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Microplastic in Commercial Fish in the Mediterranean Sea, the Red Sea and the Arabian Gulf. Part 1: The Mediterranean Sea

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Abstract

Microplastic has become a ubiquitous environmental pollutant. Microplastic in the oceans has detrimental effects on aquatic organisms. The presence of microplastic in marine fish heightens the chance of finding microplastic in seafood targeted for human consumption. The Mediterranean Sea is known to suffer from significant plastic pollution. It is also one of the most thoroughly studied water bodies in regard to microplastic contamination. The manuscript reviews the available literature of 2015-2021 on the presence of microplastic in commercially important fish species in the Mediterranean Sea. The literature data on microplastic content on beaches, in subtidal sediment, in the sediment from the ocean floor and in surface water of different regions of the Mediterranean Sea is reviewed, also.

Keywords

Review, Commercial Fish, Mediterranean Sea, Microplastic, Environmental Pollution

1. Introduction

Microplastics (MP) are small plastic particles of 5 mm or less in size. Either, these particles are synthesized in this small size (primary microplastics) or stem from the fragmentation of larger plastic pieces (secondary microplastics). One of the final resting places of MP is aquatic ecosystems, where there is significant transport of MP from land to water through run-offs [1], via wastewater treatment plants [2] and through air movement and subsequent atmospheric deposits [3] [4]. In addition, there is significant direct plastic input into the sea through fishing operations and through shipping. Almost all ocean regions are affected by MP, where MP has been found in Arctic [5] and Antarctic waters [6] as well. The Mediterranean Sea, the Arabian Gulf and the Red Sea are the most important larger water bodies for the MENA region. Not only do they provide the countries along their shores access to trading routes, but they are still home to some of the richest fishing grounds in the world. All of them are semi-enclosed, enjoy heavy ship traffic, and are situated in a relatively arid region, with the Red Sea being the northernmost tropical sea. While the fish caught in the Mediterranean Sea decreased a little over the last 10 years, it was a little over 800.000 tons per year in 2018, with herring, anchovies and sardines contributing 49.5% of the total [7]. Fish catches in the Arabian Gulf have averaged 331,827 tons annually (2004-2012), with a minimum of 208,520 tons in 2004, and a maximum of 421,606 tons in 2012 [8] [9]. The total fish captures in the Red Sea amounted to 60,900 tons in 1986 [10]. With the total fish captures from the Red Sea of the Kingdom of Saudi Arabia reaching 22,700 tons in 1986 [10] and 24,016 metric tons in 2018 [11], there is a slight increase. There has always been a worry in regard to contamination in fish being passed on to humans who consume it, be it heavy metal contamination [12] [13] or persistent organic pollutants. The latest in line is MP. MP has been found in fish sold in fish markets around the world [14] [15], and thus the level of ingestion and uptake of MP by fish as well as the abundance of MP in aquatic ecosystems is of importance. There have been reviews both on MP in the Mediterranean Sea [16] [17] [18], on the effect of marine litter on fish [19] [20] [21] as well as on MP in the Arabian Gulf [22]. Less has been reported from the Red Sea and there is currently no review on MP in the Red Sea. The current contribution, the first of two, reviews the occurrence of MP in commercially valuable fish species in the Mediterranean Sea. 22 countries from three continents, home to around 480 million people, surround this semi-enclosed sea, where 33% of the population lives along with the coastal areas and roughly 55% of the population resides in coastal hydrological basins [23], where population increase has gone hand in hand with increasing environmental pressures. The Mediterranean Sea, which is known as a hotspot of plastic contamination, is likely the most studied water body in regard to microplastic contamination, with university research groups, non-governmental, governmental and interregional organizations such as UNEP and EEA providing new citable data on a weekly basis. In the following, the authors have collated the available research data on MP contamination in commercially important fish species of the Mediterranean of the last decade.

2. Data Collection

To undertake this review, the authors have used the databases Scopus®, Scifinder® and Web of Science®. Typical keyword combinations used were "Mediterranean AND microplastic", "Mediterranean AND microplastic AND fish", "Mediterranean AND beach AND microplastic", Mediterranean AND sediment AND microplastic" to give as an example 299 entries, 99 entries, 31 entries, and 89 entries, respectively, in Web of Science®. Publications by governmental organizations, intergovernmental organizations (IGO's) and or nongovernmental organizations (NGO's), which are often not abstracted by the above databases, were searched for on the world-wide-web, utilizing the search words above. Abstracts of all entries were screened. When the abstract indicated that a quantitative analysis of microplastic in the region of the Mediterranean Sea was presented, the paper was obtained through the UAEU university library. All pertinent references in the given papers were screened for any missed publications. The "forward" citations given in the databases for the entries found in the databases were also screened for any missed publications. Papers were included in this review that detail quantitative analyses of microplastic in fish, water, beaches/coasts and sediments within the region of the Mediterranean Sea. No review was discarded on the basis of the actual data presented. Where data seemed to be in conflict with other published data, the conflict was stated in the review without evaluation of the actual data. At a late stage of preparing the manuscript, publications on microplastic in fish that are not deemed of commercial value such as the lanternfishes (Myctophiformes) were excluded from the review. To decide upon the commercial values of different fishes, capture production statistics from FAO Fisheries & Aquaculture were used.

3. Microplastic-Composition, Additives and Adsorbents and Their Potential Effects on Marine Organisms

MP can come in different forms such as pellets, fragments, filaments/fibers and films, and be made of a number of different polymer types such as polyethylene (PE), polypropylene (PP), polyurethane (PU) and polystyrene (PS). Interestingly, from a meta-analysis of 39 studies from different regions, Erni-Cassola *et al.* [24] determined the make-up of the most abundant polymers discharged into water bodies to be the following: PE (polyethylene, 23%), PP (polypropylene, 13%), PS (polystyrene, 4%) and PP&A (group of polymer types formed by polyesters, PEST; polyamide, PA; and acrylics, 13%). This coincides with the report of de Haan *et al.* that PE, PP, PS, polyesters are the most dominant polymer types found in the Mediterranean Sea [25]. Polymers carry additives. These can be small organic molecules such as phthalates [26], terephthalates, alkanedioates, trimellitates, trialkyl phosphates and siloxanes [27]. Furthermore, there can inorganic filling materials involved, mostly salts, that provide bulk but influence other properties of plastics as well such as stickiness of the surface of the plastic. In addition, there are colorants that can either be organic dyes or inorganic pigments. Small organic molecules can easily attach to the hydrophobic surface of the MPs, and so MPs can act as carriers of organic contaminants already present in the water body. Many of the organic compounds are known to bio-accumulate along the food chain. Thus, Capriotti *et al.* detected organic pollutants such as polychlorinated biphenyls (PCBs), organophosphous compounds, and polycyclic aromatic hydrocarbons (PAHs) on the surface of MPs collected in Italian coastal waters of the central Adriatic Sea [28]. K. Karkanorachaki *et al.* (2018) could detect concentrations of 13 different types of PAHs on the surfaces of MPs collected from 9 beaches in Crete [29]. While not necessarily having MPs as their origin, significant concentrations of the phthalates dibutyl phthalate (DBP, 0.017 - 0.055 $mg \cdot L^{-1}$), diisobutyl phthalate (DiBP, 0.075 - 0.219 $mg \cdot L^{-1}$), and di(2-ethylhexyl)phthalate (DEHP, 0.071 - 4.594 $mg \cdot L^{-1}$) were found along the coast of the Mahdia governorate, Tunisia, and these phthalates were noted to bioconcentrate in the gilt-head bream (*Sparus aurata*) caught in the same area [DBP, 0.389 - 0.817 $mg \cdot L^{-1}$; DiBP, 0.101 - 0.921 $mg \cdot L^{-1}$; DEHP 0.726 - 1.771 $mg \cdot L^{-1}$] [30]. M. Fossi *et al.* have estimated that within the Pelagos sanctuary (Ligurian Sea) the Mediterranean basking shark (*Cetorhinus maximus*) can ingest as many as 540 $MP \cdot h^{-1}$ based on the MP concentration data of 2012. The group links the occurrence of mono(2-ethylhexyl)phthalate (MEHP) as primary metabolite of DEHP in Cetorhinus maximus with its ingestion of MP [31]. Nevertheless, Schmidt *et al.* noted that in their study on the concentration of phthalates and MPs in surface seawater, sediment and zooplankton samples in Marseille Bay (NW Mediterranean Sea) no clear correlation could be seen between the two [32]. Some of the additives in microplastics are mild estrogens and could act as hormonal disruptors under certain conditions. Other possible adsorbents such as polychlorinated biphenyls (PCBs) can act as neurotoxins [33] or can exhibit genotoxicity [34]. Neurotoxicity and genotoxicity have also been documented in animals exposed to microplastics under laboratory controlled conditions along with oxidative stress, reduced food consumption, growth, reproduction and survival rates [35] [36] [37]. Metals have also been seen to hitchhike rides on plastic surfaces of MP, with a recent study from the Mediterranean Sea showing aluminum, iron, chromium, zinc, nickel, molybdenum, manganese, lead cobalt, and copper at concentrations of mg/kg plastic and arsenic, vanadium, rubidium, and cadmium at concentrations of μg/kg plastic [38].

4. Abundance of Microplastic in the Mediterranean Sea

The concentration of microplastic [39] as of plastic [40] in the Mediterranean Sea has been described to be very high compared to other large water bodies, representing as much as 5% - 10% of global MP by weight [41]. Floating plastic debris in the Mediterranean Sea has already been investigated scientifically in 1980 [42]. Different models have been forwarded that reflect the input and distribution of MP in the Mediterranean Sea [43] [44]. For their model, Kandoorp *et al.* [43] estimated that in 2015, there was an input of 2100 - 3400 tonnes of MP, and that of plastics released since 2006, about 170 - 420 tonnes remain afloat in the surface waters, 49% - 63% ended up on coastlines, and 37% - 51% have sunk down to the sea floor. With many MP possessing positive buoyancy in salt water and with microbial colonization and biofilm formation on MP changing their density over time [45], this leaves about 1% of total MP in the water column according to the model [44].

Physical studies on the occurrence of MPs along the coast, the water column, the sea floor and in marine organisms of the Mediterranean Sea are quite extensive. Thus, MP quantification in sediments along the coastline of the Mediterranean Sea has been carried out in a number of locations (Figure 1). Starting with the Northwestern coastline and then turning clockwise, the following are some of the values that have been published, given either as number of MP per kg of dry sediment or number of MP per m^2 surface with a defined thickness of layer analyzed: Coast of Granada: **Herradura** (beach) (45.0 ± 24.7 MP/kg), **Motril** (beach) (31.5 ± 21.5 MP/kg), **La Rábita** (beach) (22.0 ± 23.2 MP/kg), all Spain [46]; **Denia** (beach), Costa Blanca, Spain (156 ± 29 MP/kg, [47]); **Barcelona** (beach), Spain (148 ± 23 MP/kg, [47]); **Andratx**, Mallorca (shallow coastal sediment, 10 m depth), Spain (120 ± 100 - 160 ± 90 MP/kg, [48]), **Santa Maria**, Cabrera (shallow coastal sediment, 10 m depth), Spain (240 ± 30 - 900 ± 100 MP/kg, [48]); **Es Port**, Cabrera (shallow coastal sediment, 10 m depth), Spain (100 ± 60 MP/kg, [48]), **La Crouste**, Canet-en-Roussillion (beach), France (166 ± 205 MP/kg, [49]); **Plage del Forat** (beach), Paulilles, France (58 ± 31 MP/kg, [49]), Cassis (beach), France (124 ± 36 MP/kg; [47]); **Tuscany**: San Rossore (beach) (958.7 ± 792.0 MP/kg), Marina di Vecchiano (beach) 471.3 ± 333.0 MP/kg), Viareggio (beach) (175.4 ± 42.0 MP/kg), Italy [50]; **Tuscany**: Talamone, (sediment sample, 62 ± 24 MP/kg); Osa (sediment and beach, 286 ± 37 MP/kg) and Albegna (sediment and beach, 453 ± 424 MP/kg); Capalbio (beach and intertidal, 466 ± 297 MP/kg), Italy [51]; **Tuscany**: Albegna (river mouth, 57 - 395 MP/kg), Giannella (beach, 134 - 1069 MP/kg), Ombrone (river mouth, 99 - 118 MP/kg), Trapolla, Maremma (beach, 250 - 271 MP/kg), Marina di Alberese (beach, 200 - 282 MP/kg) [52]; **Latium** (shallow coastal water sediment, 3 × 3 sampling sites) Mignone (485.9 ± 133.8 MP/kg [10 m depth], 330.7 ± 182.1 MP/kg [27.7 m depth], 175.4 ± 157.9 MP/kg [35.7 m depth]; Civitavecchio 131.1 ± 50.7 MP/kg [10 m depth], 401.4 ± 204.2 MP/kg [30 m depth], 339 ± 169.5 MP/kg [37.7 m depth]; Capo Linaro 279.9 ± 15.5 MP/kg [10 m depth], 194.9 ± 127.1 MP/kg [28.0 m depth], 116.7 ± 34 MP/kg [37.5 m depth], Italy [53]; **Sicily**

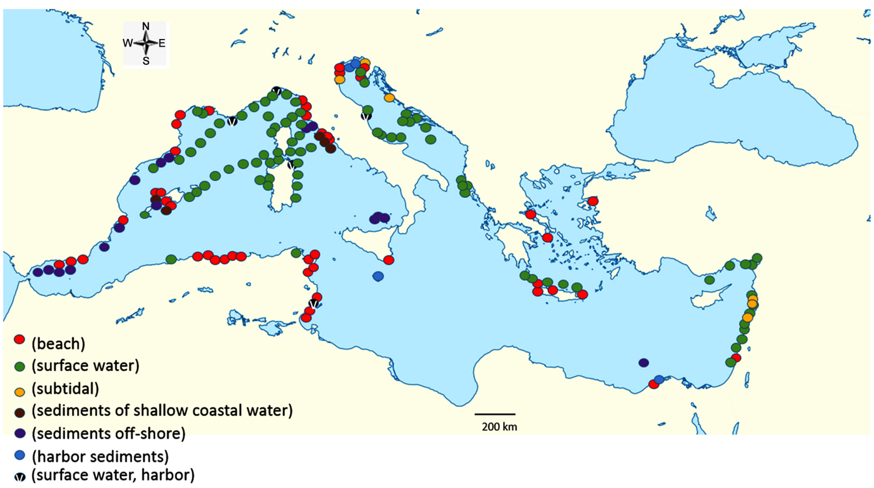

Figure 1. Sampling sites of microplastics on beaches, in coastal sediments and in surface water.

(beach), Italy (160 ± 31 MP/kg; [47]); **La Valetta** (harbor, at 4 - 22 m depth), Malta 0 - 23 ML/kg [54]; **San Mauro a Mare** (beach), Italy (84 ± 12 MP/kg; [47]); **Lagoon of Venice** (subtidal), Italy (672 - 2175 MP/kg; [55]), **Caorle** (intertidal area), Italy (710 MP/kg [56]); **Lido de Dante** (beach), Italy (1512 ± 187 MP/kg; [47]); **Gulf of Trieste**, Italy (subtidal) 30 - 870 ML/kg [57]; **Slovenia** average of 6 beaches: Debeli Rtič, Jadranska, Simonov Zaliv, Bele Skale, Portorož, and Seča; 177.8 MP/kg (beach); 170.4 MP/kg (infralittoral [58]); Slovenia (average of 9 sampling sites: Portorož, Bele Skale, Simonov Zaliv, Izola, Koper, Ankaran, Debeli Rtič, Jadranska and Seča; 0.5 ± 0.5 - 1.0 ± 0.8 MP/kg; [59]); **Croatia** (subtidal) **Pilion** (beach), Greece (242 ± 93 MP/kg; [47]); **Crete** (4 beach sites for quantitative analysis: Falassarna, Stavros, Petres, Analoukas: 11.2 ± 20.8 - 169.8 ± 185.4 micropellets/m^2 and 22.8 ± 33.6 - 124.9 ± 120.3 microparticle fragments/m^2 [29]) **Dikili** (beach), Turkey (248 ± 47 MP/kg; [47]); **Levantine coast**: Tripoli, Lebanon (4680 MP/kg), average over all sampling sites: 2433 ± 2000 MP/kg [60]; **Tel Aviv** (beach), Israel (168 ± 16 MP/kg; [47]); **Eastern Harbor** (beach), **Alexandria**, Egypt (242 MP/kg [61]); **Coast of Tunisia** (beach, 8 sampling sites: Gulf Gabes (4 sites; 139 ± 12.2 - 435 ± 34 MP/kg), Gulf of Hammamat (2 sites, 145 ± 13 - 606 ± 37.5 MP/kg), Gulf of Tunis (2 sites, 129 ± 10 - 379 ± 33 MP/kg [62]); **Sidi Mansour harbor** (harbor bottom), Sfax, Tunisia (252 - 5332 MP/m^2 from 5 - 10 cm top sediment [63]); **Northern coast of Tunisia** (average of 5 sampling sites: Menzel Bourguiba, North Lake of Tunis, South Lake of Tunis, Goulette, Carthage; 141 ± 26 - 461 ± 30 MP/kg [64]); **Bizerte lagoon**, Tunisia (3000 - 18,000 MP/kg [65]); **Coast of Algeria** (4 sampling sites, beaches: Chapuis Beach, Joannonville Beach, Sidi Salem Beach, Cap Rosa Beach; 182.66 ± 27.32 - 649.33 ± 184.02 MP/kg [66]); **West coast of Algeria** (9 sampling sites, beaches: Sidi Mansour, Sablettes, Sakhra, Benabdelmalek R., Hadjadj, Petit Port (W), Petit Port (E), Sidi Abdelkader, Bahara; 7.60 ± 18.80 - 66.40 ± 44.95 plastic items/m^2 [67]). Clear differences in MP concentrations have been found on beaches that are cleaned regularly as compared to those that are cleaned less regularly. A distinction can be made between rural, semi-rural and urban beaches and coastlines. Some of the beaches on the Italian East coast in the regions Emilia Romagna and Veneto are MP hotspots with >1000 MP/kg soil as are some of the sampled locations in Lebanon and Israel [60] [68]. Nevertheless, most of the analyses of Mediterranean beaches have found MP contents > 150 MP/kg soil.

Measurements on MP concentrations on sea floors in the Mediterranean Sea, off-shore (**Figure 1**), were reported as follows, starting with the Northwestern coastline and then turning clockwise: **Spanish Mediterranean continental shelf**: 10 locations at 43 - 154 m depth; 45.9 ± 23.9 MPs/kg (Palma de Mallorca) - 280.3 ± 164.9 MPs/kg (Malaga), Spain [69]; **Piombino channel** 31 km-long transect from the port of Piombino (Tuscany) to the port of Portoferraio (Elba Island), at a depth of up to 71.5 m, Italy) 0.43 - 4.0 P/kg (65 - 600 P/m^2) [70]; **Central Adriatic Sea** (140 km long East-West transect from Pescara to the island of Pianosa at depths of 7 m to 142 m): 0 MP/m^2 - 75 ± 15 MP/m^2 [71]; **Aeolian**

archipelago: Alicudi (347.9 ± 87.4 MP/kg), Filicudi (186.2 ± 161.1 MP/kg), Vulcano (534.8 ± 24.3 MP/kg), Lipari (678.7 ± 345.8 MP/kg), Panarea (484.2 ± 124.4 MP/kg), Stromboli (151.0 ± 34.0 MP/kg), and Salina (219.1 ± 198.7 MP/kg), all at a depth of 30 m [72]; **Middle Adriatic Sea**: Božava (at 45 m depth, 190 ML/kg), Vir (at 78 m depth, 780 ML/kg), Croatia [73]; **Telaščica bay** (Eastern Adriatic Sea): 10 locations, at 3 - 15 m depth, 3.4 - 84 MP·kg^{-1} [74]; **Nile Deep Sea Fan**: (at 1176 m depth, 0 - 1 MP/25cm^2 [75]).

Measurements on the MP concentration in the water at different locations within the Mediterranean Sea have been published, also (**Figure 1**). The following gives some of the published values, starting with the Northwestern coastline and then again turning clockwise: **West Mediterranean Sea**: Balearic Islands, transect Balearic islands—Sardinia/Corsica, Sardinia, Corsica, 41 sampling sites (0.0057 - 0.13 MP/m^2) [76]; **Balearic Islands** (average over 20 sampling sites) (0.875 MP/m^2), Spain [77], **Gulf of Lion**: Rhone river plume (0.059 - 0.40 MP/m^3), Bay of Marseille (0.317 - 1.16 MP/m^3) [78], **North Western Mediterranean Sea**: Gulf of Lion-Marseille-Toulon-Portofino-Elba-Ligurian Sea—sea off west coast of Corsica (average 0.116 MP/m^2) [79]; **Toulon** (harbor), France (0.006 - 0.041 MP/m^2) [80]; **French Riviera-Ligurian Sea**: Toulon-Ste. Maxime-Cannes-Nice-Ventimiglia-Savona-Genoa-Dyfamed sampling site-Calvi (0.021 - 0.578 MP/m^2) [81]; **Genoa** (harbor), Italy (0.0056 - 0.380 MP/m^2) [79]; **Olbia** (harbor), Italy (0.0017 - 0.0058 MP/m^2) [80]; **Ligurian-Thyrrenian Sea**: 0.19 MP/m^2 (average over 34 sampling sites, data from 2018) [82]; **Ligurian-Thyrrenian Sea**: 20 sampling sites (data from 2019) (0.0013 - 3.81 MP/m^2) [83] **Tuscany**: 4 transects off-coast (at 0.5 - 5 - 10 - 20 km) (average: 0.26 ± 0.33 MP/m^2) [84]; **Bay of Calvi**, (0.062 MP/m^2), Corsica, France [85]; **Northwest coast Sardinia**: Asinara National Park, off-shore (0.17 ± 0.32 MP/m^3) [86]; **West coast of Sardinia**: off-shore (0.15 MP/m^3); Mal di Ventre (0.10 ± 0.04 MP/m^3); Caletta (0.01 ± 0.00 MP/m^3); Marceddì (0.18 ± 0.03 MP/m^3); Tirso (0.14 ± 0.08 MP/m^3) [87]; **Marche**: San Benedetto del Tronte (harbor) (0.76 ± 0.48 MP/m^3), San Benedetto del Tronte (0.93 km, 2.78 km, 11.1 km off-shore) (0.17 ± 0.11 MP/m^3 - 62.0 ± 8.03 MP/m^3), Grottammare (0.93 km, 2.78 km, 11.1 km off-shore) (0.17 ± 0.02 MP/m^3 - 3.01 ± 1.82 MP/m^3), Italy [28]; **Bay of Trieste, Slovenia**: 17 samplings (0.19 - 41.3 MP/m^3) [88]; **Middle Adriatic Sea**: Zadar channel (0.1 ML/m^3), Jabuka pit (9.7 particles/m^3), Croatia [73]; **Adriatic Sea**: (Bay of Trieste, Gulf of Split, Corfu) (average: 0.315 ± 0.569 MP/m^2) [89]; **Crete**: 25 sampling sites (0.119 MP/m^2; 0 - 1160 μg P/m^2 [90]); **Iskenderun Bay**, Turkey (0.225 MP/m^2 [91]); (1.067 MP/m^2 [92]); **Mersin Bay**, Turkey (0.683 MP/m^2 [91]), **Turkish coastline**: Mersin-Adana-Hatay (0.032 - 0.52 MP/m^2) [93]; **Levantine coastline**: Sidon (6.7 MP/m^3), Beirut (2.35 MP/m^3) average over all sampling sites, Lebanon: 4.3 ± 2.2 MP/m^3 [60]; **Israeli coastline**: 18 sampling sites-Akko (2.09 ± 1.97 MP/m^3), Herzlyya (2.53 ± 2.41 - 3.05 ± 2.14 MP/m^3), Jaffa (4.71 ± 3.26 MP/m^3), Ashdod (6.72 ± 8.48 MP/m^3), Askelon (5.11 ± 8.76 MP/m^3) [68]; **Bizerte lagoon**, Tunisia (453.0 ± 335.2 MP/m^3 [94]); **Bou-Ismail Bay, Algerian coast**: (0.86 ± 0.35 MP/m^3; [95]).

While litter concentration is generally high on the seafloor along the Mediterranean coast in comparison with many other European coastlines, the concentration is particularly high near shipping lanes, mussel farms, the entry of large rivers [78] [96] and near large cities [97], for instance along the south-east French Mediterranean coast [98], where the litter count was up to 913 ± 80 items/km^2, with 80% of the items being plastic [97]. Constant *et al.* [4] have calculated the annual MP loads of the rivers Rhône and the much smaller Têt to be 5.92 and 0.09 t, respectively, that are discharged into the Mediterranean. Apart, from the Rhone, large discharges can also be seen from the Po, Seyhan and Nile rivers [99]. In this respect, hydrological data of such river basins such as the Seyhan river will be of value to predict future discharges [100]. Large cities that seem to contribute significantly to plastic input are Izmir, Barcelona, Alexandria and Tel Aviv, in the vicinities of which MP concentrations are especially high [99]. Vlachogianni *et al.* (2017) [101] found that shoreline and recreational activities accounted for approx. 33.4% - 38.5% of the marine litter, in general, in different marine compartments in the Adriatic and Ionian Sea, with up to 23.5% coming directly from the sea, and with 6% (beach), 9% (surface water) and 17% (seafloor) coming from fishing gear. MP concentrations are often higher near the coast, *i.e.*, within 1 km of the coastline than further out, though patches with high concentrations of MP can also be found at great distances from the coast (eg., >50 km) [81]. Further off-shore, ocean currents appear to transport microplastics from shallow to deep water, dispersing MPs from open slopes and entraining microplastics transported downslope by gravity currents in submarine channels linked to the coast [102] [103]. Thermohaline bottom currents influence the distribution of MP on the seafloor, leading to hotspots of up to 3.8 MP/g floor sediment [102]. Kane *et al.* [102] found lower MP concentrations on the continental shelf and the upper slopes than at a water depth range of 600 to 900 m, near the sea bottom. Thus far, research has not shown that the nature/character of the sea floor, apart from its contours, and the marine habitat it represents plays a significant role on MP accumulation [56]. As the distribution of MP is driven in part by seasonally changing currents and as plastic input varies throughout the year as well, local MP concentrations can have considerable seasonal variations [95]. Nevertheless, by region, certain areas such as the Ligurian Sea (mean value 0.94 MP/m^3) were found to have a higher MP concentration than others such as the Sardinian Sea (mean value 0.13 MP/m^3) [31].

5. Microplastic Abundance in Fish Species in the Mediterranean Sea

The authors have found reports for 87 fish species for which plastic ingestion has been recorded, many of which are commercially important. The most affected are demersal (30.4%), pelagic (15.9%), benthopelagic (24.6%), bathypelagic (11.6%), and bathydemersal (5.8%) fish [18]. Especially the demersal species are of economic importance. The demersal/semi-pelagic bouge fish (*Boops boops*) has been subject to a number of studies on microplastic ingestion [104] [105]

[106] [107] [108]. The global annual catch of B. boops is estimated to be 40.850 tons (as of 2016 [109]). Mediterranean fisheries rely on this fish. In Algeria, it is ranked 4th in commercial importance after sardine, mackerel and round sardinella, representing 3% of the catch [110]. In all studies except for one (South Sardinia [107]), *B. boops* shows a high ingestion of MP, especially along the Spanish, French and Italian coasts. Ingestion varies significantly from site to site. Garcia-Garin *et al.* see *B. boops* as a bioindicator of MP pollution along the Spanish Catalan coast, finding more fish with MP ingestion caught in the area off Barcelona (65%) than in the areas off Blanes and Cap de Creus (35% and 38%, respectively) [104]. Nadal *et al.* [105] showed that within the Balearic Islands, a big difference was noted in MP ingestion by *B. boops* when comparing Eivissa (78.13%) and Mallorca (39.55%). Even within Mallorca, very different MP ingestion values for *B. boops* were found for e.g. Cala Ratjada (51%) and Cap Blanc (24.68%). The European pilchard (sardine) (*Sardina pilchardus*) is another fish that is of tremendous commercial importance for the Mediterranean, making for about 20% of the fish landings in the Mediterranean Sea (59% of the landings in Algeria [110]). Numerous studies on the fish [93] [101] [108] [111] [112] [113] [114] have shown that its MP ingestion is high in most regions of the Mediterranean, where often over 12% of the fish have been found with MP in their gastrointestinal tract with the highest frequency of 96% reported in the Adriatic Sea [115]. Interestingly, less is known about the MP ingestion behavior of the round sardinella (*S. aurita*), a species that is fished on both sides of the Atlantic as well as in the Mediterranean (22% of the landings in Algeria [109]). Studies are known from the West African coast [116], where 22% of *S. aurita* showed MP ingestion, but the authors could only find a single study from the Mediterranean which comes from an extreme MP hotspot (Eastern Harbor, Alexandria, Egypt; [117]) and describes a situation where all fish showed MP ingestion at a very high level. The European anchovy (*Engraulis encrasicolus*) is a major commercial fish, mainly caught in the Mediterranean Sea and the Black Sea, the 508,959 tonnes caught in 1995 making up 82.2% of the world production. MP ingestion in *Engraulis encrasicolus* has been studied both in the Western Mediterranean Sea and the Eastern Mediterranean Sea (Levantine coast, [60]). MP ingestion for this fish in the Western Mediterranean Sea has been found to be moderate (0% - 14.3% [60] [108] [110] [118]). Frequently studied are the red mullet (*Mullus barbatus*) and the striped red mullet (*Mullus surmuletus*). Both are seen as delicacies in the Mediterranean since the era of Ancient Rome. Alone in the Strait of Sicily, 1700 tons of red mullet are landed annually (data of 2015 [119]). Usually, the fish feed over soft substrates such as sand. All except for one study have found MP ingestion in red mullets to some degree, where especially in the Ionian Sea and along the coast of Turkey high ingestion rates were found, with 32% [113] [114] and 42% [93], respectively, of the fish exhibiting MP in their gastrointestinal tract. Avio *et al.* reported high ingestion rates from the Adriatic Sea as well, with 64% of the fish specimen with MP. Also, red striped mullets caught in Adriatic Sea [113], along the coast of Turkey [93]

and also in the Balearic Islands [120] were found frequently with MP content (23.5% - 70% of the fish). Other goatfish species that have been studied include the golden grey mullet (*Chelon auratus*), the goldband mullet (*Upuneus moluccensis*) and Por's goatfish (*Upeneus pori*). Most of these were studied by Güven *et al.* [93] along the Turkish coast, where in 29% - 36% of the fish's stomach MP was found. Anastasopolou *et al.* [113] report a very MP intake by *Chelon auratus* in the Northern Adriatic Sea (Slovenian Sea) with 95% of the fish specimen studied having ingested MP, with a large number of MP found in the fish. *Merluccius merluccius*, the European hake, is commercially a very important fish that can be found in the East Atlantic, the Black Sea and the Mediterranean Sea. About 100,000 tonnes were landed by European fisheries in 2010, but the species is thought to be overfished. It is a predatory fish, predating also on pilchard and European anchovy. MP ingestion is relatively high for *Merluccius merluccius* [121] [122] [123], with the exception of data from two studies in the North Thyrrenian Sea [121] and the East Ionian Sea [113]. Looking at mackerels from the Carangidae family, early data, from 1998, showed little ingestion (1% of the fish studied) in both Mediterranean horse mackerel (*Trachurus mediterraneus*) and blue jack mackerel (*Trachurus picturatus*), where the data may reflect the time period [124]. Later investigations showed much higher rates of ingestion, with 10% - 48% of the fish from both the East Mediterranean along the Turkish coast [93] and the West Mediterranean Sea (Balearic Islands) [108] showing MP. Also, the Atlantic horse mackerel (*Trachurus trachurus*), caught in the South Adriatic Sea, showed appreciable (24% of the fish) MP ingestion. The Mediterranean horse mackerel is commercially an important fish, both in the Mediterranean and the Black Sea, although regionally the catch has declined due to overfishing [125]. The Atlantic horse mackerel has been classified as a vulnerable species. Looking at the mackerels of the Scombridae family, data is known for the Atlantic chub mackerel (*Scomber colias*) and the Pacific mackerel (*Scomber japonicus*) as well as for two tuna fish, the albacore (*Thunnus alalunga*) and the bluefin tuna (*Thunnus thynnus*). The annual *Thunnus alalunga* catch in the Mediterranean is variable, but in 2010 it amounted to 2123 tonnes, with Italy being the main producer at 1109 tonnes [126]. In 2009, F.S. Karakulak *et al.* studied stomach contents of 218 bluefin tuna (from the Eastern Mediterranean Sea and had found plastic in 37 stomachs [127]. These plastics could be labelled as meso and macroplastics. At the time, the presence of MP was not documented. In 2015-2020, a number of studies were forwarded regarding MP ingestion in these fish, where the percentage of fish with MP was recorded at 12.9% for *Thunnus alalunga* [128], 32.3% for *Thunnus thynnus* [128], 66.7% for *Scomber colias* [123] and 43.2% - 57% for *Scomber japonicus* [93]. In addition to *B. boops*, a number of seabream and porgy species were the subject of studies in the Adriatic Sea and the East Mediterranean Sea. Most studied is the common pandora (*Pagellus erythrinus*). The annual worldwide production of the common pandora decreased from about 10,000 tonnes (1981-1985) to 4500 tonnes [129]. The species is overexploited in several Mediterranean subareas. A study from the

North Adriatic Sea and the NE Ionian Sea with altogether 80 specimen showed low MP ingestion (2% - 3.3%) [101]. Other studies, partially from the same area, but also from the East Mediterranean showed a higher percentage of fish with MP (22% - 50%) [93] [113] [114]. Other seabream species that were studied are the black seabream (*Spondyliosoma cantharus*), the white seabream (*Diplodus sargus*), the striped seabream (*Lithognathus mormyrus*), the axillary seabream (*Pagellus acarne*) the blackspot bream (*Pagellus bogaraveo*), the gilt-head bream (*Sparus aurata*) and the red porgy (*Pagrus pagrus*). All these species show heavy MP ingestion. Finally, MP ingestion of the common sole (*Solea solea*), a demersal species, a commercially important fish with catches worldwide amounting to 33,997 tonnes (FAO Fishfinder, species fact sheets, *Solea solea*) and with catches in the Adriatic Sea (Italy, Croatia, Slovenia) equaling 1645 tonnes in 2011 [130], has been studied a number of times in the Adriatic Sea. Results are varied, however, the largest study with 533 specimen, showed that 95% of the fish had MP in their gastrointestinal tract [131] (**Figure 2**).

Looking at the elasmobranch fish, sharks, many species of which are endangered [132], have been investigated extensively for MP content. In the Mediterranean Sea, elasmobranch fish catches make up only 1.15% of the total landings [133]. Additionally, the catches show a decreasing trend from 26,000 tons in 1983-1984 to 14,000 tons in 2015 [133]. Among the elasmobranch fish, the velvet belly lanternshark (*Etmopterus spinax*) has been one of the most studied in the Mediterranean Sea in regard to MP content [124] [134] [135] [136]. Although the species is of no commercial importance per se, it is often found in bycatch, especially in deepwater fishing operations. Here, MP findings are heterogeneous, where a number of studies have reported low MP ingestion rates for this shark species [135] [136]. Nevertheless, of 34 specimen of the velvet belly lanternshark from the Tyrrhenian Sea, 21 (61.8%) were found with MP in their gastrointestinal tract. The blackmouth catshark (*Galeus melastomus*), a fish of limited commercial value within the Mediterranean region, is another species that has been thoroughly investigated for MP contamination [134] [135] [137] [138] [139]

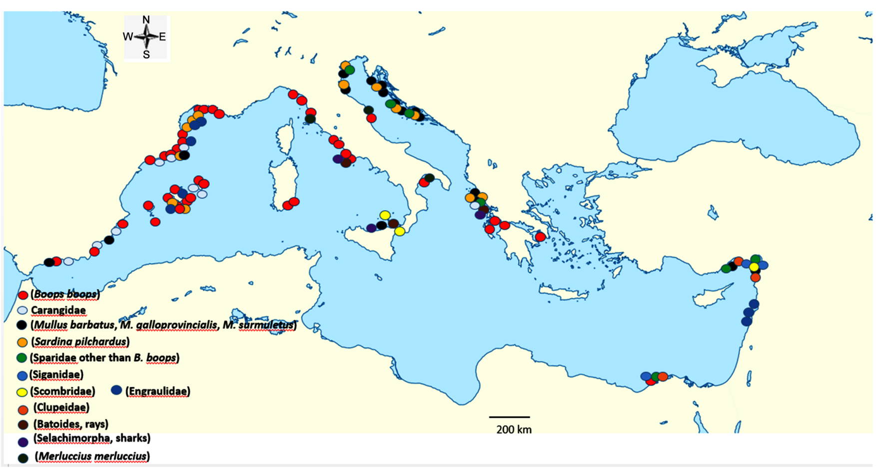

Figure 2. Sampling sites for different fish species for microplastic content screening.

with large numbers of specimen per research study. Two reports [134] [135], from 2013 and 2016, noted that about 3.2% of 866 specimen showed ingested MP. Later studies of the time period 2017-2020 [137] [139] reported higher ingestion rates in the blackmouth catshark from the Balearic Islands and from Thyrrenean Sea. Of more value for deepwater commercial fisheries is the Portuguese dogfish (*Centroscymnus coelolepis*), which is prized for its oil. For this species, two studies found little to no MP ingestion [135] [136]. The spiny dogfish (*Squalus acanthias*) is globally one of the more common shark species, however, in the Western Mediterranean it is quite rare. It is more common in the Eastern Mediterranean and also in the Black Sea, where it is fished commercially. Nevertheless, in the Mediterranean Sea the species is seen as endangered. A study of 2013 from the East Ionian Sea showed no MP ingestion in 10 spiny dogfish, a study of 2015 found MP in 4 out of the 9 spiny dogfish examined [122]. The small spotted catshark (*Scyliorhynus canicula*) is one of the most abundant sharks in the Mediterranean, but is of limited commercial value in the Mediterranean region. Two studies [138] [139], both from the Thyrrenian Sea, with 12 and 30 specimen, respectively, showed appreciable MP contamination in this species. Lastly, much less is known about MP ingestion of rays, where only a few specimen of the longnosed ray (*Raja oxyrinchus*, 10 specimen, 0% MP) [134], the thornback ray (*Raja clavata*, 2 specimen, 0% MP) [134] and the brown ray (*Raja miraletus*, one ray found with MP content) [138] have been analyzed for MP content.

6. Conclusions

Overall, the published data on MP content in fish of the Mediterranean Sea is quite heterogeneous. Keeping in mind that most of the data stems from 2013-2020 and that therefore the research area is still rather novel, having been previously focused on meso- and macroplastic ingestion, and that the research methodology has been refined over the years, early data [101] [134] often shows relatively little MP ingestion. Otherwise, there are areas within the Mediterranean where fish during the time of the study showed less MP ingestion. A typical example comes from the species *B. boops* where only 16.7% of the fish were found with MP in a study from the Balearic islands [108] and 13.0% in a study from South Sardinia [107]. Again, this data represents a "screenshot" of the species in that location at that particular time. Fish in neighboring locations within the same general region may give completely different data ([104], see above). There is an indication that deep sea catches show less MP content, though some of the data come from the early years of study (see above). Also, seasonal variations in currents and waste discharges can bring about significant differences in MP content along the water column as isolated events such as ship wrecks [140] or ships losing cargo en route. For litter in general, Vlachogianni *et al.* [101] [141] found the average number of litter per gut higher in fish from the South Adriatic Sea (2.2 P/gut) than from the northeastern Ionian and North Adriatic Sea (1.0 P/gut).

What danger MP containing fish represent to humans is debatable, as with the gutting of fish most MP content is avoided. However, about 20% of fish landings go into fish meal which then is affected by the MP content in the fish. As fish meal also constitutes the offal of fish, the risk to utilize parts of the fish that hold MP is quite high [142]. *E. encrasicolus*, *S. pilchardus*, and *T. trachurus* are some of the main fish species that contribute to fish meal production, and studies have shown that these species carry MP content, when caught in the Mediterranean Sea.

To curb the increase in MP in the Mediterranean Sea, it is important to limit the entry of plastics in general by a better waste management at the community level, especially in the larger cities on the Mediterranean coast. Certain contributors to primary MP such as microbeads in cosmetics will be phased out in the near future and will no longer be of importance, others such as textile fibers and microtires will remain contributors to MP in general, although microtires specifically have not been recorded in fish to date. More important will be secondary MP resulting from the gradual breakdown of the overall solid plastic waste entering the Mediterranean Sea. Even without the introduction of additional plastic waste, secondary MP will remain with us for an indeterminable time in the future due to the long half-life of plastic materials, much of which will lastly degrade by passing through MP stages.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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