/sites/default/files/montenegro_2021_report_eng.pdf).

European Commission, Joint Research Centre (JRC) (2023): Guidance on monitoring of marine litter in European Seas. (Available at: https://mcc.jrc.ec.europa.eu/main/dev.py?N=41&O=466).

Fajković, H., N. Cukrov, S. Frančišković-Bilinski, O. Hasan, M. Necemer & D. Jakovčević (2022): Correlation of metals and degraded marine (micro)plastic litter in geologically similar coastal areas with different anthropogenic characteristics. Mar. Pollut. Bull., 183: 114041.

Fastelli, P., A. Blašković, G. Bernardi, T. Romeo, H. Čižmek, F. Andaloro, G. F. Russo, C. Guerranti & M. Renzi (2016): Plastic litter in sediments from a marine area likely to become protected (Aeolian Archipelago's islands, Tyrrhenian Sea). Mar. Pollut. Bull., 113: 526–529.

Frère, L., I. Paul-Pont, E. Rinnert, S. Petton, J. Jaffré, I. Bihannic, P. Soudant, C. Lambert & A. Huvet (2017): Influence of environmental and anthropogenic factors on the composition, concentration and spatial distribution of microplastics: A case study of the Bay of Brest (Brittany, France). Environ. Pollut., 225: 211–222.

Gago, J., F. Galgani, T. Maes & R. C. Thompson (2016): Microplastics in seawater: Recommendations from the Marine Strategy Framework Directive

Implementation Process. Front. Mar. Sci., 3: 219.

Gajšt, T., T. Bizjak, A. Palatinus, S. Liubartseva & A. Kržan (2016): Sea surface microplastics in the Slovenian part of the Northern Adriatic. Mar. Pollut. Bull., 113: 392–399.

Galgani, F., G. Hanke, S. Werner & L. De Vrees (2013): Marine litter within the European Marine Strategy Framework Directive. ICES J. Mar. Sci., 70: 1055–1064.

Galgani, F., C. K. Pham, F. Claro & P. Consoli (2018): Marine animal forests as useful indicators of entanglement by marine litter. Mar. Pollut. Bull., 135: 735–738.

Galloway, T. S., M. Cole & C. Lewis (2017): Interactions of microplastic debris throughout the marine ecosystem. Nat. Ecol. Evol., 1: 0116.

Gigault, J., A. ter Halle, M. Baudrimont, P. Y. Pascal, F. Gauffre, T. L. Phi, H. El Hadri, B. Grassl & S. Reynaud (2018): Current opinion: What is a nanoplastic? Environ. Pollut., 235: 1030–1034.

Gomiero, A., P. Strafella, K. B. Øysæd & G. Fabi (2019): First occurrence and composition assessment of microplastics in native mussels collected from coastal and offshore areas of the northern and central Adriatic Sea. Environ. Sci. Pollut. Res., 26(24): 24407–24416.

Government of Montenegro (2016): National Strategy for Sustainable Development until 2030. Ministry of Sustainable Development and Tourism, Podgorica, 508 pp.

Hanke, G., F. Galgani, S. Werner, L. Oosterbaan, P. Nilsson, D. Fleet, S. Kinsey, R. Thompson, J. Van Franeker, T. Vlachogianni, M. Scoullos, J. M. Veiga, A. Palatinus, M. Matiddi, T. Maes, S. Korpinen, A. Budziak, H. Leslie, J. Gago & G. Liebezeit (2013): Guidance on monitoring of marine litter in European Seas. JRC Scientific and Policy Reports, EUR 26113 EN. Publications Office of the European Union, Luxembourg, 124 pp.

Hartley, B. L., R. C. Thompson & S. Pahl (2015): Marine litter education boosts children's understanding and self-reported actions. Mar. Pollut. Bull., 90: 209–217.

Hermabessiere, L., A. Dehaut, I. Paul-Pont, C. Lacroix, R. Jezequel, P. Soudant & G. Duflos (2017): Occurrence and effects of plastic additives on marine environments and organisms: A review. Chemosphere, 182: 781–793.

Hermsen, E., S. M. Mintenig, E. Besseling & A. A. Koelmans (2018): Quality criteria for the analysis of microplastic in biota samples: A critical review. Environ. Sci. Technol., 52: 10230–10240.

Jin,Y., L. Lu, W. Tu, T. Luo & Z. Fu (2019): Impacts of polystyrene microplastic on the gut barrier, microbiota and metabolism of mice. Sci. Total. Environ., 649: 308–317.

Jung, M. R., F. D. Horgen, S. V. Orski, C. V. Rodriguez, K. L. Beers, G. H. Balazs, T. T. Jones, T. M. Work, K. C. Brignac, S. J. Royer, K. D. Hyrenbach, B. A. Jensen & J. M. Lynch (2018): Validation of ATR FT-IR to identify polymers of plastic marine debris, including those ingested by marine organisms. Mar. Pollut. Bull., 127: 704–716.

Käppler, A., D. Fischer, S. Oberbeckmann, G. Schernewski, M. Labrenz, K. J. Eichhorn & B. Voit (2016): Analysis of environmental microplastics by vibrational microspectroscopy: FTIR, Raman or both? Anal. Bioanal. Chem., 408: 8377–8391.

Kershaw, P. J., A. Turra & F. Galgani (2019): Guidelines for the monitoring and assessment of plastic litter in the Ocean. GESAMP Reports and Studies No. 99. IMO/FAO/UNESCO-

IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection, London, 130 pp.

Koelmans, A. A., M. Kooi, K. L. Law & E. van Sebille (2017): All is not lost: Deriving a top-down mass budget of plastic at sea. Environ. Res. Lett., 12: 114028.

Koelmans, A. A., N. H. Mohamed Nor, E. Hermsen, M. Kooi, S. M. Mintenig & J. De France (2019): Microplastics in freshwaters and drinking water: Critical review and assessment of data quality. Water Res., 155: 410–422.

Kosuth, M., S. A. Mason & E. V. Wattenberg (2018): Anthropogenic contamination of tap water, beer, and sea salt. PLOS ONE, 13: e0194970.

Kovačić, I., K. Štefanko, V. Špada, E. Pustijanac, M. Buršić & P. Burić (2024): Microplastics in Mediterranean mussel Mytilus galloprovincialis: Comparison between cultured and wild-type mussels from the Northern Adriatic. Appl. Sci., 14(5): 2056.

Kraus, R. & N. Supić (2011): Impact of circulation on high phytoplankton blooms and fish catch in the northern Adriatic (1990–2004). Estuar. Coast. Shelf. Sci., 91: 198–210.

Krelling, A. P., A. T. Williams & A. Turra (2017): Differences in perception and reaction of tourist groups to beach marine debris that can influence a loss of tourism revenue in coastal areas. Mar. Policy, 85: 87–99.

Lebreton, L. C. M., J. van der Zwet, J. W. Damsteeg, B. Slat, A. Andrady & J. Reisser (2017): River plastic emissions to the world's oceans. Nat. Commun., 8: 15611.

Leslie, H. A., M. J. M. van Velzen, S. H. Brandsma, A. D. Vethaak, J. J. Garcia-Vallejo & M. H. Lamoree (2022): Discovery and quantification of plastic particle pollution in human blood. Environ. Int., 163: 107199.

Lindeque, P. K., M. Cole, R. L. Coppock, C. N. Lewis, R. Z. Miller, A. J. R. Watts, A. Wilson-McNeal, S. L. Wright & T. S. Galloway (2020): Are we underestimating microplastic abundance in the marine environment? A comparison of microplastic capture with nets of different mesh-size. Environ. Pollut., 265: 114721.

Lippiatt, S., S. Opfer & C. Arthur (2013): Marine debris monitoring and assessment. NOAA Technical Memorandum NOS-OR&R-46. NOAA, Silver Spring, MD, 82 pp.

Liubartseva, S., G. Coppini, R. Lecci & S. Creti (2016): Regional approach to modeling the transport of floating plastic debris in the Adriatic Sea. Mar. Pollut. Bull., 103(1–2): 115–127.

Liubartseva, S., G. Coppini, R. Lecci & E. Clementi (2018): Tracking plastics in the Mediterranean: 2D Lagrangian model. Mar. Pollut. Bull., 129: 151–162.

Lu, Y., Y. Zhang, Y. Deng, W. Jiang, Y. Zhao, J. Geng, L. Ding & H. Ren (2016): Uptake and accumulation of polystyrene microplastics in zebrafish (Danio rerio) and toxic effects in liver. Environ. Sci. Technol., 50: 4054–4060.

Lusher, A. L., N. A. Welden, P. Sobral & M. Cole (2017): Sampling, isolating and identifying microplastics ingested by fish and invertebrates. Anal. Methods, 9: 1346–1360.

Mandić, M. (2021): Towards a marine Good Environmental Status (GES) in Montenegro. Assessment of marine litter (EO10). Ministry of Ecology, Spatial Planning and Urbanism, Podgorica, 38 pp.

Mansui, J., G. Darmon, T. Ballerini, O. van Canneyt, Y. Ourmieres & C. Miaud

(2020): Predicting marine litter accumulation patterns in the Mediterranean basin: Spatio-temporal variability and comparison with empirical data. Prog. Oceanogr., 182: 102268.

Marchetto, D., L. De Ferri, A. Latella & G. Pojana (2022): Micro- and mesoplastics in sea surface water from a Northern Adriatic coastal area. Environ. Sci. Pollut. Res., 29(25): 37471–37497.

Mathalon, A. & P. Hill (2014): Microplastic fibers in the intertidal ecosystem surrounding Halifax Harbor, Nova Scotia. Mar. Pollut. Bull., 81: 69–79.

Mistri, M., V. Infantini, M. Scoponi, T. Granata, L. Moruzzi, F. Massara, M. De Donati & C. Munari (2017): Small plastic debris in sediments from the Central Adriatic Sea: Types, occurrence and distribution. Mar. Pollut. Bull., 124(1): 435–440.

Mistri, M., M. Scoponi, A. A. Sfriso, C. Munari, M. Curiotto, A. Sfriso, M. Orlando-Bonaca & L. Lipej (2021): Microplastic contamination in protected areas of the Gulf of Venice. Water Air Soil Pollut., 232(9): 379.

MONSTAT (2023): Statistical yearbook of Montenegro 2023. Statistical Office of Montenegro, Podgorica (Available at: https://monstat.org/eng/publikacije_page.php?id=1891).

Montanari A. (2012) Hydrology of the Po River: Looking for changing patterns in river discharge. Hydrol. Earth Syst. Sci., 16(10): 3739–3747.

Mouat, J., R. L. Lozano & H. Bateson (2010): Economic impacts of marine litter. KIMO International, Lerwick, 117 pp.

Murphy, F., C. Ewins, F. Carbonnier & B. Quinn (2016): Wastewater treatment works (WwTW) as a source of microplastics in the aquatic environment. Environ. Sci. Technol., 50: 5800–5808.

Oberbeckmann, S., M. G. J. Löder & M. Labrenz (2015): Marine microplastic-associated biofilms – A review. Environ. Chem., 12: 551–562.

Panti, C., M. Giannetti, M. Baini, F. Rubegni, R. Minutoli & M. C. Fossi (2015): Occurrence, relative abundance and spatial distribution of microplastics and zooplankton NW of Sardinia in the Pelagos Sanctuary Protected Area, Mediterranean Sea. Environ. Chem., 12: 618–626.

Pizzurro, F., S. Recchi, E. Nerone, R. Salini & N. B. Barile (2022): Accumulation evaluation of potential microplastic particles in *Mytilus galloprovincialis* from the Goro Sacca (Adriatic Sea, Italy). Microplastics, 1(2): 303–318.

Poulain, P. M. & B. Cushman-Roisin (2001): Circulation. *In*: Cushman-Roisin B., M. Gačić, P. M. Poulain & A. Artegiani (Ed.): Physical oceanography of the Adriatic Sea. Springer, Dordrecht. pp. 67–109.

Poulain, M., M. J. Mercier, L. Brach, M. Martignac, C. Routaboul, E. Perez, M. C. Desjean & A. ter Halle (2019): Small microplastics as a main contributor to plastic mass balance in the North Atlantic subtropical gyre. Environ. Sci. Technol., 53: 1157–1164.

Prata, J. C. (2018): Airborne microplastics: Consequences to human health? Environ. Pollut., 234: 115–126.

Prata, J. C., J. P. da Costa, I. Lopes, A. C. Duarte & T. Rocha-Santos (2020): Environmental exposure to microplastics: An overview on possible human health effects. Sci. Total. Environ., 702: 134455.

Primpke, S., M. Wirth, C. Lorenz & G. Gerdts (2018): Reference database design for the automated analysis of microplastic samples based on Fourier transform infrared (FTIR) spectroscopy. Anal. Bioanal. Chem., 410: 5131–5141.

Quinn, B., F. Murphy & C. Ewins (2017): Validation of density separation for the rapid recovery of microplastics from sediment. Anal. Methods, 9: 1491–1498.

Renner, G., T. C. Schmidt & J. Schram (2018): Analytical methodologies for monitoring micro(nano)plastics: Which are fit for purpose? Curr. Opin. Environ. Sci. Health, 1: 55–61.

Rochman, C. M., E. Hoh, T. Kurobe & S. J. Teh (2013): Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. Sci. Rep., 3: 3263.

Rochman, C. M., C. Brookson, J. Bikker, N. Djuric, A. Earn, K. Bucci, S. Athey, A. Huntington, H. McIlwraith, K. Munno, H. De Frond, A. Kolomijeca, L. Erdle, J. Grbic, M. Bayoumi, S. B. Borrelle, T. Wu, S. Santoro, L. M. Werbowski, X. Zhu, R. K. Giles, B. M. Hamilton, C. Thaysen, A. Kaura, N. Klasios, L. Ead, J. Kim, C. Sherlock, A. Ho & C. Hung (2019): Rethinking microplastics as a diverse contaminant suite. Environ. Toxicol. Chem., 38: 703–711.

Šaravanja, A., T. Pušić & T. Dekanić (2022): Microplastics in wastewater by washing polyester fabrics. Materials, 15(7): 2683.

Schwabl, P., S. Köppel, P. Königshofer, T. Bucsics, M. Trauner, T. Reiberger & B. Liebmann (2019): Detection of various microplastics in human stool: A prospective case series. Ann. Intern. Med., 171: 453–457.

Schymanski, D., C. Goldbeck, H. U. Humpf & P. Fürst (2018): Analysis of microplastics in water by micro-Raman spectroscopy: Release of plastic particles from different packaging into mineral water. Water Res., 129: 154–162.

Setälä, O., V. Fleming-Lehtinen & M. Lehtiniemi (2014): Ingestion and transfer of microplastics in the planktonic food web. Environ. Pollut., 185: 77–83.

Strafella, P., G. Fabi, A. Spagnolo, F. Grati, P. Polidori, E. Punzo, T. Fortibuoni, B. Marceta, S. Raicevich, I. Cvitkovic, M. Despalatovic & G. Scarcella (2015): Spatial pattern and weight of seabed marine litter in the northern and central Adriatic Sea. Mar. Pollut. Bull., 91: 120–127.

Suaria, G. & S. Aliani (2014): Floating debris in the Mediterranean Sea. Mar. Pollut. Bull., 86: 494–504.

Suaria, G., C. G. Avio, A. Mineo, G. L. Lattin, M. G. Magaldi, G. Belmonte, C. J. Moore, F. Regoli & S. Aliani (2016): The Mediterranean plastic soup: Synthetic polymers in Mediterranean surface waters. Sci. Rep., 6: 37551.

Sussarellu, R., M. Suquet, Y. Thomas, C. Lambert, C. Fabioux, M. E. J. Pernet, N. Le Goïc, V. Quillien, C. Mingant, Y. Epelboin, C. Corporeau, J. Guyomarch, J. Robbens, I. Paul-Pont, P. Soudant & A. Huvet (2016): Oyster reproduction is affected by exposure to polystyrene microplastics. Proc. Natl. Acad. Sci. USA, 113: 2430–2435.

Talvitie, J., A. Mikola, A. Koistinen & O. Setälä (2017): Solutions to microplastic pollution – Removal of microplastics from wastewater effluent with advanced wastewater treatment technologies. Water Res., 123: 401–407.

Teuten, E. L., J. M. Saquing, D. R. U. Knappe, M. A. Barlaz, S. Jonsson, Å. Björn, S. J. Rowland, R. C. Thompson, T. S. Galloway, R. Yamashita, D. Ochi, Y. Watanuki, C. Moore, P. H. Viet, T. S. Tana, M. Prudente, R. Boonyatumanond, M. P. Zakaria, K. Akkhavong, Y. Ogata, H. Hirai, S. Iwasa, K. Mizukawa, Y. Hagino, A. Imamura, M. Saha & H. Takada (2009): Transport and release of chemicals from plastics to the

environment and to wildlife. Philos. Trans. R. Soc. B, 364: 2027–2045.

Thompson, R. C., Y. Olsen, R. P. Mitchell, A. Davis, S. J. Rowland, A. W. G. John, D. McGonigle & A. E. Russell (2004): Lost at sea: Where is all the plastic? Science, 304: 838.

UNCTAD (2021): Review of maritime transport 2021. United Nations Conference on Trade and Development, Geneva, 147 pp.

UNEP/MAP (1995): Convention for the protection of the marine environment and the coastal region of the Mediterranean (Barcelona Convention). United Nations Environment Programme/Mediterranean Action Plan, Athens, 96 pp.

UNEP/MAP (2013): Regional plan on marine litter management in the Mediterranean. UNEP(DEPI)/MED IG.21/9. United Nations Environment Programme/Mediterranean Action Plan, Athens, 31 pp.

UNEP/MAP (2020): State of the Environment and Development in the Mediterranean (SoED) 2020. United Nations Environment Programme/Mediterranean Action Plan, France, 344 pp.

UNEP/MAP (2023): MarineLitterMED II: Mediterranean marine litter management. (Available at: https://www.unep.org/unepmap/what-we-do/projects/MarineLitterMED-II).

UNEP/MAP-PAP/RAC-SPA/RAC & MESPU (2021): Integrated Monitoring Programme – Montenegro. GEF Adriatic Project. United Nations Environment Programme/Mediterranean Action Plan, Podgorica, 172 pp.

Van Cauwenberghe, L. & C. R. Janssen (2014): Microplastics in bivalves cultured for human consumption. Environ. Pollut., 193: 65–70.

Vianello, A., A. Boldrin, P. Guerriero, V. Moschino, R. Rella, A. Sturaro & L. Da Ros (2013): Microplastic particles in sediments of Lagoon of Venice, Italy: First observations on occurrence, spatial patterns and identification. Estuar. Coast. Shelf. Sci., 130: 54–61.

Vianello, A., L. Da Ros, A. Boldrin, T. Marceta & V. Moschino (2018): First evaluation of floating microplastics in the Northwestern Adriatic Sea. Environ. Sci. Pollut. Res., 25(28): 28546–28561.

Vilibić, I. & M. Orlić (2001): Least-squares tracer analysis of water masses in the South Adriatic (1967–1990). Deep Sea Res. Part I, 48: 2297–2330.

Vlachogianni, T., T. Fortibuoni, F. Ronchi, C. Zeri, C. Mazziotti, P. Tutman, D. B. Varezić, A. Palatinus, Š. Trdan, M. Peterlin, M. Mandić, O. Markovic, M. Prvan, J. Radović, G. Suaria, S. Aliani, A. Conversi, H. Kaberi, M. Prevenios & G. Hanke (2017): Marine litter assessment in the Mediterranean 2015. UNEP/MAP, Athens, 45 pp.

Von Moos, N., P. Burkhardt-Holm & A. Köhler (2012): Uptake and effects of microplastics on cells and tissue of the blue mussel *Mytilus edulis* L. after an experimental exposure. Environ. Sci. Technol., 46: 11327–11335.

Wegner, A., E. Besseling, E. M. Foekema, P. Kamermans & A. A. Koelmans (2012): Effects of nanopolystyrene on the feeding behavior of the blue mussel (*Mytilus edulis* L.). Environ. Toxicol. Chem., 31: 2490–2497.

Werner, S., A. Budziak, J. van Franeker, F. Galgani, G. Hanke, T. Maes, M. Matiddi, P. Nilsson, L. Oosterbaan, E. Priestland, R. Thompson, J. Veiga & T. Vlachogianni (2016): Harm caused by marine litter. MSFD GES Technical Subgroup on

Marine Litter. Publications Office of the European Union, Luxembourg, 92 pp.

Wesch, C., K. Bredimus, M. Paulus & R. Klein (2016): Towards the suitable monitoring of ingestion of microplastics by marine biota: A review. Environ. Pollut., 218: 1200–1208.

Whitmarsh, D. & M. G. Palmieri (2009): Social acceptability of marine aquaculture: The use of survey-based methods for eliciting public and stakeholder preferences. Mar. Policy, 33: 452–457.

Woodall, L. C., A. Sanchez-Vidal, M. Canals, G. L. J. Paterson, R. Coppock, V. Sleight, A. Calafat, A. D. Rogers, B. E. Narayanaswamy & R. C. Thompson (2014): The deep sea is a major sink for microplastic debris. R. Soc. Open Sci., 1: 140317.

Wright, S. L. & F. J. Kelly (2017): Plastic and human health: A micro issue? Environ. Sci. Technol., 51: 6634–6647.

Wright, S. L., R. C. Thompson & T. S. Galloway (2013): The physical impacts of microplastics on marine organisms: A review. Environ. Pollut., 178: 483–492.

Zampoukas, N., A. Palialexis, A. Duffek, J. Graveland, G. Giorgi, C. Hagebro, G. Hanke, S. Korpinen, M. Tasker, V. Tornero, V. Abaza, P. Battaglia, M. Caparis, R. Dekeling, M. Frias Vega, M. Haarich, S. Katsanevakis, H. Klein, W. Krzyminski, M. Laamanen, J.-C. Le Gac, J.-M. Leppanen, U. Lips, T. Maes, E. Magaletti, S. Malcolm, J. C. Marques, O. Mihail, C. Murray, S. Niiranen, C. O'Brien, H. Offringa, M. Penna, C. Piroddi, J. Reker, D. Sakellariou, M. Serviss, O. Solaun, L. Tunesi, W. van de Bund, A. Weiss & A. S. Wernersson (2014): Technical guidance on monitoring for the Marine Strategy Framework Directive. EUR 26499 EN. Publications Office of the European Union, Luxembourg, 175 pp.

Zeri, C., A. Adamopoulou, D. Bojanić Varezić, T. Fortibuoni, M. Kovač Viršek, A. Kržan, M. Mandić, C. Mazziotti, A. Palatinus, M. Peterlin, M. Prvan, F. Ronchi, J. Siljic, P. Tutman & T. Vlachogianni (2018): Floating plastics in Adriatic waters (Mediterranean Sea): From the macro- to the micro-scale. Mar. Pollut. Bull., 136: 341–350.

Zettler, E. R., T. J. Mincer & L. A. Amaral-Zettler (2013): Life in the "plastisphere": Microbial communities on plastic marine debris. Environ. Sci. Technol., 47: 7137–7146.

Received: 03.12.2025
Revised: 06.02.2026
Accepted: 01.03.2026

Zagađenje mikroplastikom u Jadranskom moru sa posebnim osvrtom na Crnu Goru: Rasprostranjenost, izvori, metode, biota, politika i implikacije

Antonija AVDALOVIĆ, Mirko ĐUROVIĆ, Milica MANDIĆ, Ines KOKIĆ

SAŽETAK

Jadransko more je prepoznato kao područje intenzivne akumulacije plastičnog otpada u okviru Mediterana. Mikroplastika je detektovana u površinskim vodama, sedimentima i bioti, uz izraženu prostornu i vremensku varijabilnost povezanu sa hidrodinamikom, riječnim unosima i sezonalnošću. Ovaj pregledni rad sumira postojeće dokaze o rasprostranjenosti, sastavu, izvorima i pokretačima mikroplastike širom Jadranskog mora, sa posebnim naglaskom na Crnu Goru, gdje istraživanja sedimenta i školjki ukazuju na značajnu kontaminaciju u kojoj dominiraju polietilen i polipropilen. Obalni sedimenti Crne Gore u prosjeku sadrže 300–600 čestica mikroplastike kg^{-1} suvog sedimenta, pri čemu su najveće koncentracije zabilježene u zatvorenim područjima poput Bokokotorskog zaliva. Iako Okvirna direktiva o morskoj strategiji pruža institucionalni okvir za praćenje i upravljanje, metodološka heterogenost među studijama i značajni nedostaci podataka, posebno nedostatak sezonskih podataka o mikroplastici na površini mora duž istočnog Jadrana, trenutno ograničavaju regionalnu uporedivost i procjenu dugoročnih trendova. Prioritetne potrebe za Crnu Goru i širi Jadran uključuju usklađeno praćenje površinskih voda, integraciju hidrodinamičkog konteksta i procjene relevantne za zainteresovane strane koje povezuju ekološke indikatore sa akvakulturom, turizmom i bezbjednošću hrane iz mora.

Ključne riječi: mikroplastika, Jadransko more, Crna Gora, zagađenje mora, Mediteran