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Microplastics and Nanoplastics

REVIEW

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Microplastics in the Mediterranean marine environment: a combined bibliometric and systematic analysis to identify current trends and challenges

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Abstract

In recent decades, the potential toxicological and environmental effects of microplastics (MPs) in the Mediterranean Sea region have received growing attention. The number of studies in this area has increased; however, presently there is no scientometric perspective addressing this topic. The purpose of this study was to identify the intellectual base and research front using the visualization and analysis software, CiteSpace, in combination with a systematic review. We retrieved 150 articles, published in print or online as an early-access article between 1979 and 2020, from the Web of Science with a topic search related to MPs, environment, and uptake by biota. We then analysed synthesized networks of co-authorship (author, institution, country), co-citation (author document, journal) and co-occurring keywords. The annual publication output has trended upwards since 2011, with interest in MP abundance in the Mediterranean Sea particularly high in the past 5 years (2016–2020). Authors based in Italy accounted for 25% of the total publications, followed by Spain (16%); but overall publications from Belgium and the Netherlands were more influential. Major research themes identified include the abundance of MPs on beaches, in surface waters, sediments and biota. Secondary microplastics, such fibres and fragments, of a wide range of sizes and chemical composition were dominant in scientific reports, albeit citizen science collection of plastic resin pellets for International Pellet Watch suggests such primary MPs are also widespread, even if their numerical abundance from such collections is unclear. Few studies reported chemical contamination of MPs in the Mediterranean albeit a significant amount of information on the level of chemical contamination of plastic resin pellets is available on the International Pellet Watch website.

Keywords: Microplastic, beach, sediment, marine waters, biota

Introduction

Although largely considered to be a twentieth Century phenomenon, the first synthetic polymers based on nitrocellulose were developed in the nineteenth Century. However, plastic materials were enthusiastically embraced by both industry and the community in the first half of the twentieth Century as new types (such as polyamides (PA), polycarbide (PC), polyurethanes (PU), polyvinylchloride (PVC), polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET) and polystyrene (PS)) were invented and new uses found for them. As of 2018, worldwide plastic production is estimated to be more than 350 million tonnes, with plastic production in Europe in excess of 60 million tonnes [140]. There are many well-recognised benefits that plastic materials have brought society. For instance, in developed nations around one third of the plastic consumed is used in building construction and other infrastructure, e.g., piping

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and other plumbing products, and PS insulation, while a further third is used in plastic packaging and wrapping, which protects and preserves consumables and other goods, while reducing weight in transportation, which saves fuel and reduces greenhouse gas emissions. Many of the mass-produced modern plastics are based on saturated hydrocarbon polymers, which contributes to their chemical and biological stability [84]. However, that relative stability leads to persistence of these plastics in the environment.

Plastic debris in the terrestrial environment originating from domestic, urban business and industrial activities, may be transported by stormwater flows into local streams, from whence it may be transported into rivers and ultimately the marine environment. Plastic materials may also enter the oceans directly in the discharge from the wastewater treatment systems of coastal communities, or indirectly via estuaries where wastewater is discharged into rivers [89]. Other sources include materials lost by professional maritime activities and recreational fishing, debris dumped by commercial, cruise or private ships, and windblown transport from the land. Lebreton et al. [99] suggested that the Mediterranean Sea is a marine environment with one of the highest levels of plastic pollution worldwide, as was to be expected for a semi-enclosed sea surrounded by a vibrant coastline with few outlets [55]. In that context, it has recently been estimated that the Mediterranean Sea receives between 150 and 610 thousand tonnes of plastics each year (average 229 thousand tonnes), 94% of which is microplastic debris and 6% microplastics [27]. Egypt, Italy, and Turkey are considered to be the top three emitters of plastic, with hotspots associated with major rivers and/or near large urban areas.

Plastic particles that have a density lower than seawater (most synthetic polymers) float on the water's surface [102], while particles with higher density will sink and be deposited on the seafloor. However, buoyant particles may also sink as a result of biofouling and particle adherence [155]. Beaches are a deposition point for floating debris deposited by waves and are also capable of accumulating sinking plastic particles [88]. Although there is still some debate as to what is the minimum size particles should be to be classified as MPs, there is a general consensus that they are pieces of plastic with a diameter smaller than 5 mm. Microplastics are further defined as being primary MPs, which includes such things as plastic resin pellets, the raw materials for plastic manufacture, and small particles manufactured for use in cleansing or beauty products (microbeads), in textile (microfibres); secondary MPs are those MPs that result from the breakdown of larger pieces of plastics by physical and chemical degradation, or biological decomposition [102].

The extent and mechanisms of MPs impacts on the environment are still being established. It is known the first report on MPs in the Mediterranean Sea was by Shiber [137], although more detailed research did not begin to be published until the early 2000s. Microplastics have now been observed in the water column, in marine sediments, on beaches and in biota in the region. Moreover, while the ecotoxicological hazard of microplastics due to simple mechanical and physical damage induced by MPs is known, other direct or indirect effects may occur when the very smallest particles travel through the food chain [11], living organisms are exposed to toxic chemicals in/sorbed to MPs [124], and new geological materials ('plasticrusts') are created by sea waves smashing plastic debris against rocks [64]. In that context, the aim of this study was to identify the peer-reviewed literature that presents the environmental levels of MPs in the marine environment of Mediterranean basin, including the Black Sea. The search to identify relevant publications allowed for the construction of a database with the references on research carried out on microplastics in the Mediterranean Sea since 1979, when the first scientific publications related to the subject studied appeared. Thereafter we sought to answer the following questions: (i) how has the scientific research on microplastics evolved in the Mediterranean Sea basin in recent years?; (ii) in which journals were these studies published?; (iii) which were the educational and research institutes involved; (iv) are there collaborative networks among research institutions?; (v) are there any gender biases in publication; (vi) what were the findings of microplastic surveys?; and (vii) what are the main knowledge gaps to inform and guide future work?

Methods

Data collection

A search to identify relevant publications was conducted using the SCOPUS and Web of Science core collection databases on 21 September 2020. The search was limited to published original, peer-reviewed research articles written in English. The search terms, "(microplastic OR nanoplastic) AND Mediterranean AND (water OR sediment OR beach OR fish OR mussel OR whale OR invertebrate)" were applied to article Title, Abstract, or Keywords. Primary documents identified by these two searches were downloaded from publishers' websites to the extent that RMIT's Library access allowed. To remove duplicates, the bibliographic details of all retrieved studies were manually collated in Excel with duplicates deleted from the spreadsheet (Supplementary Information Fig. S 1). Then, an initial screening of article content was undertaken to assess relevance for inclusion in the

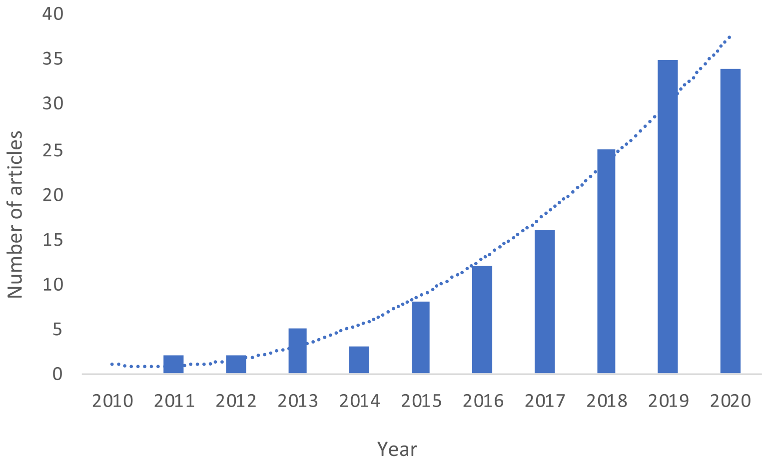

Fig. 1 Number of peer-reviewed articles on microplastic particles in the Mediterranean Sea basin published per year (2010–2020 data only). The line depicts the relationship between the number of articles and year. This figure only includes articles that met the inclusion criteria of this review

review. The inclusion criteria applied for the subsequent review and analysis were:

1. Article written in English, was published in a recognized peer-reviewed journal, and described primary research e.g., was not a review that had been misidentified. Technical reports, course monographs, academic dissertations and theses, and abstracts or full papers of conference proceedings were not considered.
2. Article reported micro- or nano- plastics detection levels in the marine environment of the Mediterranean Sea basin, including the Black Sea; studies were included even if their primary focus was macroplastic or other debris provided there was data on microplastics; studies that focused on sources in riverine catchments, or riverine levels, and measurements in estuaries or enclosed lagoons/harbours were not included in the scientometric review.
3. Article reported environmental uptake by biota, i.e., not a laboratory uptake experiment or modelling.

A more detailed screening of article content was then undertaken which resulted in an additional 84 papers being identified from citations within the articles (Fig. S1). Thereafter, additional relevant articles were obtained as/when identified through journal alerts.

Once articles were selected, study characteristics and data items were extracted from article content (Table S1) and managed in Excel. For instance, we used Bendels et al. [19] method to define the proportion of female authorships (FAP), this being the quotient between the number of female authorships and the total sum of male and female authorships (F/(F + M). Bendels et al. [19] female-to-male authorship odds ratio (FAOR) for 1st authorship ($FAOR_{First} = FemaleOdds_{First}$ / $MaleOdds_{First}$) was also calculated for the same 166 articles, with $FemaleOdds_{First} = Female_{NumberFirst}$ / ($Female_{NumberCoauthor} + Female_{NumberLast}$) and $MaleOdds_{First} = Male_{NumberFirst}$ / ($Male_{umberCoauthor} + Male_{NumberLast}$). The female-to-male authorship odds ratio for last authorship ($FAOR_{Last}$) was calculated using data where there are three or more authors on a paper.

Scientometric analysis

Network analyses and visualizations were performed on 146 articles with CiteSpace (version 5.7.R3), which is an open source bibliometrics software developed by Chen [40]. All bar 4 WoS database records from 1979 to 2020 were successfully converted to a CiteSpace-friendly format. The parameters used to synthesize each final stable network were node selection g-index (k = 50), time slicing (years per slice) = 1, pruning (pathfinder, pruning sliced networks), term source (title, abstract, author keywords, and keywords plus), links (retaining factor = 10), and visualization (cluster view-static and show merged network). Cluster labelling was conducted automatically using the log-likelihood ratio (LLR) function.

The modularity Q index [112] and average silhouette score [127] were used to measure the structural quality of the network. The modularity, Q, ranging from 0 to 1, measures the degree to which a network can be separated into independent components [40, 43]. The silhouette metric, ranging from − 1 to 1, reflects a cluster's degree of homogeneity and estimates the uncertainty involved in interpreting a cluster. The connectivity of the network was measured by betweenness centrality (ranging from 0 to 1) for each node in the network [74]. Temporal properties of the networks and clusters were evaluated by burst strength [92] and sigma score (Σ) [42]. High burst strength indicates a strong and sudden surge of interest in a particular theme. Sigma (Σ) is a measure of scientific novelty, derived from burst strength and betweenness centrality.

Results and Discussion

Publication trends

The first publications on microplastics in the coastal marine environment appeared in the 1970s, discussing pollution from primary plastic sources such as resin pellets in water [37] and on beaches [86]. The first scientific articles specifically dealing with MPs in water, marine sediments and on beaches in the Mediterranean Sea basin were published in 1980 (Morris), 2013 (van Cauwenberghe et al.) and 1979 (Shiber), respectively. Our selection process identified 150 articles (1979–2020) that described levels of MPs in the one or more compartments of the Mediterranean Sea, of which 45 reported levels in water, 24 in marine sediments, 30 on beaches and 56 in field collected biota. Articles were predominantly published in journals with primary discipline designations of agricultural and biological science (59%), and environmental science (29%). There was a strong positive correlation between the numbers of articles and years published in the period 2010–2020 (Fig. 1; $r^2 = 0.95$) which supports the general impression of growing interest in MPs research since 2010.

Country, institution and authors of origin

Country of authorship

Authors were based across 35 countries (Fig. 2), within which there were 4 main clusters. The main countries where authors were based include Italy ($n = 55$, 25.1%), Spain ($n = 36$, 16.4%), France ($n = 20$, 9.3%), and Turkey and Greece ($n = 13$, 6.0%). Overall, 17 (65%) of the 26 countries surrounding the Mediterranean and Black Seas were represented in the authorship records. Most of the authors were based in developed countries (98.5%) with only a small number in developing countries (1.1%) or countries in transition (0.4%; as defined by [147]). The network of co-authors' countries consisted of 35 nodes (Fig. 2; E = 70, density = 0.1176). The five highest ranked countries by betweenness centrality were Italy (centrality = 0.70), France (centrality = 0.53), Greece (centrality = 0.24), Spain (centrality = 0.17), and England (centrality = 0.12). In comparison, the top ranked countries by burst strength were Belgium (strength = 3.49), the Netherlands (strength = 0.69), Slovenia (strength = 0.54) and Norway (strength = 0.52). This signifies that these latter countries have had a more important role in collaborations in the field of MPs than the other countries.

Organisation

An organisational analysis was used to reveal academic collaborations at the level of institutions (Fig. 3). The network consisted of 210 nodes (E = 448, density = 0.0204), and was divided into 39 clusters (modularity Q = 0.3766, average silhouette = 0.9401). The institution co-authorship was dominated by six interlinked networks that together form one large sub-network that represented 69% (nodes = 146) of the whole network. The top 5 organisations with the largest research output were CNR (Consiglio Nazionalle delle Recherche), Italy (records = 15, 7.1%), the Bioscience Research Center, Italy (11, 5.2%), the University of Messina, Italy (10, 4.8%), the University of Siena (9, 4.2%) and the University of Barcelona, Spain and the Centro Oceanografico de Baleares, Spain (8, 3.8%).

Institutions with higher betweenness centrality are instrumental in facilitating collaborations across several countries. The largest sub-network was centred on CNR (Fig. 4), the highest ranked organisation by betweenness centrality, and featured strong links to organisations in the eastern Mediterranean, and an early network focussed on linking the Italian National Institute for Environmental Protection and Research (ISPRA), the University of Messina, Italy and the University of Siena, Italy. Another older network in this region links the Institute of Water Slovenian Republic with the fifth highest ranked organisation based on burst strength, the University of Ghent (strength = 1.28). The three smaller (mid-size) sub-networks clearly identifiable were collaborations between institutions based in one or two countries. The earliest small sub-network is comprised of institutions based in Belgium and France (University of Liege, strength = 1.66; IFREMER, strength = 0.65). More recent sub-networks are comprised of institutions based in France and Spain e.g., linking the University of Barcelona, the University of Cadiz, and the University of Southern Brittany. There was also one very small, isolated network linking three organisations without collaborative links to any other organisation in the region. Nodes in the network were connected by links of varying thickness, which suggests varying degrees of intensity of inter-cooperation among them. Institutions in eastern Mediterranean tended to collaborate more with those based in Italy, whereas those in the western Mediterranean tended to collaborate with organizations in that region. Links between institutions in the two halves

Fig. 2 Distribution of the number of records attributed to authors based in each country: (threshold = 5, modularity Q = 0.1985, average silhouette = 0.8744). Node size signifies the number of papers that originated from the country. Distance between nodes and link thickness indicates the level of collaboration, link colour indicates earliest period of establishment (purple, oldest; yellow, most recent). Nodes without labels were below the threshold

of the Mediterranean basin have formed, albeit most have been initiated in the last 5 years.

Authorship

The five most prolific authors of the articles related to MPs in the Mediterranean environment (1979–2020) are Guerranti C and Renzi M (records = 11, 7.6%), Fossi MC and Blašković A (8, 5.5%), and Romeo T (6, 4.2%). The remaining authors each contributed ≤5 records, with more than half of the authors contributing to only 1 record.

The author analysis was used to reveal academic collaborations among authors. The network consisted of

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CiteSpace, v. 5.7.R3 (64-bit)
January 11, 2021 2:08:44 PM AEDT
WoS: /Users/graemeallinson/Documents/Work (citespace)/Med MPs/data/data Wos unique
Timespan: 2011-2020 (Slice Length=1)
Selection Criteria: g-index (k=50), LRF=-1.0, LBY=5, e=1.0
Network: N=210, E=448 (Density=0.0204)
Largest CC: 146 (69%)
Nodes Labeled: 1.0%
Pruning: None
Harmonic Mean(Q, S)=0
```

Fig. 3 Distribution of organisations based on number of records attributed to authors based in each organisation (modularity Q = 0.3766, average silhouette = 0.9401). Node size signifies the number of papers that originated from the country. Distance between nodes and link thickness indicates the level of collaboration, link colour indicates earliest period of establishment (purple, oldest; yellow, most recent). Nodes without labels were below the threshold (*n* = 5)

329 nodes (E = 1036, density = 0.0192), and was divided into 57 clusters. The largest sub-network contained 92 nodes and accounted for 27% of the overall network. Overall, the network was centred around six nodes, (Fig. 4) with many very isolated sub networks. There were no nodes with a betweenness centrality > 0.06. This suggests that the authors tended to cooperate in small teams, and collaboration between teams was limited. Given that the analysis covers oceanographic surveys of the water column, marine sediment surveys, beach and biota surveys this analysis is consistent with each group having a specific research speciality that does not necessitate co-collaboration.

Publications that undergo a sudden surge in interest give individual authors a high burst strength. The author with the strongest burst strength was Fastelli P (Table 1), who has published on MPs levels in the water column and marine sediments (e.g., [68]). Other

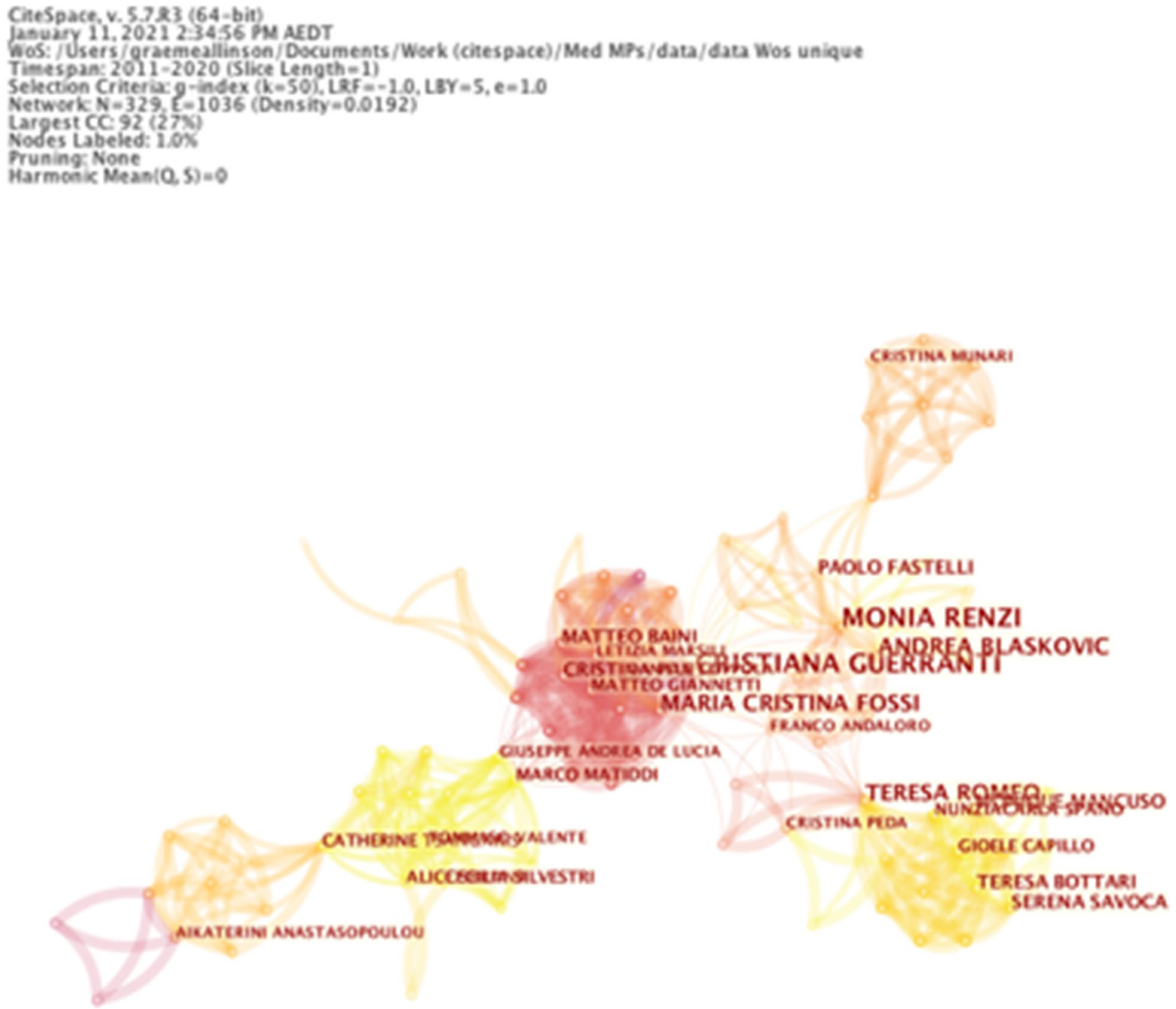

Fig. 4 Author co-authorship network, where each node represents an author, modified to show only main network (see Fig. S2 for complete network; modularity Q = 0.4281, average silhouette = 0.9354). Link colour signifies the earliest period that the link was established (purple, oldest; yellow, most recent). Nodes without labels were below the threshold ($n = 3$)

influential authors also reported on concentration of plastic in cetaceans (e.g., [73]), and in fish (e.g., [50]).

Influential Authors, Documents, and Journals: Co-citation analyses

Author co-citation analysis (ACA)

The author co-citation analysis (ACA) is used to obtain the distribution of highly cited authors in a research field [41]. It can also reveal the research focus of similar authors, the distribution of their subject areas through the co-citation network and identify influential authors. The ACA network contained 618 nodes in one large network divided into 7 co-citation clusters (E = 35,289, density = 0.1848, modularity Q = 0.0688, average silhouette = 0.6885) The top five most cited authors in the field of Mediterranean MPs research were Galgani F (citations $n = 78$), Cozar A ($n = 77$), Cole M ($n = 71$), Lusher AL and Eriksen M ($n = 70$). The first two of these authors were among the first to report on detection of MPs in the Mediterranean environment (e.g., [51, 55]) with the remaining authors reporting on MPs in other marine systems.

The authors ranked highly by burst strength published on the topics of microplastics in the marine environment, albeit not with specific focus on the Mediterranean. The

Table 1 Top 10 cited authors ordered by burst strength during period of analysis (2011–2020)

Authors	**Burst**			
	Strength	**Begins**	**Ends**	**2011 - 2020**
P Fastelli	2.14	**2017**	2018	──────🟥🟥──
MC Fossi	1.52	**2014**	2016	───🟥🟥🟥────
F Andaloro	1.52	**2015**	2016	────🟥🟥────
F Collard	1.41	**2014**	2015	───🟥🟥─────
C Guerranti	1.40	**2016**	2018	─────🟥🟥🟥──
M Renzi	1.22	**2017**	2018	──────🟥🟥──
F Regoli	1.13	**2015**	2017	────🟥🟥🟥───
M Giannetti	1.10	**2014**	2016	───🟥🟥🟥────
E Marti	1.01	**2015**	2016	────🟥🟥────
F Rubegni	1.01	**2015**	2016	────🟥🟥────

author with the strongest burst was Moore CJ (Table 2), reported on concentration of plastic in the Pacific [108]. Other influential authors include Teuton EL, who reported the potential for plastics to transport hydrophobic contaminants [143], and Morét-Ferguson S, who reported the size, mass, and composition of plastic debris in the western North Atlantic Ocean [109], and Boerger CM who published on plastic ingestion by planktivorous fishes in the North Pacific [25].

Journal co-citation analysis (JCA)

The 146 publications on microplastics in the Mediterranean environment examined scientometrically occurred across 32 different journals. The top five journals responsible for publishing most of the identified articles were: Marine Pollution Bulletin (articles $n = 68$; 46.3%), Environmental Pollution ($n = 19$, 12.9%), Science of the Total Environment ($n = 9$, 6.1%), Marine Environmental Research (n = 6, 4.1%), and jointly Environmental Science and Pollution Research and Estuarine, Coastal and Shelf Science ($n = 5$, 3.4%).

A Journal Co-citation Analysis (JCA) was performed on the 2010–2020 dataset to identify the most influential journals since the JCA can provide an improved appraisal of a journal's relevance and influence on a research field compared to considering only the number of publications [154]. The single, large network contained 358 nodes (E = 11,063, density = 0.1731), divided into 6 overlapping

Table 2 Top 10 co-cited authors ordered by burst strength in the analysis period (2011–2020)

Cited Author	**Burst**			
	Strength	**Begin**	**End**	**2011 - 2020**
CJ Moore	4.59	**2012**	2016	─🟥🟥🟥🟥🟥────
EL Teuten	4.53	**2012**	2016	─🟥🟥🟥🟥🟥────
S Morét-Ferguson	4.05	**2016**	2018	─────🟥🟥🟥──
MR Gregory	3.91	**2011**	2015	🟥🟥🟥🟥🟥─────
CM Boerger	3.65	**2014**	2016	───🟥🟥🟥────
KL Law	3.58	**2012**	2016	─🟥🟥🟥🟥🟥────
MJ Doyle	3.16	**2012**	2015	─🟥🟥🟥🟥─────
P Davison	3.09	**2013**	2016	──🟥🟥🟥🟥────
RC Thompson	3.01	**2012**	2015	─🟥🟥🟥🟥─────
T Kukulka	2.78	**2014**	2016	───🟥🟥🟥────

co-citation clusters. The network was moderately structured (Q = 0.1769), and clusters had acceptable heterogeneity (average silhouette = 0.6118). None of the top 10 journals with the highest frequency in the bibliometric analysis (Marine Pollution Bulletin (n = 142), Environmental Pollution (n = 133), Marine Environmental Research (n = 127), Environmental Science & Technology (n = 124), PLOS One (n = 98), Science (n = 92), Philosophical Transactions of the Royal Society B (n = 91), Science Reports (n = 90), Science of the Total Environment (n = 72) or Estuarine, Coastal and Shelf Science (n = 67)) appeared in the top ten journals ranked by burst strength (Table 3). This suggests that the scope of the journals with the strongest citation bursts tended to be related to mechanistic studies, whereas the scope of journals with the highest citation frequency tended to be related to marine environment and environmental science.

Document co-citation analysis (DCA)

The document co-citation analysis (DCA) identifies research clusters with common themes linked via document co-citations [43, 138]. The synthesized DCA network contained 607 nodes (E = 22,317, density = 0.1213) and was divided into 6 co-citation clusters. The modularity Q of the network is 0.1057, which indicates a loosely structured network, and the average silhouette was 0.7630, which suggests a good degree of homogeneity for clusters overall. The top five documents most frequently returned by this analysis were [55]; n = 55) [89]; n = 45), [141]; n = 44), [65]; n = 43), and [5]; n = 39). Of these documents only that by Cozar et al. [55], Suaria et al. [141] and Alomar et al. [5] specifically reported on detection of MPs in the Mediterranean environment with the remaining documents are reviews of the levels of MPs in other marine systems, or methods for the measurement thereof.

The research described in publications with high burst strength is influential and often associated with major research milestones that are pivotal to the development of the field [9, 44]. In that context, only two of the top 10 documents by burst strength (Table 4) were co-authored by one of the top 10 cited authors in the network (Table 1), specifically the papers co-authored by Fossi et al. [72] and Collignon et al. [51], the latter with F Collard. However, half the documents include one of the top 10 co-cited authors based on burst strength, RC Thompson (Table 4).

The network is divided into 6 co-citation clusters. The silhouette values for the 6 clusters were in the range of 0.68–0.99, which indicates a high level of homogeneity for these clusters and that cluster labelling is reflecting cluster content [43]. These clusters are labelled by index terms from their own citers. In that context, cluster labelling and identification of representative terms was conducted automatically using the log-likelihood ratio (LLR) function [63]. Representative terms are selected from noun-phrases in the titles and abstracts of citing articles, ranked by the LLR algorithm, and the top-ranked term is designated as the cluster label [43, 44]. The longest clusters depicted in the timeline visualization (Fig. 5) were cluster #2, automatically labelled as 'western Sardinian coast,' followed by cluster #0 boops boop, and cluster #1 adriatic sea. The most recently initiated, and current cluster was cluster #0 boops boop.

The largest cluster (#0) was labelled as 'boops boop' by LLR, although the cluster's theme based on the major

Table 3 Top 10 journals ordered by burst strength

Cited Journal	**Burst**			
	Strength	**Begin**	**End**	**2011 - 2020**
NATURE	3.27	**2012**	2016	🟦🟥🟥🟥🟥🟥🟦🟦🟦🟦
J COASTAL RES	2.52	**2012**	2014	🟦🟥🟥🟥🟦🟦🟦🟦🟦🟦
GEOPHYS RES LETT	2.05	**2014**	2016	🟦🟦🟦🟥🟥🟥🟦🟦🟦🟦
J FISH BIOL	2.03	**2015**	2016	🟦🟦🟦🟦🟥🟥🟦🟦🟦🟦
J MAR BIOL ASSOC UK	2.00	**2015**	2016	🟦🟦🟦🟦🟥🟥🟦🟦🟦🟦
ENVIRON TECHNOL	1.82	**2012**	2014	🟦🟥🟥🟥🟦🟦🟦🟦🟦🟦
CHEMOSPHERE	1.61	**2011**	2013	🟥🟥🟥🟦🟦🟦🟦🟦🟦🟦
LIMNOL OCEANOGR-METH	1.28	**2013**	2014	🟦🟦🟥🟥🟦🟦🟦🟦🟦🟦
AMBIO	1.28	**2013**	2015	🟦🟦🟥🟥🟥🟦🟦🟦🟦🟦
MAR BIOL	1.32	**2014**	2015	🟦🟦🟦🟥🟥🟦🟦🟦🟦🟦

Table 4 Top 10 cited documents ordered by burst strength (2011–2020)

Reference	Burst			
	Strength	**Begin**	**End**	**2011–2020**
Andrady [7]	7.22	**2013**	2016	▒▒████▒▒▒▒
Collignon et al. [51]	7.01	**2012**	2017	░██████▒▒▒
Lusher et al. (2013)	6.57	**2015**	2018	░░▒▒████▒▒
Fossi et al. [72]	6.49	**2014**	2017	░▒▒████▒▒▒
Claessens et al. [48]	5.77	**2013**	2016	▒▒████▒▒▒▒
Boerger et al. [25]	5.65	**2012**	2015	▒████▒▒▒▒▒
Hidalgo-Ruz et al. [88]	5.52	**2012**	2017	░██████▒▒▒
Browne et al. [29]	5.29	**2013**	2016	▒▒████▒▒▒▒
Wright et al. (2013)	5.17	**2015**	2018	░░▒▒████▒▒
Barnes et al. [15]	5.00	**2012**	2014	▒███▒▒▒▒▒▒

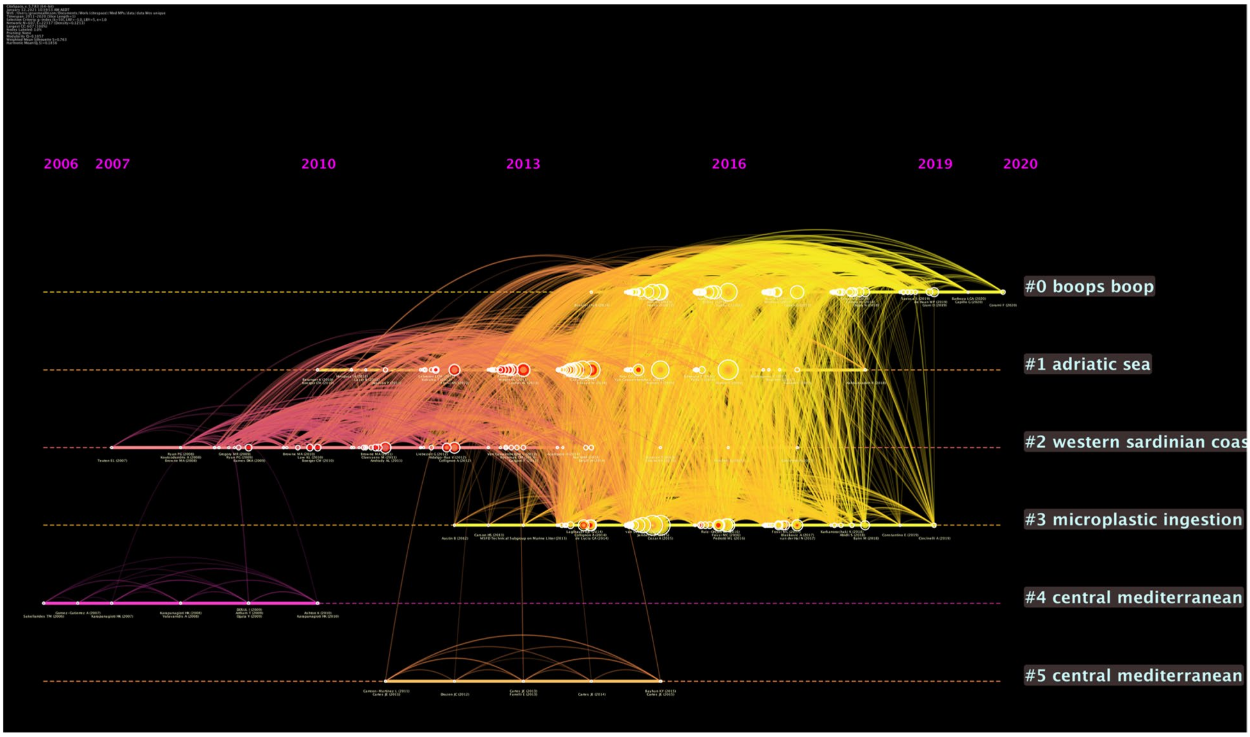

Fig. 5 Document Co-citation Analysis visualised as a timeline with automatically generated cluster labels (threshold by burst = 5). Nodes represent cited documents labelled with first author and year of publication. Nodes below the threshold were not labelled. The colour of co-citation links is indicative of the transition of research focus over time, with the most recently established links in yellow. Modularity Q = 0.1057, average silhouette = 0.7630.

index terms was more broadly related to deep-sea environment, flagship species, macrodebris, and floating plastic pollution with a focus on ingestion by organisms. This cluster contained articles with strong citation bursts, albeit that, as noted earlier, most of the top ten articles by burst strength concerned studies outside the Mediterranean Sea basin. In that context, the top Mediterranean Sea focussed article by burst strength was titled, "Neustonic microplastic and zooplankton in the North Western Mediterranean Sea," [51]. The next two highest article by burst strength were titled, "Are baleen whales exposed to the threat of microplastics? A case study of the Mediterranean fin whale (*Balaenoptera physalus*)" [72], and "Microplastic particles in sediments of Lagoon of Venice, Italy: First observations on occurrence, spatial patterns and identification" [151]. Such studies are pivotal in that they played a key role highlighting the importance of MPs in the Mediterranean Sea basin, whereas previously the major focus of MPs research was elsewhere.

Are there any gender biases in authorship?

It is generally understood that representation of women in academia drops off as they progress through the system, e.g., even where females represent at least 50% of undergraduate cohorts in a discipline, the proportion of women is reduced at each successive tier, with the greatest discrepancy at the highest ranks [19]. Moreover, the publication of peer reviewed journal articles is often used to project potential in initial hiring and subsequent internal organisational promotion processes. In that context, the position of an author in the authorship list is important in many research areas, including environmental science, albeit for reasons that bear no relation to the physical and intellectual contributions of the various authors to the article's content. In the environmental sciences, including marine sciences, it is commonly understood that the first author indicates the person who did most of the work that made the paper possible (often, but not always, a research student or non-tenured research fellow), with the last author being the person whose work or role made the study possible (typically, but not always, project leader or supervisor). Consequently, authorship prestige follows a ranked order with the higher reputations being that of first and last authorships; co-authorships, i.e., all authorships listed between the first and last authors, have lower prestige, especially in long authorship listings. First authorship, in particular, is viewed a measure of academic success in early career researchers, with 'last author' an important measure of success for established researchers, e.g., for grant funding success.

To assess whether there are any gender biases/barriers, we first estimated the gender distribution in articles where authors were listed using only initials, which Bendels et al. [19] suggest may itself be a strategy employed by some women to pre-empt perceived and/or actual gender bias in the publication process. In this context, there are 23 articles in our database in which authors are recognised only using initials. Of the 106 unique authors in those papers, 53% are female, 46% male, and 1% unassignable. It is worth noting that few of those authors only ever used initials on the papers in our database, most use their given,surname on other papers, suggesting initialization is not a common strategy amongst this group of female researchers to try to avoid real or perceived gender bias in publication.

Given the importance of first author publications for hiring and advancement, we also sought to quantify whether women are underrepresented as first authors in the studies of microplastics in the Mediterranean basin in our database. In that context, there are 596 individual author names across the papers reviewed, of which 296 (49.7%) were female names, 296 (49.7%) were male with 4 authors (0.7%) whose gender could not be attributed. Of the 166 articles (1979 – April 2021), five of articles were single author papers, all authored by men; two articles were authored by a person whose given name, and hence gender, could not be ascertained. Using Bendels et al. [19] approach, the FAP for our database is 0.64. In other words, women are 64% of all 1st authors in our database. Bendels et al. [19] FAOR for 1st authorship ($FAOR_{First}$) for women in our database is 1.82. Given the rapid increase in publications post 2015, we assessed whether the FAP changed over time, but found that there was only a weak positive correlation for female 1st authorship ($r^2=0.32$). Analysis of last authorships also provides for some preliminary conclusions regarding the academic status of women in the organisations undertaking the studies. In that context, the FAP_{Last} for our database is 0.48, i.e., women are 48% of last authors. The female-to-male authorship odds ratio for last authorship ($FAOR_{Last}$) was 1.84. Overall, the data suggests that women studying microplastics in the Mediterranean basin may be over-represented relative to the proportion of women in early career positions (assumed to be 30–50% [19]), and just as likely to be last authors in microplastics studies as men, perhaps suggesting women in this field are just as likely to be in senior project/academic positions as men? A more detailed survey of the number of post-graduate students, post-doctoral research fellows and junior academic/other researchers would, however, need to be conducted to confirm that conclusion.

Microplastics in the Mediterranean Environment

Microplastics in surface water

There have been more than forty articles reporting the levels of MPs in surface water since 1980, although not all differentiate microplastic data from that of other debris, including, for instance, the most cited 'first report' on MPs in the Mediterranean Sea [110]. Consequently, articles that did not differentiate between macro-, meso- and microplastic particles/debris are not considered in the following discourse.

As noted by Cincinelli et al. [46], there is a lack of standardized sampling methods for the collection of MPs in surface waters. The variety of study designs, including the number of replicates, gear and net mesh sizes complicates the comparison of different studies. The most commonly reported method of MPs identification is visual inspection of collected material using a microscope, albeit it is becoming more common that putative plastics are confirmed using analytical techniques such as Fourier Transform Infrared Spectroscopy (FTIR). Further complicating comparisons between studies is (a) the tendency for authors to report their findings in different units, e.g., MPs/km^2, g/km^2, mg/m^3 and/or MPs/m^3, (b) that not all studies report the size range of the MPs collected or their shapes, or (c) polymer types or (d) whether observed MPs are primary plastics e.g. virgin plastic resin pellets / microbeads or secondary particles resulting from the natural weathering of microplastic debris. This lack of standardization with respect to data reporting also makes estimating the potential impact of MPs in surface waters difficult, as noted by Everaert et al. [66].

The Strait of Sicily effectively divides the Mediterranean into Eastern and Western basins, with the Dardanelles Strait and the Bosporus in turn separating the Eastern basin from the Sea of Marmara and the Black Sea. In that context, there have been several studies in the north western part of the Western basin. For instance, Faure et al. [69] and Schmidt et al. [135] both reported MPs levels in surface water in the Gulf of Lion (Table 5; MPs/km^2. Note: studies reporting data in g/km^2, mg/m^3 and/or MPs/m^3 are summarised in Supplementary Information Tables S2, S3, S4). Schmidt et al. [135] sampled areas close to wastewater treatment plants and river mouths several times for a period of 2 years and reported mean concentrations of 112,000 MPs/km^2. Those concentrations were similar to the results obtained from the earlier trawling study in the same region (130,000 MPs/km^2 [69]). Similar levels were, however, reported by de

Table 5 Summary of microplastic concentrations in Mediterranean seawater (MPs/km^2; all surface water samples)

Country	Location	Maritime Area	MP concentration			Reference
			Min	Max	Mean	
			MPs/km^2			
Bulgaria	Burgas Bay to Cape Kaliakra	Black Sea	11,400	191,000	46,200 ± 54,700	Berov & Klayn [20]
Croatia	Archipelago of the Zadar County	Northern Central Adriatic Sea	17,875	1,549,549	127,135 ± 294,847	Palatinus et al. [115]
France	Gulf of Lion	Western Mediterranean	6000	1,000,000	112,000	Schmidt et al. [135]
France	Gulf of Lion	North western Mediterranean	20,000	420,000	130,000	Faure et al. [69]
France	Bay of Calvi, Corsica	North Western Mediterranean	0	613,000	51,000	Collignon et al. [52]
Israel	Israeli south coast	Israeli Mediterranean		64,813	1,518,340	van der Hal et al. [150]
Italy	Province of Ascoli Piceno	Central Adriatic Sea	5	400		Capriotti et al. [36]
Italy		Ligurian and Tyrrhenian Sea	1286	3,666,898	233,927 ± 810,357	Caldwell et al. [31]
Italy		Ligurian and Tyrrhenian Sea	505	93,983	19,220	Caldwell et al. [30]
Italy	Tuscany	Ligurian Sea	3158	347,040	69,161 ± 83,244	Baini et al. [14]
Italy	Pelagos Sanctuary Protected Area	Ligurian and Sardinian Sea		4,830,000		Fossi et al. [72]
Slovenia	Piran Bay to Koper Bay	North Adriatic Sea			259,310 ± 57,096	Viršek et al. [153]
Slovenia	Trieste Bay	Northern Adriatic Sea	12,000	2,660,000	406,000	Gajst et al. [77]
Spain	Balearic Islands	Balearic sea			410,000 ± 30,000	Capo et al. [35]
Spain	Barcelona	Balearic sea	18,000	330,000	94,500	Camins et al. [32]
Spain	North Catalan coast & south-eastern coast of Spain	Western Mediterranean	9000	497,000	102,000 ± 90,000	de Haan et al. [58]
Spain	Menorca Channel	Balearic sea			133,517 - 336,131	Ruiz-Orejón et al. [129]
Spain	Balearic Islands	Balearic sea			875,466	Ruiz-Orejón et al. [128]
Turkey	Mersin Bay	Levantine Sea	198,198	1,427,027	539,189	Gündoğdu et al. [83]
Turkey	Mersin Bay	Levantine Sea	881,319	19,344,417	7,699,716	Gündoğdu et al. [83]
Turkey	Iskenderun and Mersin Bay	Levantine Sea			376,000	Gündoğd and Cevik [82]
Turkey	Iskenderun Bay	Levantine Sea	98,412	2,888,889	1,067,120	Gündoğdu [82]
Turkey	South-eastern coast of Turkey	North-eastern Mediterranean	16,339	520,213	140,418	Guven et al. [85]
Turkey	Sinop Sarikum Coast	Southern Black Sea			656,000	Oztekin and Bat [114]
	Multiple locations	Adriatic and Western Mediterranean		4,520,000	400,000 740,000	Suaria et al. [141]
		Adriatic and Western Mediterranean			1304,81 ± 609,426	Suaria et al. [141]
		Mediterranean-wide	0	479,455	48,789	Eriksen et al. [65]
		North-western Mediterranean	0	892,000	116,000	Collignon et al. [51]

Haan et al. [58] off the coast of south-eastern coast of Spain (102,000 MPs/km^2). Most recently, Camins et al. [32] reported an average of 94,500 MPs/km^2 in the Balearic Sea, which was an order of magnitude lower than the concentrations reported for the same region in 2018 (875,466 MPs/km^2 [128]).

The Adriatic Sea in the Eastern Basin is often considered as one of the most polluted regions of the Mediterranean [141], in part because of the extensive marine traffic in the region, but also because of the large riverine inputs from the River Po [152], which flows through various industrial regions and opens to a wide delta in the northern part of the Adriatic, and the numerous touristic centres around the coastline. There has been a wide range of MPs concentrations reported in the Adriatic Sea, from low numbers in the central Adriatic (up to 400 MPs/km^2 [36]) to several hundred thousand MPs/km^2 [77, 153] (Table 5). Trieste and the river Po are among the top ten sources of marine litter in the Adriatic [104]. Data from just offshore of the Veneto lagoon suggests that average MPs levels close to the lagoon are almost three times higher than off the Po estuary (1.208 MPs/m^2 cf. 0.472 and 0.315 MPs/m^2 [152]), as well as having a significantly higher maximum value (10.4 MPs/m^2 cf. 3.098 and 3.234 MPs/m^2). Further east, Gündoğdu et al. [83] reported that MPs in the Levantine Sea increased 10-fold after rain (average 535,189 MPs/m^2 cf. 7,669,716 MPs/m^2). The Levantine coast of Turkey is heavily polluted by numerous industries and the reported abundance of MPs on the water surface reflects that influence [82]. There have been fewer reports of MPs in surface waters of the Black Sea, but these are consistent with other eastern Mediterranean basin studies, i.e., averaging tens of thousands of MPs/km^2 [20] to hundreds of thousands of MPs/km^2 [114].

Most of the studies sampling of surface waters filter only the topmost layer of water, which can be sufficiently representative in no/low-wind conditions, but less so when winds induce mixing of the water and trawls are unable to collect all the MPs that are pushed beneath the surface of the water [95]. Studies that sample sub-surface waters for MPs are limited to Lefebvre et al. [100], Baini et al. [14], and Oztekin and Bat [114] who reported 0.23 ± 0.20, 0.16 ± 0.47, and 24.475 ± 26.153 MPs/m^3 in the Gulf of Lion, the Ligurian Sea, and the Southern Black Sea, respectively (Table S4). Such types of investigations are rare because of the expense of sampling; however, they are necessary to fully understand the spatial distribution of MPs in the water column and the potential exposure of organisms therein.

Microplastics in marine sediments

There have been more than twenty articles reporting the levels of MPs in marine sediments since the first report in 2013, although not all differentiate microplastic data from that of other debris, including the most cited 'first report' on MPs in the Mediterranean Sea sediments [149]. Consequently, articles that did not differentiates between microplastic and larger particles/debris are not considered in the following discourse.

As noted by [102]) there is a lack of standardized sampling methods for the collection of MPs in sediments, with a variety of sediment grabs or corers used to collect samples.

Extraction of the MP particles from the sediment is typically done using a density separation method, most commonly by adding a defined density liquid to the sediment and stirring the mixture up. This allows for the MPs less dense than the liquid phase to rise to the surface, or stay in suspension as the denser sand, grit and gravels in the sediment settle. Most of the papers reviewed hereafter added NaCl to the sample, mixed for 2 min, and then allowed the mixture to settle for 4 min before collecting MPs. A large proportion of MP particles can be lost in this process, especially the smaller sized pieces that can get fixed on the equipment used, or MPs made from high density polymers, e.g., PVC. Repeating this process several times with increasingly dense solutions allows for higher yields and greater recovery of denser polymers. Extraction efficiencies vary depending on the technique used, and also the shape, size and polymer type of the model particles used for recovery experiments, but extraction efficiencies in the range 80–100% have been reported [102]. The vast majority authors report their findings in MPs/kg sediment (dry weight), albeit g/kg (d.w.) and g/kg and MPs/m^2 have also been reported (Table S5).

There have been several recent studies in the southern part of the Western Mediterranean basin. In that context, Missawi et al. [107] and Abidli et al. [2] reported almost identical average levels of MPs in sediments in Tunisia (315 and 316 MPs/kg d.w., respectively; Table 6), albeit the highest concentrations observed by Abidli et al. [2] were in the Bizerte Lagoon (461.25 ± 29.74 MPs/kg), whereas the highest concentration observed by Missawi et al. [107] were offshore in the Gulf of Cabes (606 ± 37.5 MPs/kg). Both these locations are reportedly heavily polluted by agricultural, aquaculture and industrial wastewaters. Dahl et al. [57], Krüger et al. [94], and Filgueiras et al. [70] reported up to 3819, up to 213, and up to 440 MPs/kg, respectively, off the Spanish coast, and around the Balearic Islands (Table 6). North of Sicily, Renzi et al. [122] found 49.0 ± 1.4, 153.5 ± 41.7, and 106.0 ± 104.7 MPs/kg in sediments associated with landslides, cliffs, and banks, respectively, around Salina Island in the Tyrrhenian Sea.

To date, the lowest levels reported in sediments in the eastern Mediterranean have been in the Aegean Sea

Table 6 A summary of the number of MPs found in marine sediments around the Mediterranean basin (items per kg dry weight)

Country	Location	Maritime Area	MPs concentration			Reference
			Min	Max	Mean	
			MPs/kg (d.w.)			
Croatia	Telašćica Archipelago	Adriatic Sea	32.3	377.8	177.6 ± 112.7	Renzi & Blašković [119]
Croatia	Silba Archipelago	Adriatic Sea	113.4	284.8	86.0 ± 98.4	Renzi & Blašković [119]
Croatia	Archipelago of the Zadar County	Northern Central Adriatic Sea	190	780	360 ± 169.1	Palatinus et al. [115]
Croatia	Natural Park of Telašćica Bay	Adriatic Sea	32	378	178	Blašković et al. [23]
Greece	Samos Island	Aegean Sea	1	37	12	de Ruijter et al. [59]
Italy	Salina Island	Tyrrhenian Sea			49.0 ± 1.4	Renzi et al. [122]
Italy	Salina Island	Tyrrhenian Sea			153.5 ± 41.7	Renzi et al. [122]
Italy	Salina Island	Tyrrhenian Sea			106.0 ± 104.7	Renzi et al. [122]
Italy	South Tuscany	Tyrrhenian Sea	42	1069	317	Cannas et al. [33]
Italy	Maremma Regional Park	Tyrrhenian Sea	45	397		Guerranti et al. [81]
Italy	Aeolian Archipelago	Southern Tyrrhenian Sea	151.0 ± 34.0	678.7 ± 345.8	371	Fastelli et al. [68]
Lebanon	Levantine Basin	Eastern Mediterranean			2433 ± 2000	Kazour et al. [91]
Slovenia	Gulf of Trieste	Adriatic Sea			170.4	Laglbauer et al. [97]
Spain	Almería coast and Balearic islands	West Mediterranean	0	3819		Dahl et al. [57]
Spain	Tarragona Coast	West Mediterranean			32.4	Expósito et al. [67]
Spain		West Mediterranean	0	213	32–69	Krüger et al. [94]
Spain	Algeciras to Barcelona coast	West Mediterranean	45.9 ± 23.9	280.3 ± 164.9	113.2 ± 88.9	Filgueiras et al. [70]
Spain	Mallorca & Carbera Islands	Balearic Sea	100 ± 60	900 ± 100	270	Alomar et al. [5]
Tunisia	Tunisian coast	Southern Mediterranean	129 ± 10	606 ± 37.5	314.5	Missawi et al. [107]
Tunisia	Northern Tunisian coast	Southern Mediterranean	141.20 ± 25.98	461.25 ± 29.74	316.03 ± 123.74	Abidli et al. [2]
		Black Sea	0	390	106	Cincinelli et al. [47]
	Caorle shore	Northern Adriatic Sea	137	703	255	Renzi et al. [120]

(up to 37 MPs/kg d.w [59])., whereas the highest concentrations have been found along the Lebanese coast (2433 ± 2000 MPs/kg d.w [91])., perhaps because of poor local waste management or because Lebanon is a potential landfall for plastics from other Eastern Mediterranean regions [62]. Microplastic concentrations in Adriatic Sea sediments have typically been reported in the 10s - 100s MPs/kg, e.g., 86.0 ± 98.4 [119] and 360 ± 169.1 ([115]; Table 6), albeit much higher levels (up to 2175 MPs/kg) have been reported in the Venice lagoon [151]. Similar levels have been reported in the Black Sea (up to 390 MPs/kg [47]).

Microplastics on beaches

There have been more than thirty articles reporting the levels of MPs in/on Mediterranean beaches since the first report in 1979. These articles report the presence of industrial plastic beads or granules, plastic. Fragments, and plastic fibres, albeit some studies do not provide concentration data or differentiate MPs from other plastic debris. There is a lack of standardized sampling methods for the collection of MPs from beaches [21, 98] with a variety of processes used for sampling, extraction, and subsequent quantification. The major inconsistencies relate to sampling location (usually on the high tideline where debris accumulates, but often stochastic), sampling design (e.g. beach walks for specific linear distance cf. quadrats at specified locations/distances apart), sample collection (e.g. collect only visible MP pieces by subjective judgement or bulk sampling), the depth sampled when bulk sampling (e.g. top 1 cm, 5 cm or up to 530 cm) and units of measurement (abundance in surface area, weight or volume). Most of the studies analysed herein used bulk sampling as their technique, albeit the limitations associated with sample extraction and determination methods are consistent with those discussed earlier for water and marine sediments. The vast majority authors report their findings in MPs/kg sand (dry weight), albeit MPs/m^2, g/m^3, and MPs/m^3 and have also been reported (Tables S6, S7, S8, S9).

In the western Mediterranean basin, Godoy et al. [79] reported maximum concentrations of MPs in the range 45.0 ± 24.7 MPs/kg on beaches in the province of Granada (Table 7). This is lower than the 148 ± 23 to 156 ± 29 MPs/kg reported by Lots et al. [103] in the Balearic Sea. The beaches around the Gulf of Lion had mean values of 112 MPs/kg [54]. Similar MPs concentrations have been observed in beaches on the Ionian

Table 7 A summary of the number of MP found on beaches around the Mediterranean basin (items per kg of dry weight)

Country	Location	Maritime Area	MPs concentration			Reference
			Min	Max	Mean	
			(MPs/kg of dry weight)			
Algeria	Gulf of Annaba	Western Mediterranean	182.66 ± 27.32	649.33 ± 184.02		Tata et al. [142]
Bosnia		Central Adriatic Sea			76 ± 13	Lots et al. [103]
France	Gulf of Lion	Western Mediterranean	12	798	112	Constant et al. [54]
France	Cassis	Western Mediterranean			124 ± 36	Lots et al. [103]
Greece	Samos Island	Aegean Sea	1.1 ± 0.9	37.2 ± 6.9	11.5 ± 10.5	De Ruijter et al. [59]
Greece	Northern Crete	Aegean Sea	5 ± 5	85 ± 141		Piperagkas et al. [118]
Greece	Salamina Island	Aegean Sea				Tziourrou et al. [146]
Greece	Pilion	Aegean Sea			232 ± 93	Lots et al. [103]
Israel	Tel Aviv	Israeli Mediterranean			168 ± 16	Lots et al. [103]
Italy	Maremma Regional Park	Tyrrhenian Sea	134	1069		Guerranti et al. [81]
Italy	San Mauro	Northern Adriatic Sea			84 ± 12	Lots et al. [103]
Italy	Lido di Dante	Northern Adriatic Sea			1512 ± 187	Lots et al. [103]
Italy	Sicily	Ionian Sea			160 ± 31	Lots et al. [103]
Malta		Central Mediterranean	1.07	10.95		Axiak et al. [13]
Malta		Central Mediterranean				Turner and Luke Holmes [145]
Slovenia		Adriatic Sea	0	3.1 ± 2.6		Korez et al. [93]
Slovenia	Gulf of Trieste	Adriatic Sea		177.8		[97]
Spain	Tarragona Coast	Western Mediterranean			10.7	Expósito et al. [67]
Spain	La Herradura, Granada	Alboran Sea			45.0 ± 24.7*	Godoy et al. [79]
Spain	Motril, Granada	Alboran Sea			31.5 ± 21.5*	Godoy et al. [79]
Spain	La Rábita, Granada	Alboran Sea			22.0 ± 23.28*	Godoy et al. [79]
Spain	Barcelona	Balearic Sea			148 ± 23	Lots et al. [103]
Spain	Denia	Balearic Sea			156 ± 29	Lots et al. [103]
Turkey		Sea of Marmara			8.38 ± 7.77	Artüz et al. [8]
Turkey	Istanbul	Black Sea			20.7	Şener et al. [136]
Turkey	Datça Peninsula	Aegean Sea	593	2073	1154	Yabanli et al. [156]
Turkey	Dikili	Aegean Sea			248 ± 29	Lots et al. [103]

Sea (160 ± 31 MPs/kg [103]). In comparison, the Tyrrhenian Sea seems may have accumulated more MP debris. For instance, Guerranti et al. [81] reported up to 1069 MPs/kg, albeit from samples near a river mouth (Table 7). River mouths are an important source of MP pollution into the sea, and in that context, Simon-Sánchez et al. [139] reported 422 ± 119 MPs/kg in the Ebro River delta, while Blašković et al. [24] found a maximum of 191 MPs/kg in the Cecina River estuary (Ligurian Sea).

In the eastern basin, there have been multiple reports from the Adriatic Sea with concentrations ranging from the very low (max 3.1 ± 2.6 items/kg [93]; Table 7) to intermediate (76 ± 13 items/kg [103]) to high levels (1512 ± 187 items/kg [103]). The latter sampling location was between the mouths of two rivers, which again highlights the importance of riverine inputs. Beach sediments on both the Greek and Turkish coasts of the Aegean Sea had 232 ± 93 and 248 ± 29 MPs/kg, respectively [103]. An exceptionally high mean abundance of 1154 MPs/kg has been observed on a tourist beach after the peak tourist season in the Aegean Sea in Turkey [156]. Much lower levels were reported from a tourist beach on Samos Island in the Aegean Sea also sampled after peak tourist season (mean abundance 11.5 ± 10.5 MPs/kg [59]). When the numbers of MPs are reported on an aereal basis (27 MPs/m^2), De Ruijter et al. suggest that beach would be classified as, “extremely dirty”.

Microplastics in field collected biota

There have been more than forty articles reporting the levels of MPs in Mediterranean biota since 1979. These articles mostly report the presence of plastic and plastic fibres, albeit some studies do not provide concentration data or differentiate MPs from other plastic debris. There is a lack of standardized sampling methods for the collection of MPs from organisms Lakshmi Kavya et al. [98], with how samples are collected is a major variable, i.e., market basket surveys cf. the wide variety of field sampling protocols used. However, a major inconsistency relates to methods used to separate MPs from extraneous biological material, including whether acid or alkali or enzymes are used to decompose tissues, and the temperature at which the decomposition is undertaken. Most of the studies analysed herein report numerical abundance per organism, albeit the limitations associated with determination methods are consistent with those discussed earlier for water and marine sediments.

Anchovy (*Engraulis encrasicolus*), sardines (*Sardina pilchardus*) and the bogue (*Boops boops*) are amongst the most commonly studied fish, and, in that context the number of MPs reported in fish in the western Mediterranean basin are generally very low, typically only a few MPs per organism (Table 8). The picture is, however, mixed. For instance, 12% of sardines and 11% of anchovy in French coastal waters were reportedly contaminated with 0.20 ± 0.69 and 0.11 ± 0.31 MPs/org, respectively [100]. A higher percentage of anchovy and sardines contaminated with higher levels of MPs was observed in the Alboran Sea off the Iberian coast (anchovy, 87%, 1.92 ± 0.95 MPs/org; sardines, 87%, 1.77 ± 1.42 MPs/org, respectively [71]). Forty-seven percent of bogue in French coastal waters were contaminated by an average 1.77 ± 0.22 MPs/org [144]), with similar (47%; 1.85 ± 0.15 MPs/org) as well as higher values (81%; 3.97 ± 0.23 MPs/org) reported in the Tyrrhenian Sea [144], and the Balearic Sea (46%; 1.96 ± 0.20 MPs/org [144]) and 58%, 3.75 ± 0.25 MPs/org [111]). The highest levels of contamination were seen in the blackmouth catshark (*Galeus melastomus*; 78%, 4.47 ± 1.10 MPs/org [148]) and the silver scabbardfish (*Lepidopus caudatus*; 78%, 4.8 MPs/org, [26]) from the Tyrrhenian Sea.

Fish in the eastern Mediterranean basin are also consistently contaminated with a few MPs per organism (Table 9), albeit the highest levels reported in fish are in organisms collected in the Adriatic Sea, e.g., in the golden grey mullet (*Chelon auratus*, 95%; 9.9 ± 8.1 MPs/org) and gilt head bream (*Sparus aurata*, 100%, 7.3 ± 6.6 MPs/org [6]).

Filter feeding invertebrates in the Mediterranean have also been shown to contain MPs (Tables S10, S11). The most contaminated bivalves were oysters from the Levantine Basin (*Scutiger spinosus*, 86%, 7.2 ± 1.4 MPs/org [91]). Mussels (*Mytilus* spp.*)* have tended to be less contaminated (e.g., 46%; 1.9 ± 0.2 MPs/org [61]). Sixty-six percent of shrimp (*Aristeus antennatus*) in Sardinia had 1.66 ± 0.1 MPs/org [39]. These were less contaminated than lobster (*Nephrops norvegicus*, 83%, 5.5 ± 0.8 MPs/org from the same waters.

Studies that target microplastic exposure in marine mammals, turtles and seabirds are limited due to the large size of the animals, their protected status and the challenges of obtaining reliable samples in good condition at the time of post-mortem analysis [17]. But, in that context, there have been two studies of MPs in dolphins in the Mediterranean (Table S12). For instance, Novillo et al. [113] reported 91% of striped dolphin (*Stenella coeruleoalba*) from the Balearic Sea had MPs in their digestive system (14.9 ± 22.3 MPs/org). Similarly, 100% of the short-beaked common dolphin (*Delphinus delphis*) found on the Galician Coast and examined by Hernandez-Gonzalez et al. [87] were contaminated by MPs (12 ± 8 MPs/org). There has been one report of MPs in Mediterranean Sea turtles, with Di Renzo et al. [60] reporting that 66% of Adriatic Sea loggerhead turtles (*Caretta caretta*) they investigated were contaminated by an average of 4.75 MPs/org. There has also only been one study of MPs in Mediterranean seabirds, with the highest levels of MPs observed in Northern Gannet (*Morus bassanus*, 49.3 ± 77.7 MPs/org [49]).

Microplastics characteristics

Presentation of information on the type and colour of MPs is common in the reviewed papers. Some studies were content to present information on the size and shape of the MPs, and to classify them as fibres, films, foams, and fragments, while many also described the surface characteristics such as colour.

Colour

In 94 of the 166 studies reviewed, the colours of the MPs observed were reported, including whether they were colourless, white, yellow, green, brown, red, blue or black (Kutralam-Muniasamy et al. [96] suggest that colour affects the sorting of MPs under stereomicroscopes, potentially affecting the number and type of particles identified. In all the matrices examined, black/blue coloured MPs were dominant.

Shape

The shape of MPs can indicate their potential origins. For instance, plastic resin pellets represent fugitive losses during the transport and use of these primary MPs, whereas secondary MPs such as fibres may be derived from synthetic textiles and fishing nets. Microplastics shapes were described in almost all the studies reviewed. Fibres were the most frequent shape reported across all sample types. That this was the most dominant shape reported was perhaps to be expected as it has been found that a single garment can release more than 1900 fibres in one washing machine cycle [29].

Table 8 A summary of the number of MP items found in fish around the western Mediterranean basin

Country	**Location**	**Area**	**Name**	**Mean**	**Freq** ^{*a}	**Reference**
				MPs/animal	**(%)**	
France	French coastal waters	Northwestern Mediterranean	*Boops boops*	1.77 ± 0.22	47	Tsangaris et al. [144]
France	Gulf of Lion	Northwestern Mediterranean	*Sardina pilchardus*	0.20 ± 0.69^{a}	12	Lefebvre et al. [100]
France	Gulf of Lion	Northwestern Mediterranean	*Engraulis encrasicolus*	0.11 ± 0.31^{a}	11	Lefebvre et al. [100]
France	Gulf of Lion	Northwestern Mediterranean	*Engraulis encrasicolus*	1.13	80	Collard et al. [50]
Italy	Anzio	Tyrrhenian sea	*Scomber colias, Merluccius merluccius, Trigla lyra*	2.73	66	Bianchi et al. [22]
Italy	Sicily	Southern Tyrrhenian Sea	*Mullus barbatus, Trigla lyra, Galeus melastomus, Scyliorhinus canicular, Raja miraletus*	1.72	17	Capillo et al. [34]
Italy	Sicily	Southern Tyrrhenian Sea	*Sardina pilchardus*	0.53^{a}		Savoca et al. [132]
Italy	Sicily	Southern Tyrrhenian Sea	*Engraulis encrasicolus*	0.26^{a}		Savoca et al. [132]
Italy	Latium, Sardinia and Liguria	Tyrrhenian and Ligurian Sea	*Boops boops*	1.8 ± 0.2	56	Sbrana et al. [133]
Italy	Sicily	Southern Tyrrhenian Sea	*Coryphaena hippurus*	3.9	65	Schirinzi et al. [134]
Italy	Liguria	Northwestern Mediterranean	*Boops boops*	1.85 ± 0.15	47	Tsangaris et al. [144]
Italy	Lazio	Tyrrhenian Sea	*Boops boops*	3.97 ± 0.23	81	Tsangaris et al. [144]
Italy	South Sardinia	Tyrrhenian Sea	*Boops boops*	1.46 ± 0.24	13	Tsangaris et al. [144]
Italy	Sicily	Tyrrhenian Sea	*Lepidopus caudatus*	4.8	78	Bottari et al. [26]
Italy	Sicily	Tyrrhenian Sea	*Zeus faber*	2.1^{a}	51	Bottari et al. [26]
Italy	Leghorn, Taranto and Ortona	North Tyrrhenian Sea, Adriatic Sea and Ionian Sea	*Mullus barbatus*	1.08	20	Giani et al. [78]
Italy	Leghorn, Taranto and Ortona	North Tyrrhenian Sea, Adriatic Sea and Ionian Sea	*Merluccius merluccius*	1.38	27	Giani et al. [78]
Italy	Sicily	Tyrrhenian Sea	*Merluccius merluccius*	1	46	Mancuso and Bottari [105]
Italy	Rasocolmo Cape and Termini Imerese	Tyrrhenian Sea	*Pagellus* spp.		9	Savoca et al. [131]
Country	Location	Area	Name	Mean	Frequency	Reference
				MPs/animal	(%)	
Italy		Tyrrhenian Sea	*Galeus melastomus*	4.47 ± 1.10	78	Valente et al. [148]
Italy		Tyrrhenian Sea	*Scyliorhinus canicula*	2.50 ± 0.52	67	Valente et al. [148]
Italy		Tyrrhenian Sea	*Etmopterus spinax*	1.18 ± 0.26	62	Valente et al. [148]
Italy	Giglio Island	Tyrrhenian Sea	*Scorpaena* sp., *Uranoscopus scaber, Phycis phycis, Spondyliosoma cantharus*	2.47 ± 2.0	77	Avio et al. [11]
Italy	Giglio Island	Tyrrhenian Sea	41 fish types	4.0 ± 1.83	95	Avio et al. [11]
Italy	Strait of Messina	Central Mediterranean Sea	*Trachinotus ovatus*		24	Battaglia et al. [16]
Italy	Strait of Sicily	Central Mediterranean Sea	*Myctophidae*	1	3	Romeo et al. [126]
Italy	Aeolian Islands	Tyrrhenian Sea	*Xiphias gladius, Thunnus thynnus and Thunnus alalunga*	1.32	18	Romeo et al. [125]
Spain	Iberian coast	Alboran Sea	*Engraulis encrasicolus*	1.92 ± 0.95	87	Filgueiras et al. [71]
Spain	Iberian coast	Alboran Sea	*Sardina pilchardus*	1.77 ± 1.42	87	Filgueiras et al. [71]
Spain	Iberian coast	Alboran Sea	*Callionymus lyra*	2.53 ± 1.88	79	Filgueiras et al. [71]
Spain	Iberian coast	Alboran Sea	*Mullus surmuletus*	1.56 ± 0.53	60	Filgueiras et al. [71]
Spain	Central region of the Spanish coast	Western Mediterranean	*Boops boops*	1.74 ± 0.14	53	Tsangaris et al. [144]

Table 8 (continued)

Country	Location	Area	Name	Mean	Freq *[a]	Reference
Spain	Northern coast of Catalonia	Balearic sea	*Boops boops*	1.96 ± 0.20	46	Tsangaris et al. [144]
Spain	Alicante	Balearic Sea	*Sardina pilchardus*	1–2	58	Pennino et al. [117]
Spain	Mallorca Island	Balearic Sea	*Galeus melastomus*	0.34 ± 0.07[a]	16	Alomar & Deudero [3]
Spain	Catalan coast	Balearic Sea	*Boops boops*	1.42–2.59	46	Garcia-Garin et al. [76]
Spain	Iberian Peninsula coast	Balearic and Alboran sea	*Trachurus mediterraneus*	1.13 ± 1.99[a]	43	Rios-Fuster et al. [123]
Spain	Balearic Islands	Balearic Sea	*Engraulis encrasicolus*	0.03 ± 0.16[a]	3	Rios-Fuster et al. [123]
Spain	Spanish coast	Alboran and Balearic Sea	*Sardina pilchardus*	0.21 ± 0.23[a]	15	Compa et al. [53]
Spain	Spanish coast	Alboran and Balearic Sea	*Engraulis encrasicolus*	0.18 ± 0.20[a]	14	Compa et al. [53]
Spain	Mallorca Island	Balearic Sea	*Mullus surmuletus*	0.42 ± 0.04[a]	27	Alomar et al. [4]
Spain	Barcelona, Cartagena, Málaga, Ciutadella and Mahon	Alboran and Balearic Sea	*Mullus barbatus*	1.9 ± 1.29	19	Bellas et al. [18]
Spain	Balearic Islands	Balearic Sea	*Boops boops*	3.75 ± 0.25	58	Nadal et al. [111]

[a] , calculated from Author figures/data; Frequency, % of species that ingested MPs out of all sampled species

Table 9 A summary of the number of MP items found in fish around the eastern Mediterranean basin

Country	Location	Area	Name	Mean MPs/animal	Frequency (%)	Reference
Croatia		Northern and Middle Adriatic Sea	*Mullus surmuletus*	2.7 ± 1.8	70	Anastasopoulou et al. [6]
Croatia		Northern and Middle Adriatic Sea	*Pagellus erythrinus*	2.1 ± 1.6	50	Anastasopoulou et al. [6]
Croatia		Northern and Middle Adriatic Sea	*Sardina pilchardus*	2.5 ± 1.1	37	Anastasopoulou et al. [6]
Greece	Kefallonia	Southern Ionian Sea	*Boops boops*	1.13 ± 0.07	21	Tsangaris et al. [144]
Greece	Saronikos Gulf	Aegean Sea	*Boops boops*	1.45 ± 0.25	30	Tsangaris et al. [144]
Greece	Corfu island	North eastern Ionian Sea	*Mullus barbatus*	1.5 ± 0.8	32	Anastasopoulou et al. [6]
Greece	Corfu island	North eastern Ionian Sea	*Pagellus erythrinus*	1.9 ± 0.6	42	Anastasopoulou et al. [6]
Greece	Corfu island	North eastern Ionian Sea	*Sardina pilchardus*	1.8 ± 0.9	47	Anastasopoulou et al. [6]
Greece	Corfu Island	Northern Ionian Sea	*Sardina pilchardus*	1.8 ± 0.2	47	Digka et al. [61]
Greece	Corfu Island	Northern Ionian Sea	*Pagellus erythrinus*	1.9 ± 0.2	42	Digka et al. [61]
Greece	Corfu Island	Northern Ionian Sea	*Mullus barbatus*	1.5 ± 0.3	32	Digka et al. [61]
Italy	Venice	Northern Adriatic Sea	13 fish species	1.46 ± 0.52	16	Avio et al. [12]
Italy	Ancona and Pescara	Central Adriatic Sea	13 fish species	1.32 ± 0.48	35	Avio et al. [12]
Italy	Bari and Lecce	Southern Adriatic Sea	13 fish species	1.14 ± 0.36	31	Avio et al. [12]
Italy		Central Adriatic Sea	*Sardina pilchardus*	4.63	96	Renzi et al. [121]
Italy		Central Adriatic Sea	*Engraulis encrasicolus*	1.25	91	Renzi et al. [121]
Lebanon	Levantine Basin	Eastern Mediterranean	*Engraulis encrasicolus*	2.5 ± 0.3	83	Kazour et al. [91]
Slovenia		Northern Adriatic Sea	*Chelon auratus*	9.9 ± 8.1	95	Anastasopoulou et al. [6]
Slovenia		Northern Adriatic Sea	*Sparus aurata*	7.3 ± 6.6	100	Anastasopoulou et al. [6]
Slovenia		Northern Adriatic Sea	*Solea solea*	2.9 ± 2.9	65	Anastasopoulou et al. [6]
Turkey	Southeastern coast	North eastern Mediterranean	28 types of fish	2.36	58	Güven et al. [85]
		Northern and Central Adriatic Sea	*Solea solea*	1.73 ± 0.05	95	Pellini et al. [116]
		Northern and Central Adriatic Sea	*Solea solea*	1.64 ± 0.1		Pellini et al. [116]
		Central and North Adriatic Sea	*Sardina pilchardus*	1.78 ± 0.7	19	Avio et al. [10]
		Central and North Adriatic Sea	*Squalus acanthias*	1.25 ± 0.5	44	Avio et al. [10]
		Central and North Adriatic Sea	*Merluccius merlucius*	1.33 ± 0.57	100	Avio et al. [10]
		Central and North Adriatic Sea	*Mullus barbatus*	1.57 ± 0.78	64	Avio et al. [10]
		Central and North Adriatic Sea	*Chelidonichthys lucernus*	1 ± 0	67	Avio et al. [10]

Size

Particle size affects MP transport and fate, and the way they interact with biota. The size distribution of microplastics was described in 96 studies. The size distribution of MPs varied widely across the studies: MP sizes were typically in the range: 300–5000 μm in surface water, 1–2 mm on beaches and in sediment, and > 0.50–1.5 mm in biota. There is no available data on small sized microplastics (< 50 μm) in the environment and biota.

Polymer characterisation

Most studies identified polymer type, with the three polymers most frequently reported being polyethylene (PE), polypropylene (PS) and polystyrene (PS). This is consistent with PP and PE being the polymers most commonly used in single use, disposable plastic products (SUPs), such as plastic packaging and disposable water bottles [45], and PS being widely used for take-away food containers and thermal insulation. In biota, PE was the most commonly reported polymer, with smaller amounts of PS and PP; on beaches, polyester was the most frequently reported polymer; nylon fibres were most commonly reported in water samples.

Chemical contamination

Microplastics can sorb and accumulate pollutants from surrounding water and doing so as informal passive samplers for trace metals and trace organic chemicals. In part, this is due to their small size and large surface to volume ratio, but also the materials from which they are made. For instance, PE typically sorbs more organic chemicals than other kinds of microplastics, and aged microplastics to sorb more pollutants than virgin materials [84]. The polarity of dissolved chemicals also plays a role in sorption, with non-polar chemicals more likely to sorb to non-polar MPs, and, similarly, polar chemicals more likely to sorb to MPs with polar functional groups, e.g., the nonpolar perfluorooctanesulfonamide partitions more readily onto nonpolar PE, whereas some polar antibiotics sorb readily onto the relatively polar plastic, polyacrylamide (PA). Sorbed chemical concentrations on MPs may depend on the proximity to pollution sources, i.e., sampling near the pollution sources can produce higher chemical burdens than those far from the pollution sources. Microplastic materials may also contain a range of chemical additives used during the production process, and these, along with sorbed chemicals, may also become available to organisms on ingestion. However, there are few studies reporting chemical contamination of MPs in the Mediterranean. Capriotti et al. [36] screened MPs collected in the Adriatic Sea for PCBs, PAHs, DDTs and a small number of organophosphate pesticides, noting a clear difference between inshore and offshore samples. For instance, inshore MPs were contaminated by 65.67 ng/g-plastic ΣPCB compared to 37.78 at offshore sites. A significant amount of information on the level of chemical contamination of plastic resin pellets is available on the International Pellet Watch website (http://pelletwatch.org/), albeit the Pellet Watch site does not report pellet concentration. In our database, Karapanagioti et al. [90] was the only detailed report of sorbed chemicals on pellets collected from beaches, reporting median PCB concentrations (PCB66–206) in the range 66–270,000 pg/g plastic resin pellet, with pellets collected from beaches near known pollution sources being 1–2 orders of magnitude more contaminated than pellets from remote beaches with no known local pollution source.

Limitations

Similar to other studies that utilise a bibliometric approach [9], this study has several limitations. For instance, the bibliometric analysis in this study was limited to documents written in English detectable by the adopted search strategy in 2020. Grey literature, e.g., reports and internet sources, were not included in the bibliometric analysis. The search strategy retrieved publications from both the Scopus and the WoS databases, and from other sources through secondary searching of publication bibliographies, but despite this, relevant publications may have been missed. Third, while every attempt was made to standardise terms and authors' names by compiling an alias directory in CiteSpace, certain minor cases may have been overlooked; however, it is unlikely that this will have a major effect on the overall findings.

Some environmental compartments were deliberately excluded from the bibliometric and systematic analysis, e.g., harbours, small almost entirely enclosed lagoon systems and riverine estuaries. These locations are known to be more heavily contaminated than other marine environments. For instance, Abidli et al. [2] found relatively high levels of MPs in surface sediments in harbors on the Northern Tunisian coast (316 items/kg dry weight), and Abidli et al. [1] 3000–18,000 items /kg dry sediments collected from the almost entirely enclosed Lagoon of Bizerte. Lagoon waters are also highly contaminated. For instance, Çullu et al. [56] observed MP abundance or the order 33000 particles/L in surface waters of the Küçükçekmece Lagoon, Turkey. Wastewater treatment plant inputs were also not included in this review. In general, these facilities are considered to be important local sources of MPs [101], albeit that may not always be realised in environmental surveys. In that context, Lots et al. [103] sampled three sites associated with human sewage inputs in the Mallorca islands, and two locations on the

Carbera islands that are sewage free and noted a higher abundance of debris in the Carbera island sites, rather than the more heavily impacted site in the Mallorca island. Even though such studies are extremely valuable in pinpointing major sinks and accumulation sites, they were excluded from further analyses because they do not reflect the average abundance of MPs in the rest of the Mediterranean. They do, however, highlight the need for considering oceanographic factors in the distribution of marine debris, such as winds, currents and halo- and thermohalines.

This review did not include laboratory ecotoxicology experiments or ecological risk assessments unless papers specifically included field measurements of MPs. In that context, there is an increasing number of studies that show that once microplastics are ingested by organisms that live in the Mediterranean Sea they have the potential to cause physical and toxicological harm. For instance, Bråte et al. [28] and Gonçalves et al. [80] both showed that MPs may be retained by filter feeders such as mussels. Bråte et al. [28] suggest that with PE MPs this can lead to injury of the gills and digestive system, whereas Gonçalves et al. [80] found that PS MPs were rapidly excreted by the mussels with no histopathological effects. Polystyrene microbeads did, however, affect metamorphosis of the ascidian *Ciona robusta* [106]. One group of organisms perhaps at particular risk from nano- and MPs are corals. Savinelli et al. [130] have shown that MPs impair the feeding efficiency of *Astroides calycularis* polyps when they co-occur with food items. Such studies can be integrated for probabilistic risk assessments, e.g., Everaert et al. [66] quantified the risk of MP for each year between 1950 and 2100 and found strong indications that 67% organisms in parts of the Mediterranean Sea will be at risk from MPs by 2100.

More generally, the major limitation when comparing contamination in different locations is the presentation of MP abundance in different units. A simple solution for this problem is recording multiple parameters for the MPs while undertaking the research project, e.g., number, size, volume, and weight and presenting the data in as possible different units to make them comparable. For instance, reporting floating MPs as MPs per unit volume as well as per unit area. For marine sediments and beach materials, presenting abundance as a number of items per weight or volume is the least representative method, as the sizes of the MPs are widely different. A better representation may be the total volume of MPs per volume of substrate, albeit determining the volume of MPs would be extremely time-consuming and demanding unless and until automated instrumental methods are more widely available. And in that context, collecting a sample from the surface or the top 5 cm only has been reported to be an underestimation of the total plastic debris that is accumulated on beaches. Carson et al. [38] found that only 50% of the sampled plastic was in the top 5 cm, while up to 95% was in the top 15 cm. Temporal sampling through different seasons and conditions are also crucial in obtaining accurate results for the presence of MP year-round to account for overcompensation, such as from touristic seasons.

Conclusions

Interest in MP abundance in the Mediterranean Sea has been particularly high in the past 5 years (2016–2020). The abundance of MPs on beaches, and in surface waters, sediments and biota are among the highest levels reported worldwide. Secondary microplastics, such fibres and fragments, of a wide range of sizes and chemical composition were dominant in scientific reports, albeit citizen science collection of plastic resin pellets for International Pellet Watch suggests such primary MPs are also widespread, even if their numerical abundance from such collections is unclear. Hereafter, we present some recommendations for further research, many of which are the same as put forward by Galgani et al. [75] almost a decade ago. Based on the evidence presented in this paper, areas that merit immediate attention are summarized as follows:

(1) Understanding the abundance of MPs is the first step towards understanding the extent of microplastics contamination in the region. It is important to expand the scientific efforts in countries bordering the southern Mediterranean Sea, the Levantine Sea, and the Black Sea where there is insufficient knowledge on the abundance and potential impacts of MPs in the environment.

(2) Long-term extensive monitoring programmes should be carried out to better quantify the spatial distribution of MPs in a wider range of Mediterranean sub-regions. In that context, further comprehensive understanding on the contribution of point sources such as rivers, WWTP discharges, is needed to improve measures to stop plastic debris and MPs from polluting the marine environment and translate these observations into predictive models

(3) Characterization of MPs is undertaken using a variety of methods. Standardized collection and identification methods are required to enable better comparison of data and its incorporation in transport and probabilistic risk assessment models.

(4) The majority of studies that have examined MP contamination of biota have focussed on fishes mainly

belonging to phylum Chordata. There is lack of research on higher order piscine predators, such as tuna and sharks, as well as studies of marine mammals, reptiles, and seabirds. The use of standardized methods for the exposure and analysis of sessile benthic invertebrates such as mussels across the Mediterranean Sea would provide better insight on the abundance and distribution of MPs basin wide.

(5) Currently, one of the big questions is how realistic is it that MPs will be transferred into food webs via contaminated prey under current environmental conditions. Though MP ingestion has been observed in many field-collected organisms, understanding of the intake of MPs through trophic interactions and its long-term effects is limited. Therefore, it is necessary to conduct both laboratory and field studies to understand the consequences of trophic transfer of MP in the Mediterranean region.

(6) There is very limited understanding of the abundance of nanosized plastics in the region. Greater attention should be devoted on the determination of nanosized plastic particles in future studies.

(7) Knowledge of atmospheric transport of MPs in the Mediterranean Sea region is still lacking and needs to be strengthened to improve our understanding of local and regional sources of MPs, especially to the open ocean.

(8) For a better risk assessment of MPs, more research on the levels of metals and trace organic chemicals in/on MPs is required. Knowledge of the impacts of intrinsic and/or extrinsic chemicals are lacking. Addressing the ecotoxicological risks of MP must be focused, considering the effects and interactions of MPs and the chemicals, and, indeed, the microorganisms, they carry.

(9) Last, but not least, while much of the focus on MPs has been in the marine environment, plastic pollution is fundamentally a terrestrial problem. Management strategies to cost-effectively reduce the amount of plastic used, for reducing plastic waste at source, as well as incentives for recycling and improving landfill facilities, need to be identified and implemented by all countries adjacent to the Mediterranean Sea to protect the marine environment

Abbreviations

cf.: Compared with; cm: Centimetre; d.w.: Dry weight; CNR: Consiglio Nazionalle delle Recherche; CSIC: Consejo Superior de Investigaciones Científicas; DDT: Dichlorodiphenyltrichloroethane; FAP: Proportion of female authorships; FAOR: Female-to-male authorship odds ratio; FTIR: Fourier Transform Infrared Spectroscopy; g: Gram; IFREMER: Institut Français de Recherche pour l'Exploitation de la Mer; ISPRA: Italian National Institute for Environmental Protection and Research; kg: Kilogram; km: Kilometre; L: Litre; m: Metre; mg: Milligram; mm: Millimetre; MP: Microplastic; ng: Nanogram; org: Organism; PA: Polyamide; PAH: Polycyclic aromatic hydrocarbon; PC: Polycarbide; PCB: Polychlorinated biphenyl; PE: Polyethylene; PET: Polyethylene terephthalate; pg: Picogram; PP: Polypropylene; PS: Polystyrene; PU: Polyurethane; PVC: Polyvinylchloride; RMIT: Royal Melbourne Institute of Technology; μm: Micrometre.

Supplementary Information

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Additional file 1.

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Authors' contributions

All authors contributed to the collection and collation of articles and information extracted therefrom; GA undertook the Citespace analysis; all authors contributed to the writing of the manuscript. The author(s) read and approved the final manuscript.

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Availability of data and materials

All data generated are available in supplementary information files.

Declarations

Competing interests

The authors declare that they have no competing interests.

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