Environmental Pollution 273 (2021) 116430

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Review

A critical review on marine litter in the Adriatic Sea: Focus on plastic pollution

Chiara Schmid, Luca Cozzarini, Elena Zambello*

Department of Engineering and Architecture, University of Trieste, Via Valerio 6A, 34127, Trieste, Italy

ARTICLE INFO

Article history:
Received 10 November 2020
Received in revised form
31 December 2020
Accepted 31 December 2020
Available online 18 January 2021

Keywords:
Adriatic sea
Marine litter
Microplastic
Macroplastic
Review

ABSTRACT

Marine litter affects various habitats across the world. This review focuses on the Adriatic region, considering the presence of marine litter as well as microplastics (mPs) and macroplastics (MPs) in different environments (water, beach, seabed and biota). Data from 53 scientific papers were critically analysed, providing a snapshot of this type of contamination, and evidencing critical issues. The final part of the review provides considerations on spatial and temporal trends, comparing data with the available information provided by transport forecasting models. It emerges that the most investigated areas are those most subjected to the contribution of rivers, tourism or have the greatest relevance to nature conservation. Our analysis also reveals that, even though many international research projects have played a fundamental role in the creation of shared methods and protocols, currently available data are difficult to compare. Nevertheless, our results enhance knowledge of the state of the art in the research carried out so far, and on the situation regarding pollution due to the marine litter in the Adriatic Sea, as well as highlighting avenues for future investigation.

1. Introduction

The term marine litter indicates any object which has been artificially manufactured or processed that reaches the marine environment after its use. Due to current high plastic consumption patterns, this material has become the main type of waste affecting marine environments. Most waste comes into the sea from the bordering lands and river mouths (Vlachogianni et al., 2017).

In recent years, the growing presence of microplastics (mPs) in marine environments has provoked increasing concern, particularly considering their prevalence in water, sediment and biota. Owing to their small size, these particles can pose high risks to the environment. Globally, numerous recent investigations have documented the problems related to their collection, identification and occurrence, and the associated risks to the environment and human health (Cincinelli et al., 2019; Oliveira and Almeida, 2019; Pinto da Costa et al., 2019, Schmid et al., 2020), but it is difficult to compare results from different studies as methodologies, and study designs are not uniform (Prata et al., 2019; Stock et al., 2019; Li et al., 2019; Rios Mendoza and Balcer, 2019). Only in recent years, international protocols have begun to be proposed and adopted by various territorial cooperation projects (Cheshire et al., 2009; OSPAR Commission, 2010).

Although much research has been conducted, the overall knowledge of these issues in the Adriatic Sea is still limited and fragmented. Indeed, the 2014 review by Vlachogianni and Kalampokis emphasized that information relating to the Adriatic is scarce, and available data is based on limited observations of floating waste from boats, and transect widths have been very variable, from 22 to 150 m (depending on the type of boat and its speed). Furthermore, data on the supply of waste by rivers are not reported.

The Adriatic Sea is an elongated basin which extends for about 800 km from NW to SE between Italy and the Balkan regions. It has a high land to sea ratio (Ludwig et al., 2009), and collects a third of the freshwater flowing into the Mediterranean, mainly via the River Po (Gajšt et al., 2016).

The average depth of the Adriatic ranges from about 35 m (the northern part) to 140 m (central part), reaching 260 m in the Pomo Depressions. This semi-enclosed basin, surrounded by Italy, Slovenia, Croatia, Bosnia and Herzegovina, Montenegro, Albania, and Greece, receives freshwater mainly from the River Po (Gajšt et al., 2016), the largest Italian river, but is also fed by numerous other rivers that drain the highly densely inhabited, industrialized, and intensively cultivated areas of northern and central Italy

* Corresponding author.
E-mail address: ezambello@units.it (E. Zambello).

https://doi.org/10.1016/j.envpol.2021.116430
0269-7491/

(Sagratini et al., 2008). The southern area of the basin lacks substantial riverine inputs (Mistri et al., 2017).

Along the coasts, human activity is intense, with heavy marine traffic, intensive mussel aquaculture, fish farming and seasonal tourism. These activities are fundamental economic sources for the countries bordering the basin but likely contribute to the dispersion of litter in the Adriatic Sea. It has been estimated that 40% of marine litter enters the Adriatic basin through the rivers, an additional 40% through coastal urban populations, and the remaining 20% through shipping and fishing activities (Liubartseva et al., 2016). One study calculated that the Po river discharges 120 tons of litter and 7 E+11 micro litter particles per year (Van der Wall et al., 2015). Others have reported that land-based activities are a major input of marine litter in the Adriatic Sea (Vlachogianni et al., 2017, 2018), with an increasing number of cases of waste pollution from ships in the period from 2005 to 2010 (Tisma et al., 2019).

On a larger geographical scale, studies on the spatial distribution of marine litter have identified the Adriatic region as a preferential area for plastics accumulation within the Mediterranean Sea (Liubartseva et al., 2016; Ruiz-Orejón et al., 2016; Carlson et al., 2017; Zambianchi et al., 2017) thanks especially to transboundary effects caused by sea currents (Palatinus et al., 2019). According to Pasquini et al. (2016), the Adriatic Sea is one of the areas most affected by benthic litter. Microplastic pollution in the Adriatic Sea has been demonstrated in all abiotic compartments, including beaches, surface waters, sediments and biota. Despite this fact, data is still limited, and still lacking in the standardized approach for assessing marine litter recently adopted thanks to European Directives, but whose implementation is still on going.

A recent work by Tisma et al. (2019) emphasized the importance of allocating financial resources to preserve and protect the Adriatic Sea, as the loss of benefits due to marine pollution would significantly exceed the costs needed for its prevention. Homogeneous field campaigns by several national environmental institutions are underway in order to monitor marine litter occurrence according to the Marine Strategy indications and following the protocol developed by the DeFishGear project, but collected data are not yet easily available.

The primary goals of monitoring and research must be to quantify and characterize the types of plastic affecting the area, and sites at which it accumulates. It will also be important to monitor whether the different legislative actions adopted by the different states are effective, i.e., whether there is a reduction over time. A third issue that needs to be resolved is what to do to remedy the situation. In an attempt to address these questions, we sorted, analysed and studied all the available research on marine litter in the Adriatic Sea in order to provide a comprehensive overview of the findings available to date. To improve readability, Table S1 lists and describes the most used acronyms.

2. Review framework

This review draws data from all of the 53 peer-reviewed international scientific papers and the main reports published between 2013 and 2020 (listed in Table S2) dealing with marine litter and/or mP and macroplastic (MP) occurrence in the Adriatic Sea. Table S3 lists the main information and topics addressed by the selected papers. First, we report and analyse data on the litter on the beach, in the water and on the seabed. Then, we focus the attention on macro- and microplastics in the same environments, including biota. For each investigated matrix, tables are presented in the Supplementary Data, bringing together data from the related articles, specifying the locations, dates and main results of each monitoring campaign. The temporal order of the sampling campaign is generally respected, although in some cases it was preferred to describe topics by type of campaign or investigated area. An attempt has been made to analyse spatial and temporal trends in plastics occurrence and, whenever possible, the results have also been assessed in light of transport modelling simulations. This strategy provides a fairly comprehensive overview of the situation, and identifies the most investigated and most polluted areas, as well as the most common plastic litter. It also suggests possible solutions for better monitoring and management, highlighting the most critical issues, for example sampling.

Among the selected papers, 19 works derive from the DeFishGear (DFG) project, implemented within the framework of the IPA Adriatic Cross-border Cooperation Programme for achieving comparable scientific data on marine litter in the Adriatic-Ionian macroregion (Table S3). One of the goals of DFG project (conducted over 3 years from 2013 to 2016) was to investigate, through the implementation of pilot projects, the feasibility of implementing the FFL (Fishing for Litter) initiative. Three other papers were published as part of the SoleMon project (Table S3), which concerns the ingestion of microplastics by fish, and in some cases reports the quantity of microplastics found in the sea. A further three articles were products of the FAO-ADRIAMED Project, two of the RitMare project, one of the Act4litter project, one of the Baseman, one of EPHEMARE, one of the NIXE III and one of the MONITA project (Table S3). Two recent papers were researched with the respective support of the LIFE programme (de Francesco et al., 2019), and a bilateral Slovenian and Montenegrin project (Šilc et al., 2018). The remaining 20 papers are either antecedent (Vianello et al., 2013) to the DFG project or not part of the projects mentioned.

30 investigations have been carried out in Italy, 16 in Croatia, 12 in Slovenia, 10 in Montenegro, 6 in Albania, 4 in Greece, and 3 in Bosnia Herzegovina (Fig. 1). The graph in Fig. 1b reveals that most of the campaigns were carried out between 2014 and 2015. After this date, the number of campaigns decreased due to the projects ending.

The majority of the selected articles were outputs of funded projects with different purposes and relying on different methods. Fig. 1c shows the projects' duration. About 45% of the selected articles deal with "litter", that is general waste (usually of macroscopic size), differentiated into categories, including plastics. Despite geographical differences, plastic items were in the vast majority in numerical terms. About 35% of the studies analysed investigated the presence of plastics, both macro- and microparticles, in water, sediment, and/or on the seabed. Water and seabed sediments have been the most studied environments (42%) followed by beach sediment (36%) and biota (18%). Not even one study attempted to quantify very small particles (the so-called nanoplastics). It should be noted that the definitions of macro-, meso-, micro- and nanoplastics are still ambiguous; since the size classification was not always specified, we adopt the terms as used by the respective authors. Table 1 provides an example of the different definitions applied.

3. Discussion

3.1. Sampling methods

The first review related to the DFG project (Vlachogianni and Kalampokis, 2014), highlighted the most problematic issue, namely which procedure to use for sampling microplastics. Indeed, without an accurate, standardized procedure, it is very hard to effectively compare data. Macro-waste collection on beaches (Table S4) generally follows the methodology according to the MSFD protocol (European Parliament and Council, 2008), i.e.,

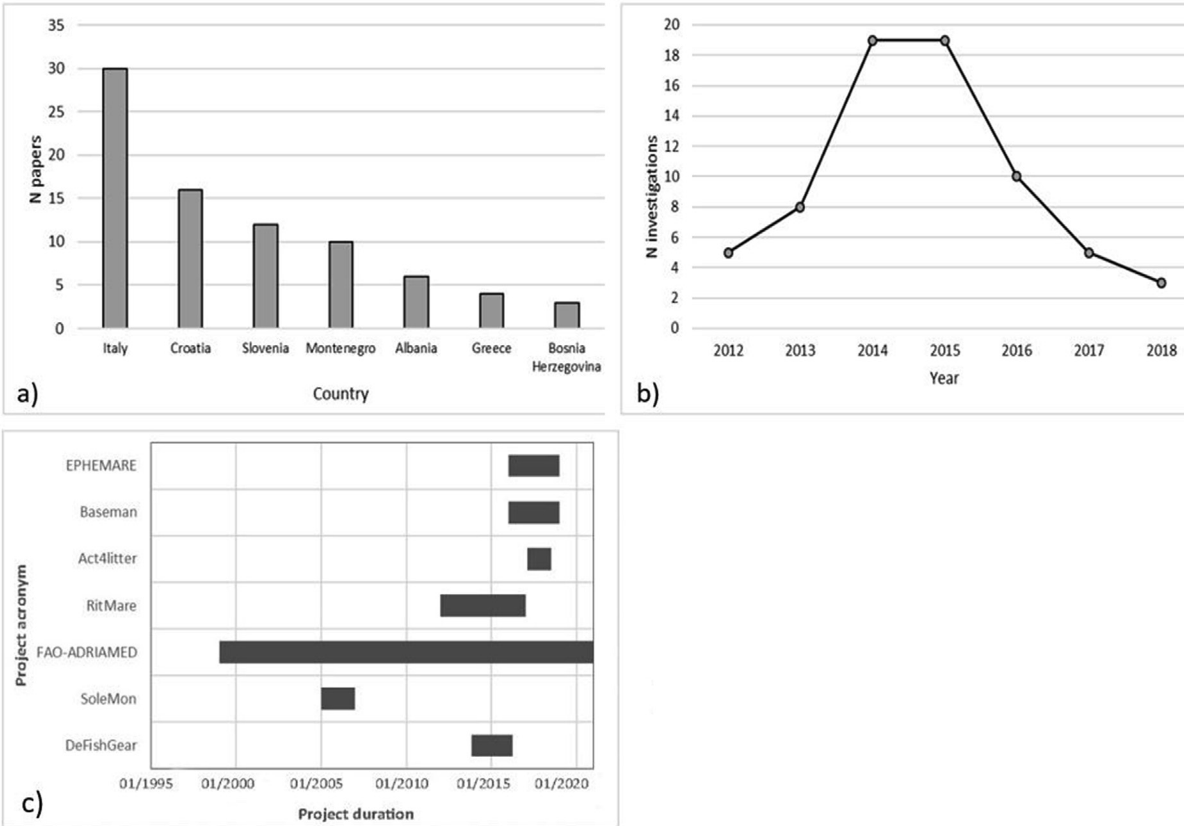

Fig. 1. Location of the field campaigns (a), number of investigations for each year (b), and project duration (c).

Table 1
Plastic waste classification according to the size reported in several references.

Reference	Macroplastics	Mesoplastics	Microplastics	Nanoplastics
Gregory (1996)				<0.5 mm
Thompson et al. (2004)			Around 0.2 mm	
Arthur et al. (2009)			<5 mm	
Imhof et al. (2012)	>20 mm	5 mm–20 mm	<5 mm	
Masura et al. (2015)		5 mm to 20 cm	<5 mm	
Gonzales et al. (2016)	>25 mm	5 mm–25 mm	<5 mm	
Gago et al. (2016)			<5 mm	
Hartmann et al. (2019)	>1 cm	1 mm–10 mm	1 μm–1000 μm	1 nm–1000 nm

detailing the number of objects collected per 100 m of beach and identifying them by type of waste (Galgani et al., 2013a; 2013b). The main purpose of the division of waste into categories, which could be defined as product sectors, was quite clearly to determine the origin of the waste, with a view to trying to cut off their flow at the source. For macro litter floating in the seawater, there has been no real sampling *per se*, merely observation (Table S5). Only in one case sampling has been performed with a manta net (Palatinus et al., 2019). Seabed litter can either be collected with bottom trawls or observed when scuba and/or snorkelling (Vlachogianni et al., 2013a; 2013b; 2013c; Vlachogianni and Kalampokis, 2014) (Table S6). However, the data gathered through visual inspection (scuba/snorkel) are reported as 27,800 items/km^2, not comparable with those above found with trawl nets (510 ± 517 items/km^2) (Vlachogianni et al., 2017). Moreover, Fortibuoni et al. (2019) noted that, as far as the sampling method is concerned, on continental shelves the use of trawl nets is an efficient method, while in shallow water it is better to perform visual surveys with scuba.

As regards the methodologies for collecting microparticles, these will also differ according to the matrix. From the different studies we examined, we consider only the data concerning plastic particles. In the case of beaches, different collection methods have been used, from box corers to spoons, implemented on the surface or at greater depth (Table S7). The same applies to offshore harvesting with different tools, ranging from fishing nets to manta trawls (Table S8). The collection of mPs from the seabed is also achieved by different sampling devices, from box corers to Van Veen grabup and glass jars (Table S9). To standardize the data monitoring of mPs, during the DFG project, Kovač Viršek et al. (2016) prepared a protocol for particles smaller than 5 mm. The protocol involved sampling the sea surface (manta net with 300-μm mesh), the separation of the microplastics from the samples collected (by flotation in NaCl solution), followed by their identification as such through ATR-FTIR and μFTIR. Based on indications by the MSFD, the results must report the shape of the microplastics (fragments, films, pellets, granules, filaments and foams) and their quantity in items/km^2. From the papers analysed in this review, it emerges that in the open sea, manta trawl, Neuston, bongo and plankton nets with mesh sizes ranging between 200 and 333 μm have been used for this purpose. Obviously, the amount of mPs collected by the different nets will differ according to their mesh size.

In the case of sediments, mP quantification has been reported in terms of the dry weight (d.w.) of sediment collected, both in number items and in weight. However, the different collection methods have different potential, and it is difficult to say which one is the most suitable in absolute terms. It has been noted (Green et al., 2018) that for floating debris the difference between the data obtained via bongo net (>500 μm), manta net (>300 μm), plankton nets (>200 μm and >400 μm), and collection of 1 L of bottled water (then filtered at 0.45 μm), can be huge, giving, for the last method, particle numbers 3 orders of magnitude higher than the others obtained. Moreover, using a PVC corer or metal spoon for sediment collection will result in different results concerning the quantity, shape and type of mPs (Piperagkas et al., 2019). Regarding the waste on the seabed, although the bottom trawling strategy may be the most appropriate, it tends to underestimate the actual waste (Vlachogianni and Kalampokis, 2014). In short, data gathered using different sampling methods can vary widely, and therefore be impossible to compare.

3.2. Marine litter

3.2.1. Beach

As can be seen from Table S4, the collection of marine litter is done manually, and the distinction between the different wastes is generally made by categories, as mentioned above (Galgani 13a and 13 b). The majority of beach litter is composed of plastic fragments with numerical percentages that vary between 57% and 94%, depending on the area. The chemical nature of these plastics is not reported, but the categorization shows that the largest share is made up of caps (PP) and packaging materials (PE). There is a systematic distinction between plastic, PS foam and rubber.

The differentiation between generic plastic and PS foam has revealed that the latter, due to its low density (15–100 kg/m^3), is also found in more inland areas (de Francesco et al., 2018; Šilc et al., 2018). Accordingly, the protocols (Galgani et al., 2013a; Masura et al., 2015) specify massive sampling must be carried out on the beaches and on the seabed, taking into account the global mass collected.

In only two cases (Laglbauer et al., 2014; Vlachogianni et al., 2017) was the mass per unit area reported, in all the other cases only the number of objects per unit area is given. On the beaches of Slovenian coasts classified as touristic, an average of 64% of waste was plastic, whereas on non-touristic beaches it was 71% (in both cases considering plastic plus rubber) (Laglbauer et al., 2014). This confirms that where cleaning for tourism purposes is not carried out, debris remains and accumulates.

More recent harvesting campaigns (in 2018) on the Italian coast (de Francesco et al., 2019), and Croatian coast (Mokos et al., 2019) have not yielded very different results, with a prevalence of plastic litter reported as 85% and 94% respectively. In the second case, the reported litter density (3.4 ± 3.6 items/m2) is higher than that reported by Vlachogianni et al. (2018) in the period 2014–2016. All the investigated beaches are sandy, and no author has specifically analysed rocky beaches to determine the difference that can occur.

3.2.2. Seawater

Regarding the presence of macro waste in the sea, the majority of the research has relied on ship-board observation (with the naked eye or binoculars) of floating litter. All the literature data related to macro litter floating in the sea are reported in Table S5. Some observations are relative to Mediterranean Sea monitoring (Suaria and Aliani, 2014; Arcangeli et al., 2018). Restricting their data to the Adriatic Sea area, the waste was differentiated by anthropological and natural origin; it is not surprising that the majority was made of plastic, of obvious anthropological origin. The reported concentrations vary from 22 items/km^2 (in the area facing Montenegro) to 52 items/km^2 (in the waters between Ancona and Zadar) (Suaria and Aliani, 2014). However, Arcangeli et al. (2018) reported an average density of anthropological litter of 4.7 ± 0.5 items/km^2; the difference in this case was probably to the different speeds of the vessels used for the survey (slower in the former case), and that the objects recognized were of different size (>2 cm in the first case, > 20 cm in the second one). Data gathered can also differ according to whether the observation is made from small boats or ferries. Taking the former as more precise, the litter density increase to 332 ± 749 items/km^2, with identification of pieces of size greater than 2.5 cm, while from ferries it is only possible to see pieces greater than 20 cm, with a numeric average of 4 ± 3 items/km^2 (Vlachogianni et al., 2017).

Furthermore, seasonal variations were observed, with the maximum density being during the winter (Arcangeli et al., 2018). Indeed, Carlson et al. (2017) compared the data reported by Suaria and Aliani (2014) with that collected in a subsequent campaign in 2015. They also found that the global average density of floating waste varies by the period, specifically 32 ± 31 items/km^2 in May 2013, 115 ± 173 items/km^2 in March 2015 and 75 ± 74 items/km^2 in November 2015.

Palatinus et al. (2019) conducted a study in the area of the Dalmatian islands of Kvarner-Velebit and the Zadar-Šibenik archipelago in April 2015, collecting floating macro debris with a manta net. The average results were 175 items/km^2 of floating macro debris and 127,000 items/km^2 of floating micro debris. It seems that the majority of macro and micro debris was plastic, but there is no numerical data provided to enable examination.

The type of floating waste has not always been reported; when reported, it turns out that the majority is composed of bags (and therefore presumably PE) and expanded PS (foam), both have a lower density than seawater and therefore float. Hence, unsurprisingly, the majority of floating macro wastes appear to be plastics.

3.2.3. Seabed

All literature data related to macro litter on the seabed are reported in Table S6. The methods used to collect data on seabed waste have been very different, varying from observation by scuba (Macic et al., 2017; Vlachogianni et al., 2017) or remotely operated underwater vehicle (ROV) (Melli et al., 2017), to actual collections with trawling nets (Strafella et al., 2015, 2019; Pasquini et al., 2016) or Van Veen grab (Palatinus et al., 2019). The type of debris on the seabed is different to what we have seen so far. Not only is plastic found, but in some cases, the most common finds are glass and metal (which, being heavier, sink). In general, the greatest quantity of seabed litter is found in coastal areas (Strafella et al., 2015; Pasquini et al., 2016; Macic et al., 2017; Palatinus et al., 2019), while offshore the seabed is less dirty. The highest density of litter is found at the mouths of rivers, in particular the Po (Strafella et al., 2015; Pasquini et al., 2016), and in the more urbanized areas, such as the Boka Kotorska (Macic et al., 2017). In this case, the percentages of plastic differ, being lower inside the Bay of Kotor (57%) and higher outside (82%).

In the study by Strafella et al. (2015) the data were also divided by sampling depth; taking into consideration only plastic and rubber, there was a significant decrease in the quantity (expressed in kg/km^2) as the depth increased, as shown in Fig. S1. These results were probably caused by a less intensive anthropic influence far from the coast. Only Melli et al. (2017) made some considerations on the possible influence due to different types of backdrops; in two campaigns conducted one year apart (May–June 2014 and July 2015) on the seabed in front of Chioggia, they found that the litter concentration was higher on the rocky seabed with respect to the soft one. This is probably because small particles can sink into the sand, and are also less visible because of the greater turbidity.

3.3. Macro- and micro-plastic

When reporting litter collection, usually macro, the chemical classification has been fairly rough. Since the studies focused on mPs, i.e., those smaller than 5 mm, however, it is important to define their chemistry as well. In reality, though, many studies have limited themselves to classification by shape (filaments, fragments and pellets) and colour. For this classification it was, and is, sufficient to use an optical microscope (more or less sophisticated). However, for determination of the polymer type, other techniques are essential. In the aforementioned DFG protocol (Kovač Viršek et al., 2016), for example, explicit reference was made to the infrared spectroscopic technique (FTIR), although, as we shall see, other techniques have been added.

3.3.1. Beach

In Table S7 all the data related to mPs on beaches are summarized. As can be seen, the research has concentrated on three distinct areas: beaches in Slovenia (Laglbauer et al., 2014; Korez et al., 2019), beaches in Croatia (Maršić-Lučić et al., 2018) and beaches around the Po Delta in Italy (Munari et al., 2017; Atwood et al., 2019; Piehl et al., 2019). In almost all the studies, identification was performed via FTIR. Exceptions are the first study of the beaches of Slovenia (Laglbauer et al., 2014), in which only the observation by optical microscopy (MO) was made, and that by Maršić-Lučić et al. (2018) (beaches of the island of Vis, Croatia). In the latter case, the purpose of the investigation was to determine the presence of heavy metals on plastic pellets, which were collected but not analysed for polymer identification.

In the case of the Slovenian beaches, there was no difference in mP density between tourist and non-tourist areas (Laglbauer et al., 2014), but a seasonal variation in mP density was observed, being lower in March than in August (Korez et al., 2019). On River Po Delta the works of Munari et al. (2017) conducted in May 2015 as well as Atwood et al. (2019) and Piehl et al. (2019) in June 2016 focussed on. In all these cases, plastic was identified by ATR-FTIR, although not on all collected particles. As is possible to see in Table S7, the reported average densities are very different because different beaches yielded different results. In any case, the most common polymers found were PE, PP and PS.

A significant relationship between the average concentration of mPs and riverine runoff was found (Munari et al., 2017). Atwood et al. (2019) hypothesized that there is a process of accumulation along the front between freshwater and seawater with greater salinity. They also reported a rough estimate of the amount of floating mPs brought by the Po; this varied between 2.2 and 3.8 tons per day (785–1402 t/year), which is close to that of the 1340 t/year estimated by Liubartseva et al. (2016). It is interesting to note that, in general, FTIR identification was not performed on all collected particles, but only on a fraction. Bearing in mind Korez et al.'s (2019) report that false positives are possible, and that only 11% of the collected particles with a size > 0.1 mm were recognized as plastic, it is important to underline that plastic identification only via MO can lead to an important overestimation as regards the density of mP.

3.3.2. Seawater

All literature data related to macro- and microplastics floating in the seawater are reported in Table S8. For the collection of macro- and microplastics at sea, nets of different mesh sizes have been used, specifically 200 μm (Suaria et al., 2016), 300 μm (Atwood et al., 2019), 308 μm (Kovač Viršek et al., 2017; Palatinus et al., 2019) 330 μm (Vianello et al., 2018; Zeri et al., 2018) and 333 μm (Ruiz-Orejon et al., 2016; de Lucia et al., 2018). de Lucia et al. (2018) also made a comparison between sampling with a manta trawl and a plankton net, both having 333 μm mesh, finding no significant differences. Plastics identification was performed via ATR-FTIR (Suaria et al., 2016; Kovač Viršek et al., 2017; Zeri et al., 2018; Atwood et al., 2019), μATR-FTIR (Vianello et al., 2018), or HSI-FTIR (Bonifazi et al., 2017), usually on a fraction of the collected particles, often the larger ones. In some cases, the % of false positives is also reported, respectively, as 4.4% (Suaria et al., 2016), 5% (Zeri et al., 2018; Palatinus et al., 2019), and 14% (Gajšt et al., 2016). It can therefore be deduced that the reported plastic densities are generally overestimated. In one case (Ruiz-Orejon et al., 2016) the data refer to plastics (macro-, meso- and microplastics) without differentiation, and the definition of plastics being based solely on MO observations. In the study by Vianello et al. (2018), however, the carbonyl index was also calculated to highlight the state of degradation of the plastics.

Kovač Viršek et al. (2017) found a significant difference in mP concentration (Slovenian water) in terms of $items/km^2$ between 2014 and 2015 (greater quantity), attributed to different climatic conditions: in August 2014 a bora wind was blowing, while in May 2015 there was a SW wind, which suggests an influence of the River Po Delta. As shown in Fig. S7, the winds influence the flow direction of the Po river discharge.

Zeri et al. (2018) only visually identified macroplastics (>2.5 cm) from small boats. Gajšt et al. (2016), on the other hand, presented the results of four campaigns on the waters from Koper to Portorož between December 2012 and August 2014, but unfortunately did not homogeneously differentiate macro litters from mPs; they assumed that all the particles of size < 5 mm were mPs, but as only 14% of the total particles were analysed via NIR, their attribution is therefore uncertain.

Nevertheless, the most abundant polymers in all the studies were PE (from 26% to 88%) and PP (from 5% to 30%). Of all the data collected, those derived from MO analysis are relative, and only take into account large–medium-sized plastics; therefore, they cannot be compared with other data. Furthermore, a variety of units of measurement were used, specifically $items/m^2$, $items/m^3$, $items/km^2$, and merely items; only in two cases was data in g/km^2 also reported (Suaria et al., 2016; Zeri et al., 2018).

3.3.3. Seabed

All literature data related to macro- and microplastics on the seabed are reported in Table S9. Plastics were collected from the seabed via either Van Veen grab (Mistri et al., 2017; Renzi et al., 2018a), box corer (Vianello et al., 2013) or scuba divers (Blašković et al., 2017; Renzi et al., 2019; Renzi and Blašković, 2020). Polymer identification was carried out by either μ-FTIR (Vianello et al., 2013; Renzi et al., 2019; Renzi and Blašković, 2020) or ATR-FTIR (Mistri et al., 2017; Renzi and Blašković, 2020), but in other cases only the shape was assessed (Renzi et al., 2018a; Blašković et al., 2017), excluding the particles dissolved by HCl (Blašković et al., 2017). In the latter cases, obviously, it cannot be said that a real chemical identification was performed. Moreover, not all the collected particles were always subjected to FTIR analysis. However, when the total amount of particles was analysed (Renzi and Blašković, 2020), many fibres were found to be cellulose or cellulose acetate, defined by the authors as non-synthetic; this statement is perplexing, given that cellulose acetate, although derived from natural fibres, is "denatured" by actual chemical processes.

According to the data reported, the mP concentrations, often expressed in items/kg d.w., are highly variable, depending strongly on the geographical area. For example, in the stretch of sea between Pescara and Pianosa (Mistri et al., 2017) mP density ranged from 2.5 to 88 items/m^2 (between 2 and 1700 mg/m^2). In the islands in front of Zadar (Croatia) in December 2015, on the other hand, average values were reported as between 32 and 397 items/kg d.w. (Blašković et al., 2017), while Renzi et al. (2019), in October 2017, found an average concentration of 307 $\pm$ 108 items/kg d.w. (mP size $\leq$5 mm). In the same area investigated by Blašković et al. (2017), Renzi and Blašković (2020), once again in October 2017, found an average mP concentration of between 113 and 378 items/kg d.w. in the sediment.

In this case too, a variety of units of measurement were used, although the majority of the authors do report the density in items/kg d.w. Chemical identification was not always performed — often it is based only on observations at the MO. Moreover, false positives were found, but not quantified. Naturally, the data reported are highly variable, as a function of the collection site; the worst situation was found within the Venice lagoon, but that was some time ago. Surprisingly, no other investigations have since been conducted in this area.Where identified, the majority of plastics were found to be PE and PP, even though significant percentages of PA and PVC were found in some cases.

3.3.4. Biota

Among the scientific research articles discussing mPs and biota, some analysed the stomachs of fish (Vlachogianni et al., 2017; Avio et al., 2015, 2020; Pellini et al., 2018) Anastasopoulou et al. (2018), and found variable values for mP/individual depending on the fishing area and type of fish; they ranged from a minimum of 1.3 items/individual (Avio et al., 2015) to a maximum of 1.8 items/individual (Avio et al., 2015). In a few other cases, it is only mentioned, in general terms, that 98% of the waste found in the biota was plastic (Vlachogianni et al., 2017; Anastasopoulou et al., 2018).

Some other research focused on invertebrates (Renzi et al., 2018b; Avio et al., 2020; Piarulli et al., 2020; Gomiero et al., 2019). In all these cases, mPs were found in different proportions, depending, once again, on the area and the species. For instance, there was a difference in mPs between mussels gathered in 2013 between Cesenatico and Ancona in the coastal area (1.06–1.33 items/g wet weight if fragments, 0.6 items/g w.w. if fibres) and those found in the open sea (half for both measurements) (Gomiero et al., 2019). For several species of invertebrates, gathered in 2016 in the northern Adriatic, a concentration of 1.44 items/individual was found, with no significant difference in mP concentrations in fish from same area (Avio et al., 2020). In other cases, however, a higher concentration, 12.4 items/mussel (9.2 items/g w.w.), was found in commercial mussels from around Cesenatico (Renzi et al., 2018b).

When the types of plastic were identified via FTIR, there was a prevalence of PVC, PP and PE (Pellini et al., 2018); in other cases, it was found that 89% of the fibres collected (fishes and invertebrates) were non-synthetic (Avio et al., 2020). Renzi and Blašković (2020) during a harvesting campaign in October 2017 (Croatian islands of Silba and Telašćica), compared the occurrence and type of mPs found in sea cucumbers (Holothurians) and sediments from the seabed adjacent to the animals. The average particle density was higher in sediment than in sea cucumbers (0.6–9.4 items/animal), with a size ranging from 1.4 μm to 10.5 μm. They found many "natural" fibres (cellulose and cellulose acetate), which were therefore not counted as microplastics.

Frapiccini et al. (2018) studied the accumulation of polycyclic aromatic hydrocarbons (PAHs) in specimens of sole (*Solea solea*) fished between November and December 2014 in the upper Adriatic, between the River Po Delta and towards Venice. From the data presented, however, it is not clear whether PAHs accumulate or not, and it is not clear whether mPs play any role in this. Pinto et al. (2019), on the other hand, analysed the communities of bacteria that develop on commercial plastics (PVC, PP, LDPE and HDPE) under different conditions on samples from the seawater 500 m from the Rovinj coast. This analysis provided results that differed according to the plastic in question, but the authors concluded that in the early stages the surface morphology of the plastic plays a bigger contribution, while over time the surface biofilm becomes dominant. However, it is important to note that they did not investigate the influence of additives in the plastics.

As we have seen, several approaches to mPs and biota have been taken, making data difficult to compare. Although it is possible to compare findings regarding mPs found in fish stomachs, there were differences related to the species and their habitat. Moreover, comparison of mussel data is problematic, especially as incomparable units have been used (items/individual versus items/g w.w.). In many cases, fibres were predominant, but were often not synthetic.

3.4. Geographical distribution and temporal trends

As can be seen from the analysis above, some areas have received more attention (like River Po Delta and Slovenia) while others have been poorly investigated. Fig. S2 shows the geographical distribution of the research concerning beach monitoring campaigns. In the areas around the River Po Delta, eight articles have been published (Munari et al., 2017; Vianello et al., 2018; Piehl et al., 2019; Pasquini et al., 2016; Vlachogianni et al., 2018; Atwood et al., 2019; Bonifazi et al., 2017; de Lucia et al., 2018); the position of the field campaigns is reported in Fig. S3, highlighting the object and type of environment considered in the analysis. From these images, it is evident that most of the studies on the Po Delta have focused on mPs. Munari published two reports (Munari et al., 2016, 2017), both relating to the same sampling campaign in 2015; the first dealing with macro litter, and the second with microplastics. Table S7 presents the data for each beach. The quantities are expressed as number of items per beach area (item/m^2) for macro litter, while mP concentration is expressed as both the number of particles per area of beach and the number of particles per kg of sediment dry weight.

Data on macro litter distribution are fairly homogeneous (apart from that pertaining to Volano beach, the closest to the Po Delta). It is interesting to note that, for mPs, there is a systematic high density on the beaches downstream and south of the mouths of rivers: Rosolina below the Adige river (245 items/m^2), Volano below the Po river (320 items/m^2), Casalborsetti below the Reno river (131 items/m^2); while Bellocchio, above the Reno river, has a lower density (88.6 items/m^2). These data show, once more, that rivers are also responsible for mP pollution. Vianello et al.'s (2018) paper reports data for two different periods in 2014, March and April, recorded at different depths facing the Venice lagoon (Pellestrina) and the River Po (Della Pila). In the sea by Pellestrina, apart from a particularly high data point offshore, there was no difference between the two months, while by the River Po they found 1.7 items/m^2 in March, but this concentration dropped to 0.2 items/m^2 in April (Table S8); this difference is likely due to the great variability in the Po river flows.

Melli et al. (2017) (Table S6) photographed macro litter on the seabed in the sea off Chioggia (Sottomarina) in two campaigns, one in May–June 2014 and one in July 2015, but, as already reported, there was no difference in concentration between 2014 and 2015. However, it is not possible to compare these results with those of others. Table S9 reports all the available data, ordered by year of sampling. Due to the differences in the data, even in apparently identical sites, it is not possible to clearly define a temporal trend. As can be expected, the abundance of microplastics on the seabed is highest in the Venice lagoon, not only due to pollution from the land but also due to the reduced flow of currents. Considering only the data from the beaches reported using the same unit of measurement (items/kg d.w.), it appears that the situation is almost static. Fluctuations depend on the fact that the analysed beaches do not all have the same degree of cleanliness, as well as potential differences in climatic conditions.

Another area for which several datasets are available is the waters and beaches of Slovenia in the Gulf of Trieste (Fortibuoni et al., 2019; Gajšt et al., 2016; Korez et al., 2019; Kovač Viršek et al., 2017; Laglbauer et al., 2014; Pasquini et al., 2016; Renzi et al., 2018a; Ronchi et al., 2019; Vlachogianni, 2019; Vlachogianni et al., 2018; Zeri et al., 2018). All the data regarding Slovenia are summarized in Table S10. As already mentioned, chemical identification via FTIR, when performed, usually concerns only a fraction of the collected particles (Gajšt et al., 2016; Korez et al., 2019), making it difficult to consider the reported mP data as completely reliable. Zeri et al. (2018) sampled the Gulf of Trieste (Slovenian waters), among other areas, between autumn 2014 and summer 2015. The paper does not report the individual data, but the global ones related to the Adriatic Sea. The data reported in Table S10 are taken from their Fig. 2 for the Gulf of Trieste. The data reported (Renzi et al., 2018a) is also inferred from their work; it pertains to the sea area off Piran. As already reported, Korez et al. (2019) detected an increase in mPs in August, with respect to March. If we compare the data collected by the different authors, more or less in the same period, we see a very strong variation, which can only be explained by the strong influence of winds on the displacement of plastic fragments (macro and/or micro), as pointed out by Kovač Viršek et al. (2017). In this regard, the maps of the individual sample collection sites for Slovenia are reported in Fig. S4, in order to highlight how they almost overlap. Comparing the data from the two papers by Vlachogianni (2019) and Vlachogianni et al. (2018), as regards the beaches of Strunjan and Bele Skale (shown in Table S11), it is evident that the situation can

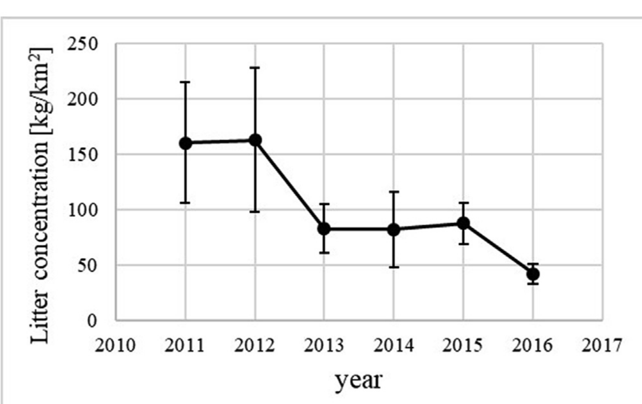

Fig. 2. Trend in litter concentration in the Adriatic according to Strafella et al. (2019); average data with standard deviation.

improve over time. Considering the data on the quantity of generic litter reported by Strafella et al. (2019), there is a significant decreasing trend between 2011 and 2016, as evidenced by the statistical analysis performed by the authors, shown in Fig. 2.

According to Pasquini et al. (2016), the Adriatic is the dirtiest sea in the world in terms of litter concentration on the seabed. This can be explained by the relatively shallow depth of the sea and proximity of the coasts, which are heavily populated, as well as the presence of major rivers that can transport waste. Liubartseva et al.'s (2016) data suggests that the greatest contributor in this regard is the Po River. Examination of all the data collected, presented in Tables S4–S6 (macro litter) and S7–S9 (mPa and MPs), shows that analysis of any temporal trend is not feasible, due to various reasons; in some cases, mPs have not been clearly identified, with only "litter" being mentioned, whereas in other cases, the weather conditions preceding the sampling are not reported, and these have been seen to have a strong impact. In other cases, the data is likely to be overestimated, identifying natural fibres as mP.

3.5. Transport model simulation

The transport of marine litter and microplastic particles in seawater is affected by complex dynamics due to the movement of sea currents, changes in chemical and physical characteristics, fragmentation and aggregation phenomena (Andrady, 2017), as well as interactions with biota (Law and Thompson, 2014). In order to identify the pathways of floating marine litter in relation to the variation in the input locations, some numerical hydraulic simulations have been performed for the Adriatic Sea (Carlson et al., 2017; Gajšt et al., 2016; Liubartseva et al., 2016), defined as a highly dissipative basin with an evident seasonality in the plastic concentration and fluxes. Sea surface plastics' occurrence and fluxes over 2009–2015 were simulated by Liubartseva et al. (2016), incorporating combinations of terrestrial and marine litter inputs and wind analyses with a Lagrangian model. They found that floating debris mainly accumulates on the shoreline, and along a band from northwest to southeast, about halfway down the Adriatic Sea. In particular, the model results show that the coasts of the Po Delta receive a plastic flux of about 70 kg/km·day. The authors considered an overall floating plastic debris input of 10,000 ton/year reaching the Adriatic basin, assuming that 40% of the marine litter comes from rivers, 40% from coastal urbanization, and 20% from shipping lanes. The authors simulated daily averaged distributions of plastic debris concentration at the sea surface, and provided a map of the averaged values (2009–2015), correlating them with surface currents. In the northern Adriatic, the area with the highest concentrations of plastic was found to be the waters between the Po Delta and Gulf of Trieste. The floating debris concentration tended to correspond to the spatial distribution of the plastic debris inputs, and show connections with the patterns of the general circulation. Taking into consideration the tendency of surface currents to vary in strength in different seasons, the authors presented the different yearly distribution (Fig. S5). The maps for summer and winter are reported in Fig. S6. In all the simulations, the Po Delta was the area with the greatest occurrence of marine litter, while the degree of accumulation in other areas changes significantly. Modelling of the streams has determined that there is no possibility of the formation of "waste islands" as the long-term permanence of floating objects is not possible. The authors reported a particle half-life of 44 days (compared to that of 19 years found for the oceans), which implies that the Adriatic is very dissipative, and that the debris ends up mainly on the coast. In the same year, a work by Gajšt et al. (2016) was published, presenting the results of sea-surface monitoring of MPs; this campaign, which lasted 20 months from 2012 to 2014, covered the Slovenian part of the Bay of Trieste in the Northern Adriatic Sea. They also analysed the variability in MP occurrence on different sampling dates, using a Markov distribution model developed for the Adriatic Sea and taking into consideration winds and surface currents (spatial resolution of 2.2 km and temporal resolution of one day). This work highlighted the model's validity and utility. Carlson et al. (2017), on the other hand, proposed a model for determining "where the floating debris in the Adriatic comes from and where it goes". In their model, relying on visual observation, they simulated the trajectory of the debris, thus defining the starting points (source) and the arrival points (sink). However, they considered neither the wind nor degradation and, in practice, they only took PE and PP into account (the most abundant floating plastics). The conclusions of this paper were fairly obvious: macro debris originates from coastal sources near built-up areas, and is displaced by surface cyclonic circulation until it beaches on the southwest coast of Italy, leaves the Adriatic, or recirculates in a southern gyre.

Recently, Atwood et al. (2019) aimed to model the coastal accumulation of mPs (1–5 mm) issued by the Po River over 1.5 years. They used hydrodynamic-based and remote sensing-based modelling, including the actual conditions of the river plume and the sea surface over a fixed time. The model was validated via a field campaign for collecting water and sediment samples in the Po Delta performed in June 2016. Fig. S7 reports the results of the simulation when different wind regimes and discharge conditions were applied. Suspended particulate matter (SPM) values depict river plume shape. The results show that the remote sensing approach was able to well represent river mouth strength, and could be used to identify potential accumulation zones. From the simulation models analysed, it is evident that the most investigated areas are among those with the greatest expected accumulation of waste. Specific investigations may be necessary for areas that are affected by seasonal variations due to various changes in the presence of waste.

In general, for modelling purposes an overall knowledge of the sources od mPs is very useful. In recent times, a model that is capable of estimating riverine plastic outflows from any river was developed and validated (Mai et al., 2020). This model estimates the global plastic outflows from 1518 main rivers in the range of 57,000–265,000 MT/year in 2018 reaching the peak in the 2028 in a modelled trajectory of 2010–2050.

4. Critical considerations

Even though efforts have been made to standardize methodology, from the analysed data it is evident that the standard deviations often exceed the average values, mainly because different locations or different sampling campaigns are grouped together. These situations broaden the uncertainty about the actual knowledge of the problem due to the great variability in the information reported. In some cases, the same campaigns are analysed in different articles. Even though the aims of these studies were different, discrepancies in the reported figures often makes them difficult to interpret. In particular, the articles by Piehl et al. (2019) and Atwood et al. (2019) refer to the same campaign (June 2016), on the beaches around the River Po Delta, but report different figures (Tables S12, S13 and S14). This highlights that different data processing approaches can lead to different results, even when starting with identical data.

The relatively recent systems and projects endeavouring to catch plastics in rivers before they are poured into the Adriatic Sea (RiverCleaning, River Cleaner, Po d'AMare) should provide interesting data in this regard.

It is also worth noting that all the research considered in this review report data or protocols related to sandy beaches, but, given the diversity of the Adriatic Sea, it would also be interesting to investigate the situation on rocky beaches, creating specific protocols for sampling and analysis. Furthermore, it should be noted that most of the papers published to date report data on floating litter on the water surface or settled on the seabed, but few researchers have investigated the situation in the water column (Vianello et al., 2018). Moreover, to the best of our knowledge, no one has yet evaluated the effective influence of the thermocline in the Adriatic waters.

One element of originality is demonstrated by Vianello et al. (2018), who considered the plastic degradation index. However, when focusing on microplastics, there are some inconsistencies that need to be resolved; as microplastics originate mainly from the degradation of macroplastics, it is essential to identify the total quantity of plastics, grouped regardless of product category, among the marine litter. For example, from this perspective, differentiating rubber and "PS foam" from plastic can be misleading, as they are, in fact, all macroplastics that can degrade into microplastics. In addition, in order to better understand the magnitude of the problem and investigate effective recovery and recycling possibilities, it is vital to define the quantity of each plastic polymer type by weight, not only by the number of items. From a global point of view, it is important to standardize protocols and/or identify procedures for normalizing the results obtained via different methods in order to compare data gathered worldwide.

Regarding the release of plastic additives into water, we found no useful information. The greater concentration in plastic pellets with respect to the concentration in seawater (Maršić-Lučić et al., 2018) is not sufficient to establish that plastics absorb metals; metals may already be present in plastics due to additives. Moreover, some studies have investigated the colour distinction of plastics, as this could affect ingestion by marine fauna, but this is actually a questionable issue, since studies have found that microplastic fragments usually are covered with biofouling (Melli et al., 2017; Summers et al., 2018; Pinto et al., 2019), and therefore camouflaged. Nonetheless, it might be useful to research the dyes and additives contained in plastic and their possible release into the water in future investigations. Even though the list of additives that can be present in plastic objects is rather long, and some are unknown, not all of them will be released and/or constitute a real risk of pollution, influencing human and environmental health. All the national territories are focusing attention mainly on collecting data on marine litter occurrence in the areas that are the most polluted (i.e., touristic or places of greatest natural interest). Few studies have analysed the presence of marine litter in natural areas that are difficult to access in order to assess the situation in the absence of any anthropic influence. As suggested by Tisma et al. (2019) enhanced strategic management of marine debris can improve the preservation of the marine environment. Nonetheless, the SWOT (Strengths Weakness Opportunities Threats) analysis by Ronchi et al. (2019) shows that the major obstacle in this regard is related to bureaucratic factors and the lack, in all countries, of adequate and harmonized legislation concerning marine litter.

5. Conclusions

One of the targets of the Marine Strategy Framework Directive was to collect comparable data in order to obtain a snapshot of the problem and identify spatial and temporal trends, but the available pieces of information are still difficult to compare and analyse. Hence, at present, the magnitude of the problem cannot be fully understood. From the available data, it can, however, be concluded that (i) the most sampled polymers have been PE, PP and PS; (ii) the presence of plastic is ubiquitous, quantitatively variable and difficult to compare in spatial and temporal terms.

As foreseen by MSFD, in order to verify whether specific policies and legislations have a positive impact on marine pollution reduction, monitoring programmes should sample from fixed locations over time, using standard methodologies. The great amount of litter in the marine environment suggests that further action is needed, but no study has yet dealt with resolution of the problem. The feasibility and validity of installing permanent surface structures able to retain floating items in the areas of greatest accumulation is one solution that should be evaluated.Taking into account the various alerts from the European Community and the latest Directive issued in June 2019, it is clear that concerted actions must be developed in order to reduce the problem of plastic pollution in the marine environment.

Author contributions

Chiara Schmid: conceptualization, writing (original draft, review & editing), formal analysis, data curation, and supervision. **Luca Cozzarini:** writing (review & editing). **Elena Zambello:** writing (original draft, review & editing), and visualization.

Funding sources

This study was supported by the NET4mPLASTIC project, co-financed by the European Regional Development Fund within the framework of European cross-border territorial cooperation Interreg. IT-HR. CUP: F76C19000000007.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are grateful to Marco Caniato and Federica Bettarello for their precious suggestions during the processing stages of this research, and their aid in the acquisition of financial support. Thanks are also due to the reviewers for the constructive comments and valuable recommendations.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2021.116430.

References

Anastasopoulou, A., Kovač Viršek, M., Bojanić Varezić, D., Digka, N., Fortibuoni, T., Koren, Š., Mandić, M., Mytilineou, C., Pešić, A., Ronchi, F., Šiljić, J., Torre, M., Tsangaris, C., Tutman, P., 2018. Assessment on marine litter ingested by fish in the Adriatic and NE Ionian Sea macro-region (Mediterranean). Mar. Pollut. Bull. 133, 841–851. https://doi.org/10.1016/j.marpolbul.2018.06.050.

Andrady, A.L., 2017. The plastic in microplastics: a review. Mar. Pollut. Bull. 119, 12–22. https://doi.org/10.1016/j.marpolbul.2017.01.082.

Arcangeli, A., Campana, I., Angeletti, D., Atzori, F., Azzolin, M., Carosso, L., Di Miccoli, V., Giacoletti, A., Gregorietti, M., Luperini, C., Paraboschi, M., Pellegrino, G., Ramazio, M., Sarà, G., Crosti, R., 2018. Amount, composition, and spatial distribution of floating macro litter along fixed trans-border transects in the Mediterranean basin. Mar. Pollut. Bull. 129, 545–554. https://doi.org/10.1016/j.marpolbul.2017.10.028.

Arthur, C., Baker, J., Bamford, H., 2009. Proceedings of the International Research Workshop on the Occurrence, Effects and Fate of Microplastic Marine Debris. NOAA Technical Memorandum. Sept. (Accessed 9 November 2008). NOS-OR&R-30.

Atwood, E.C., Falcieri, F.M., Piehl, S., Bochow, M., Matthies, M., Franke, J., Carniel, S., Sclavo, M., Laforsch, C., Siegert, F., 2019. Coastal accumulation of microplastic particles emitted from the Po River, Northern Italy: comparing remote sensing and hydrodynamic modelling with in situ sample collections. Mar. Pollut. Bull. 138, 561–574. https://doi.org/10.1016/j.marpolbul.2018.11.045.

Avio, C.G., Gorbi, S., Regoli, F., 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. https://doi.org/10.1016/j.marenvres.2015.06.014.

Avio, C.G., Pittura, L., d'Errico, G., Abel, S., Amorello, S., Marino, G., Gorbi, S., Regoli, F., 2020. Distribution and characterization of microplastic particles and textile microfibers in Adriatic food webs: general insights for biomonitoring strategies. Environ. Pollut. 258, 113766. https://doi.org/10.1016/j.envpol.2019.113766.

Blašković, A., Fastelli, P., Čižmek, H., Guerranti, C., Renzi, M., 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. https://doi.org/10.1016/j.marpolbul.2016.09.018.

Bonifazi, G., Palmieri, R., Serranti, S., Mazziotti, C., Ferrari, C.R., 2017. Hyperspectral imaging based approach for monitoring of microplastics from marine environment. In: OCM, Optical Characterization of Materials - Conference Proceedings, pp. 193–205.

Carlson, D.F., Suaria, G., Aliani, S., Fredj, E., Fortibuoni, T., Griffa, A., Russo, A., Melli, V., 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. 4, 1–16. https://doi.org/10.3389/fmars.2017.00078.

Cheshire, A.C., Adler, E., Barbière, J., Cohen, Y., Evans, S., Jarayabhand, S., Jeftic, L., Jung, R.T., Kinsey, S., Kusui, E.T., Lavine, I., Manyara, P., Oosterbaan, L., Pereira, M.A., Sheavly, S., Tkalin, A., Varadarajan, S., Wenneker, B., Westphalen, G., 2009. UNEP/IOC Guidelines on Survey and Monitoring of Marine Litter, UNEP Regional Seas Reports and Studies.

Cincinelli, A., Martellini, T., Guerranti, C., Scopetani, C., Chelazzi, D., Giarrizzo, T., 2019. A potpourri of microplastics in the sea surface and water column of the Mediterranean Sea. Trends Anal. Chem. 110, 321–326. https://doi.org/10.1016/j.trac.2018.10.026.

de Francesco, M.C., Carranza, M.L., Stanisci, A., 2018. Beach litter in Mediterranean coastal dunes: an insight on the Adriatic coast (central Italy). Rend. Lincei 29, 825–830. https://doi.org/10.1007/s12210-018-0740-5.

de Francesco, M.C., Carranza, M.L., Varricchione, M., Tozzi, F.P., Stanisci, A., 2019. Natural protected areas as special sentinels of littering on coastal dune vegetation. Sustain. Times 11, 1–16. https://doi.org/10.3390/su11195446.

de Lucia, G.A., Vianello, A., Camedda, A., Vani, D., Tomassetti, P., Coppa, S., Palazzo, L., Amici, M., Romanelli, G., Zampetti, G., Cicero, A.M., Carpentieri, S., Di Vito, S., Matiddi, M., 2018. Sea water contamination in the Vicinity of the Italian minor islands caused by microplastic pollution. Water (Switzerland) 10. https://doi.org/10.3390/w10081108.

European Parliament and Council, 2008. Marine strategy framework directive (MSFD). Off. J. Eur. Union 19, 95–97.

Fortibuoni, T., Ronchi, F., Mačić, V., Mandić, M., Mazziotti, C., Peterlin, M., Prevenios, M., Prvan, M., Somarakis, S., Tutman, P., Varezić, D.B., Virsek, M.K., Vlachogianni, T., Zeri, C., 2019. A harmonized and coordinated assessment of the abundance and composition of seafloor litter in the Adriatic-Ionian macroregion (Mediterranean Sea). Mar. Pollut. Bull. 139, 412–426. https://doi.org/10.1016/j.marpolbul.2019.01.017.

Frapiccini, E., Annibaldi, A., Betti, M., Polidori, P., Truzzi, C., Marini, M., 2018. Polycyclic aromatic hydrocarbon (PAH) accumulation in different common sole (Solea solea) tissues from the North Adriatic Sea peculiar impacted area. Mar. Pollut. Bull. 137, 61–68. https://doi.org/10.1016/j.marpolbul.2018.10.002.

Gajšt, T., Bizjak, T., Palatinus, A., Liubartseva, S., Kržan, A., 2016. sea surface microplastics in slovenian part of the northern adriatic. Mar. Pollut. Bull. 113, 392–399. https://doi.org/10.1016/j.marpolbul.2016.10.031.

Galgani, F., Hanke, G., Werner, S., Oosterbaan, L., Nilsson, P., Fleet, D., Kinsey, S., Rc, T., Van Franeker, J., Vlachogianni, T., Scoullos, M., Mira Veiga, J., Palatinus, A., Matiddi, M., Maes, T., Korpinen, S., Budziak, A., Leslie, H., Gago, J., Liebezeit, G., 2013a. Guidance on monitoring of marine litter in European seas. JRC scientific and policy reports. https://doi.org/10.2788/99475.

Galgani, F., Hanke, G., Werner, S., Vrees, L. De, 2013b. Marine litter within the European marine strategy framework directive. ICES J. Mar. Sci. 70, 1055–1064. https://doi.org/10.1093/icesjms/fst122.

Gago, J., Galgani, F., Maes, T., Thompson, R.C., 2016. Microplastics in seawater: recommendations from the marine strategy framework directive implementation process. Front. Mar. Sci. 3, 1–6.

González, D., Hanke, G., Tweehuysen, G., Bellert, B., Holzhauer, M., Palatinus, A., Hohenblum, P., Oosterbaan, L., 2016. Riverine litter monitoring - options and recommendations. MSFD GES TG marine litter thematic report. JRC Technical Report. https://doi.org/10.2788/461233. EUR 28307.

Gomiero, A., Strafella, P., Øysæd, K.B., Fabi, G., 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, 24407–24416. https://doi.org/10.1007/s11356-019-05693-y.

Green, D.S., Kregting, L., Boots, B., Blockley, D.J., Brickle, P., da Costa, M., Crowley, Q., 2018. A comparison of sampling methods for seawater microplastics and a first report of the microplastic litter in coastal waters of Ascension and Falkland Islands. Mar. Pollut. Bull. 137, 695–701. https://doi.org/10.1016/j.marpolbul.2018.11.004.

Gregory, M.R., 1996. Plastic 'scrubbers' in hand cleansers: a further (and minor)

source for marine pollution identified. Mar. Pollut. Bull. 32, 867–871. https://doi.org/10.1016/S0025-326X(96)00047-1.
Hartmann, N.B., Hüffer, T., Thompson, R.C., Hassellöv, M., Verschoor, A., Daugaard, A.E., Rist, S., Karlsson, T., Brennholt, N., Cole, M., Herrling, M.P., Hess, M.C., Ivleva, N.P., Lusher, A.L., Wagner, M., 2019. Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. Environ. Sci. Technol. 53, 1039–1047. https://doi.org/10.1021/acs.est.8b05297.
Imhof, H.K., Schmid, J., Niessner, R., Ivleva, N.P., Laforsch, C., 2012. A novel, highly efficient method for the separation and quantification of plastic particles in sediments of aquatic environments. Limnol Oceanogr. Methods 10, 524–537. https://doi.org/10.4319/lom.2012.10.524.
Korez, Š., Gutow, L., Saborowski, R., 2019. Microplastics at the strandlines of Slovenian beaches. Mar. Pollut. Bull. 145, 334–342. https://doi.org/10.1016/j.marpolbul.2019.05.054.
Kovač Viršek, M., Lovšin, M.N., Koren, Š., Kržan, A., Peterlin, M., 2017. Microplastics as a vector for the transport of the bacterial fish pathogen species Aeromonas salmonicida. Mar. Pollut. Bull. 125, 301–309. https://doi.org/10.1016/j.marpolbul.2017.08.024.
Kovač Viršek, M., Palatinus, A., Koren, Š., Peterlin, M., Horvat, P., Kržan, A., 2016. Protocol for microplastics sampling on the sea surface and sample analysis. JoVE 1–9. https://doi.org/10.3791/55161.
Laglbauer, B.J.L., Franco-Santos, R.M., Andreu-Cazenave, M., Brunelli, L., Papadatou, M., Palatinus, A., Grego, M., Deprez, T., 2014. Macrodebris and microplastics from beaches in Slovenia. Mar. Pollut. Bull. 89, 356–366. https://doi.org/10.1016/j.marpolbul.2014.09.036.
Law, K., Thompson, R.C., 2014. Microplastics in the seas - concern is rising about widespread contamination of the marine environment by microplastics. Science 84 345, 144–145. https://doi.org/10.1002/2014EF000240/polymer.
Li, J., Lusher, A.L., Rotchell, J.M., Deudero, S., Turra, A., Bråte, I.L.N., Sun, C., Shahadat Hossain, M., Li, Q., Kolandhasamy, P., Shi, H., 2019. Using mussel as a global bioindicator of coastal microplastic pollution. Environ. Pollut. 244, 522–533. https://doi.org/10.1016/j.envpol.2018.10.032.
Liubartseva, S., Coppini, G., Lecci, R., Creti, S., 2016. Regional approach to modeling the transport of floating plastic debris in the Adriatic Sea. Mar. Pollut. Bull. 103, 115–127. https://doi.org/10.1016/j.marpolbul.2015.12.031.
Ludwig, W., Dumont, E., Meybeck, M., Heussner, S., 2009. River discharges of water and nutrients to the Mediterranean and Black Sea: major drivers for ecosystem changes during past and future decades? Prog. Oceanogr. 80, 199–217. https://doi.org/10.1016/j.pocean.2009.02.001.
Macic, V., Mandic, M., Pestoric, B., Gacic, Z., Paunovic, M., 2017. First assessment of marine litter in shallow south-east adriatic sea. Fresenius Environ. Bull. 26, 4834–4840.
Mai, L., Sun, X.-F., Xia, L.-L., Bao, L.-J., Liu, L.-Y., Zeng, E.Y., 2020. Global riverine plastic outflows. Environ. Sci. Technol. 54, 10049–10056. https://doi.org/10.1021/acs.est.0c02273.
Maršić-Lučić, J., Lušić, J., Tutman, P., Bojanić Varezić, D., Šiljić, J., Pribudić, J., 2018. Levels of trace metals on microplastic particles in beach sediments of the island of Vis, Adriatic Sea, Croatia. Mar. Pollut. Bull. 137, 231–236. https://doi.org/10.1016/j.marpolbul.2018.10.027.
Masura, J., Baker, J., Foster, G., Arthur, C., Herring, C., 2015. Laboratory methods for the analysis of microplastics in the marine environment: recommendations for quantifying synthetic particles in waters and sediments. Natl. Ocean. Atmos. Adm. U.S. Tech. Memo. NOS-OR&R- 48, 18.
Melli, V., Angiolillo, M., Ronchi, F., Canese, S., Giovanardi, O., Querin, S., Fortibuoni, T., 2017. The first assessment of marine debris in a site of community importance in the North-western Adriatic Sea (Mediterranean Sea). Mar. Pollut. Bull. 114, 821–830. https://doi.org/10.1016/j.marpolbul.2016.11.012.
Mistri, M., Infantini, V., Scoponi, M., Granata, T., Moruzzi, L., Massara, F., De Donati, M., Munari, C., 2017. Small plastic debris in sediments from the Central Adriatic Sea: types, occurrence and distribution. Mar. Pollut. Bull. 124, 435–440. https://doi.org/10.1016/j.marpolbul.2017.07.063.
Mokos, M., Zamora Martinez, I., Zubak, I., 2019. Is central Croatian Adriatic Sea under plastic attack? Preliminary results of composition, abundance and sources of marine litter on three beaches. Rend. Lincei 30, 797–806. https://doi.org/10.1007/s12210-019-00851-3.
Munari, C., Corbau, C., Simeoni, U., Mistri, M., 2016. Marine litter on Mediterranean shores: analysis of composition, spatial distribution and sources in north-western Adriatic beaches. Waste Manag. 49, 483–490. https://doi.org/10.1016/j.wasman.2015.12.010.
Munari, C., Scoponi, M., Mistri, M., 2017. Plastic debris in the Mediterranean Sea: types, occurrence and distribution along adriatic shorelines. Waste Manag. 67, 385–391. https://doi.org/10.1016/j.wasman.2017.05.020.
Oliveira, M., Almeida, M., 2019. The why and how of micro(nano)plastic research. Trends Anal. Chem. 114, 196–201. https://doi.org/10.1016/j.trac.2019.02.023.
OSPAR Commission, 2010. Guideline for Monitoring Marine Litter on the Beaches in the OSPAR Maritime Area.
Palatinus, A., Kovač Viršek, M., Robič, U., Grego, M., Bajt, O., Šiljić, J., Suaria, G., Liubartseva, S., Coppini, G., Peterlin, M., 2019. Marine litter in the Croatian part of the middle Adriatic Sea: simultaneous assessment of floating and seabed macro and micro litter abundance and composition. Mar. Pollut. Bull. 139, 427–439. https://doi.org/10.1016/j.marpolbul.2018.12.038.
Pasquini, G., Ronchi, F., Strafella, P., Scarcella, G., Fortibuoni, T., 2016. Seabed litter composition, distribution and sources in the northern and central Adriatic Sea (mediterranean). Waste Manag. 58, 41–51. https://doi.org/10.1016/j.wasman.2016.08.038.
Pellini, G., Gomiero, A., Fortibuoni, T., Ferrà, C., Grati, F., Tassetti, A.N., Polidori, P., Fabi, G., Scarcella, G., 2018. Characterization of microplastic litter in the gastrointestinal tract of Solea solea from the Adriatic Sea. Environ. Pollut. 234, 943–952. https://doi.org/10.1016/j.envpol.2017.12.038.
Piarulli, S., Vanhove, B., Comandini, P., Scapinello, S., Moens, T., Vrielinck, H., Sciutto, G., Prati, S., Mazzeo, R., Booth, A.M., Van Colen, C., Airoldi, L., 2020. Do different habits affect microplastics contents in organisms? A trait-based analysis on salt marsh species. Mar. Pollut. Bull. 153, 110983. https://doi.org/10.1016/j.marpolbul.2020.110983.
Piehl, S., Mitterwallner, V., Atwood, E.C., Bochow, M., Laforsch, C., 2019. Abundance and distribution of large microplastics (1–5 mm) within beach sediments at the Po River Delta, northeast Italy. Mar. Pollut. Bull. 149, 110515. https://doi.org/10.1016/j.marpolbul.2019.110515.
Pinto da Costa, J., Reis, V., Paço, A., Costa, M., Duarte, A.C., Rocha-Santos, T., 2019. Micro(nano)plastics – analytical challenges towards risk evaluation. TrAC Trends Anal. Chem. (Reference Ed.) 111, 173–184. https://doi.org/10.1016/j.trac.2018.12.013.
Pinto, M., Langer, T.M., Hüffer, T., Hofmann, T., Herndl, G.J., 2019. The composition of bacterial communities associated with plastic biofilms differs between different polymers and stages of biofilm succession. PloS One 14, 1–20. https://doi.org/10.1371/journal.pone.0217165.
Piperagkas, O., Papageorgiou, N., Karakassis, I., 2019. Qualitative and quantitative assessment of microplastics in three sandy Mediterranean beaches, including different methodological approaches. Estuar. Coast Shelf Sci. 219, 169–175. https://doi.org/10.1016/j.ecss.2019.02.016.
Prata, J.C., da Costa, J.P., Duarte, A.C., Rocha-Santos, T., 2019. Methods for sampling and detection of microplastics in water and sediment: a critical review. Trends Anal. Chem. 110, 150–159. https://doi.org/10.1016/j.trac.2018.10.029.
Renzi, M., Blašković, A., 2020. Chemical fingerprint of plastic litter in sediments and holothurians from Croatia: assessment & relation to different environmental factors. Mar. Pollut. Bull. 153, 110994. https://doi.org/10.1016/j.marpolbul.2020.110994.
Renzi, M., Blašković, A., Fastelli, P., Marcelli, M., Guerranti, C., Cannas, S., Barone, L., Massara, F., 2018a. Is the microplastic selective according to the habitat? Records in amphioxus sands, Mäerl bed habitats and Cymodocea nodosa habitats. Mar. Pollut. Bull. 130, 179–183. https://doi.org/10.1016/j.marpolbul.2018.03.019.
Renzi, M., Čižmek, H., Blašković, A., 2019. Marine litter in sediments related to ecological features in impacted sites and marine protected areas (Croatia). Mar. Pollut. Bull. 138, 25–29. https://doi.org/10.1016/j.marpolbul.2018.11.030.
Renzi, M., Guerranti, C., Blašković, A., 2018b. Microplastic contents from maricultured and natural mussels. Mar. Pollut. Bull. 131, 248–251. https://doi.org/10.1016/j.marpolbul.2018.04.035.
Rios Mendoza, L.M., Balcer, M., 2019. Microplastics in freshwater environments: a review of quantification assessment. Trends Anal. Chem. 113, 402–408. https://doi.org/10.1016/j.trac.2018.10.020.
Ronchi, F., Galgani, F., Binda, F., Mandić, M., Peterlin, M., Tutman, P., Anastasopoulou, A., Fortibuoni, T., 2019. Fishing for litter in the adriatic-ionian macroregion (Mediterranean Sea): strengths, weaknesses, opportunities and threats. Mar. Pol. 100, 226–237. https://doi.org/10.1016/j.marpol.2018.11.041.
Ruiz-Orejón, L.F., Sardá, R., Ramis-Pujol, J., 2016. Floating plastic debris in the central and western Mediterranean Sea. Mar. Environ. Res. 120, 136–144. https://doi.org/10.1016/j.marenvres.2016.08.001.
Sagratini, G., Buccioni, M., Ciccarelli, C., Conti, P., Cristalli, G., Giardina, D., Lambertucci, C., Marucci, G., Volpini, R., Vittori, S., 2008. Levels of polychlorinated biphenyls in fish and shellfish from the Adriatic Sea. Food Addit. Contam. B 1, 69–77.
Schmid, C., Cozzarini, L., Zambello, E., et al., 2020. Microplastic's story. Mar, Pollut. Bull. https://doi.org/10.1016/j.marpolbul.2020.111820. In press.
Šilc, U., Küzmič, F., Caković, D., Stešević, D., 2018. Beach litter along various sand dune habitats in the southern Adriatic (E Mediterranean). Mar. Pollut. Bull. 128, 353–360. https://doi.org/10.1016/j.marpolbul.2018.01.045.
Stock, F., Kochleus, C., Bänsch-Baltruschat, B., Brennholt, N., Reifferscheid, G., 2019. Sampling techniques and preparation methods for microplastic analyses in the aquatic environment – a review. TrAC Trends Anal. Chem. (Reference Ed.) 113, 84–92. https://doi.org/10.1016/j.trac.2019.01.014.
Strafella, P., Fabi, G., Despalatovic, M., Cvitković, I., Fortibuoni, T., Gomiero, A., Guicciardi, S., Marceta, B., Raicevich, S., Tassetti, A.N., Spagnolo, A., Scarcella, G., 2019. Assessment of seabed litter in the northern and central Adriatic Sea (mediterranean) over six years. Mar. Pollut. Bull. 141, 24–35. https://doi.org/10.1016/j.marpolbul.2018.12.054.
Strafella, P., Fabi, G., Spagnolo, A., Grati, F., Polidori, P., Punzo, E., Fortibuoni, T., Marceta, B., Raicevich, S., Cvitkovic, I., Despalatovic, M., Scarcella, G., 2015. Spatial pattern and weight of seabed marine litter in the northern and central Adriatic Sea. Mar. Pollut. Bull. 91, 120–127. https://doi.org/10.1016/j.marpolbul.2014.12.018.
Suaria, G., Aliani, S., 2014. Floating debris in the Mediterranean Sea. Mar. Pollut. Bull. 86, 494–504. https://doi.org/10.1016/j.marpolbul.2014.06.025.
Suaria, G., Avio, C.G., Mineo, A., Lattin, G.L., Magaldi, M.G., Belmonte, G., Moore, C.J., Regoli, F., Aliani, S., 2016. The mediterranean plastic soup: synthetic polymers in mediterranean surface waters. Sci. Rep. 6, 1–10. https://doi.org/10.1038/srep37551.
Summers, S., Henry, T., Gutierrez, T., 2018. Agglomeration of nano- and microplastic particles in seawater by autochthonous and de novo-produced sources of exopolymeric substances. Mar. Pollut. Bull. 130, 258–267. https://doi.org/

10.1016/j.marpolbul.2018.03.039.
Tisma, S., Boromisa, A.M., Cermak, H., 2019. Marine Debris management in the adriatic sea: a case study of Croatia. Eur. J. Geogr. 10, 147–158.
Thompson, R.C., Olson, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science 80–. https://doi.org/10.1126/science.1094559, 304, 838.
Van der Wall, M., Van der Meulen, M., Tweehuijsen, G., Peterlin, M., Palatinus, A., Viršek, M.K., Coscia, L., Kržan, A., 2015. SFRA0025: Identification and Assessment of Riverine Input of (Marine) Litter: Final Report for the European Commission DG Environment under Framework Contract No ENV. D. 2/FRA/2012/0025: Report for Michail Papadoyannakis DG Environment. Ifremer.
Vianello, A., Boldrin, A., Guerriero, P., Moschino, V., Rella, R., Sturaro, A., Da Ros, L., 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. https://doi.org/10.1016/j.ecss.2013.03.022.
Vianello, A., Da Ros, L., Boldrin, A., Marceta, T., Moschino, V., 2018. First evaluation of floating microplastics in the northwestern Adriatic Sea. Environ. Sci. Pollut. Res. 25, 28546–28561. https://doi.org/10.1007/s11356-018-2812-6.
Vlachogianni, T., 2019. Marine Litter in Mediterranean Coastal and Marine Protected Areas How Bad Is It? A snapshot assessment report on the amounts, composition and sources of marine litter found on beaches. Interreg Med ACT4LITTER MIO-ECSDE 1–40.
Vlachogianni, T., Anastasopoulou, A., Fortibuoni, T., Ronchi, F., Zeri, C., 2017. Marine Litter Assessment in the Adriatic and Ionian Seas, vol. 168. IPA-Adriatic DeFishGear Proj. MIO-ECSDE, HCMR ISPRA.
Vlachogianni, T., Fortibuoni, T., Ronchi, F., Zeri, C., Mazziotti, C., Tutman, P., Varezić, D.B., Palatinus, A., Trdan, Š., Peterlin, M., Mandić, M., Markovic, O., Prvan, M., Kaberi, H., Prevenios, M., Kolitari, J., Kroqi, G., Fusco, M., Kalampokis, E., Scoullos, M., 2018. Marine litter on the beaches of the Adriatic and Ionian Seas: an assessment of their abundance, composition and sources. Mar. Pollut. Bull. 131, 745–756. https://doi.org/10.1016/j.marpolbul.2018.05.006.
Vlachogianni, T., Kalampokis, V., 2014. Marine Litter Monitoring in the Adriatic A review of available data and applied methods. DeFishGear 19.
Vlachogianni, T., Kalampokis, V., Rubic, U., Mačić, V., 2013a. Methodology for Monitoring Marine Litter on the Seafloor (Shallow Coastal Waters) Visual Surveys with SCUBA/snorkeling.
Vlachogianni, T., Paraskevopoulou, V., Kalampokis, V., Palatinus, A., Trdan, S., Di Muccio, S., Alcaro, L., Ronchi, F., Mazziotti, C., Zeri, C., Kamperi, E., 2013b. Methodology for Monitoring Marine Litter on Beaches.
Vlachogianni, T., Somarakis, S., Ronchi, F., Chieruzzi, T., Fortibuoni, T., Paraskevopoulou, V., Kalampokis, V., Robič, U., 2013c. Methodology for Monitoring Marine Litter on the Seafloor (Continental Shelf) Bottom Trawl Surveys.
Zambianchi, E., Trani, M., Falco, P., 2017. Lagrangian Transport of Marine Litter in the Mediterranean Sea, vol. 5, pp. 1–15. https://doi.org/10.3389/fenvs.2017.00005.
Zeri, C., Adamopoulou, A., Bojanić Varezić, D., Fortibuoni, T., Kovač Viršek, M., Kržan, A., Mandic, M., Mazziotti, C., Palatinus, A., Peterlin, M., Prvan, M., Ronchi, F., Siljic, J., Tutman, P., Vlachogianni, T., 2018. Floating plastics in Adriatic waters (Mediterranean Sea): from the macro- to the micro-scale. Mar. Pollut. Bull. 136, 341–350. https://doi.org/10.1016/j.marpolbul.2018.09.016.