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Research Article

A Comprehensive Review on Microplastic Pollution in Aquatic Ecosystems and Their Effects on Aquatic Biota

Duygu Sazlı[1], Danial Nassouhi[1], Mehmet Borga Ergönül[1], Sibel Atasağun[1]

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ABSTRACT

Plastic wastes released into the environment break down into fine particles due to exposure to meteorological events such as wind, precipitation, UV radiation, and abrasion. These smaller plastic particles, ranging between 1 µm and 5 mm, are called microplastics and they can be transported over longer distances with the aid of erosion, waste water discharges, winds, and currents. Aquatic habitats are the final sink for many pollutants including heavy metals, pesticides, nanoparticles, and microplastics released into environment. Thus, these pollutants are considered a major threat to aquatic life. In this study, we reviewed studies i: focusing on the type, size and the quantity of microplastics observed in freshwater and marine ecosystems, and ii: studies on the effects of microplastics on aquatic organisms. The data gathered clearly indicates that microplastics are quite abundant in freshwater and marine ecosystems. Furthermore, nearly in all studies reviewed, microplastic uptake and alterations in several biochemical parameters depending on microplastic exposure are recorded. The studies also point out that microplastics will become a global serious health concern both for human beings and aquatic organisms in the near future.

Keywords: Microplastic, polyethylene, PVC, plastic, pollution

ORCID IDs of the author:
D.S. 0000-0002-9511-5833;
D.N. 0000-0003-3693-6313;
M.B.E. 0000-0002-0263-9129;
S.A. 0000-0001-8507-0961

[1]Ankara University, Faculty of Science, Department of Biology, Ankara, Turkiye

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Correspondence:
Mehmet Borga Ergönül
E-mail:
borga@science.ankara.edu.tr;
ergonul@gmail.com

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INTRODUCTION

The term "plastic" is derived from the Greek word "plastikos", which means one that can easily take the desired shape (Ivleva et al., 2017). After the discovery of bakelite, the first synthetic plastic, in 1907 and the synthesis of several other plastic polymers, a revolution has taken place in modern life (Shashoua, 2012). Plastics are flexible, easy to process, cost effective, have a low density, poor thermal and electrical conductivity, are easily accessible, and are resistant to corrosion and light, (Yurtsever, 2015; Frias & Nash, 2019). They have several uses in as agriculture, packaging, the textile and automotive industries, outdoor and indoor household goods, building elements and the construction sector, and toys (PlasticsEurope, 2016; Boucher & Friot, 2017; Kawecki et al., 2018; Meng et al., 2020).

Due to the increasing demand for plastic materials, plastic production is also increasing. Eventually plastic materials became one of the main wastes released into environment (Geyer et al., 2017). The annual global plastic production in 1960 increased from 5 to 359 million tons in 2019 (PlasticsEurope, 2019). The highest plastic production takes place in Asia with 51% of the global plastic production, 20% in Europe, 18% in North America, 7% in Africa, and 4% in South America (PlasticsEurope, 2019).

Plastic wastes discharged into terrestrial and aquatic habitats are considered a serious threat to biodiversity, due to their resistance to degradation (Gall & Thompson, 2015; Carbery et al., 2018;). Plastic wastes are classified into 4 groups depending on their size; macroplastic (2.5 to 100 cm), mesoplastic (5 mm to 2.5 cm), microplastic (1 µm to 5 mm) and nanoplastics (<1 µm) (GESAMP, 2015). The amount of larger plastic wastes form huge floating islands in the oceans and are considered the 7th continent due to their size. On the contrary, the nanoplastics, invisible to the naked eye, can be found everywhere in our daily lives, even in drinking water (Hidalgo-Ruz et al., 2012; Aydın, 2020). But the effects of nanoplastics on aquatic organisms have been studied only in a limited number of studies (Al-Thawadi, 2020; Amobonye et al., 2021).

Microplastics (1-5000 μm) are defined as synthetic solid plastic particles or polymeric matrices that have a regular or irregular shape (Frias & Nash, 2019). According to Cole et al. (2011) microplastics are divided in 2 groups depending on their origin; primary and secondary microplastics. Primary microplastics refer to microbeads in various sizes, and they are mainly produced for industrial purposes and in personal care products (Fendall & Sewell, 2009), in exfoliants (Leslie, 2014), sandblasting systems (Sundt et al., 2014) or plastic pellets (Browne et al., 2011) are used in the production. Seconder microplastics are formed from larger plastics due to exposure to UV radiation, or other photochemical processes, wind, heat, physical degradation, or various mechanical forces (Rocha-Santos & Duarte, 2015; Cole et al., 2011).

The earliest record of microplastic pollution is the observation of small plastic particles in the Atlantic Ocean during the 1970s (Schymanski et al., 2018; Wilcox et al., 2019). The first comprehensive study on the distribution of plastic particles in the oceans was conducted in 2014 by Richard Thompson and his team (Law & Thompson, 2014; Rochman, 2018). Unfortunately, nowadays, it is known that microplastics are present in the sediment and pelagic zones of oceans and seas worldwide (Thompson et al., 2004; Rochman et al., 2015; Kühn & Van Franeker, 2020). Microplastics, have a tendency to float in the surface layers of lakes or seas due to their low density. These particles are ingested by aquatic organisms including plankton, aquatic invertebrates, fish, aquatic birds and even mammals since they resemble an attractive and easy prey due to their color and shape. Eventually, they block the digestive tract of these animals which in turn may lead to death (Kumar et al., 2021).

Color, shape and the chemical structure of the microplastics are crucial for their fate in aquatic habitats (Zhang, 2017). Microplastics can be spherical, rectangular, cylindrical, disc or in forms of fiber, styrofoam, film and pellets (McDermid & McMullen, 2004; Abu-Hilal & Al-Najjar 2009; Free et al., 2014). They can be found in various colors such as crystalline, white, cream, orange, red, brown, blue, purple, opaque, gray, transparent, black, green, and yellow (Hidalgo-Ruz et al., 2012). Polyethylene (PE) is one of the most manufactured plastic polymer and composes 36% of the total plastic production, followed by polypropylene (PP) (21%), polystyrene (PS) (12%), polyester (PES) (10%), and polyvinyl chloride (PVC) (9%) (Obbard et al., 2014; Horton et al., 2017; PlasticsEurope, 2018). The density and uses of the most common microplastic polymer types observed in aquatic habitats are summarized in Table 1.

Microplastics are observed in the atmosphere (Gasperi et al., 2018), almost in all aquatic habitats and in all compartments of the water bodies (Eerkes-Medrano et al., 2015; Peeken et al., 2018), and even in the most remote regions of the world, such as the Arctic region and high mountain lakes (Woodall et al., 2014; Free et al., 2014; Lusher et al., 2015). Microplastics are also found in the sub-surface layers of soil. For example, 78 items/kg of microplastics were found in surface soils (0-3 cm) in agricultural fields in Shanghai (China), and 62.5 items/kg of microplastic particles were found in deep soils (3-6 cm) (Liu et al., 2018).

Rivers, ocean currents, turbulence (Ballent et al., 2012; Turra et al., 2014; Wagner et al., 2018), surface flows from agricultural areas (Nizzetto et al., 2016), waste water treatment plants (Murphy et al., 2016), wind and erosion (Zalasiewicz et al., 2016) are responsible in the transport of microplastics to different ecosystems. Wind is considered to play a key role in the transportation of microplastics to many different regions of the world. For example, the amount of microplastics at the sea ice was found to be 38-234 particles/m^3 in the Arctic Ocean and it was noted that this is primarily due to the transport of microplastics by the wind (Obbard et al., 2014).

Aquatic habitats are considered a final sink for many pollutants including microplastics, thus microplastic pollution is handled as a serious threat to aquatic life (Al-Thawadi, 2020). Therefore, in this study, studies focusing on microplastic pollution in aquatic ecosystems and the effects of microplastic pollution on plankton, invertebrate animals and fish living in these environments have been reviewed. We focused on the papers published in the past 5-6 years to get an up-to-date view of the current situation of microplastic pollution in freshwater and marine ecosystems.

Microplastic Pollution in Freshwater Ecosystem

The data including the examined water compartment, sampling and detection methods and sampling locality gathered from the studies focusing on the amount of microplastics observed in various freshwater bodies are given in Table 2. According to the data summarized, we found that the amount of microplastic particles found in surface water samples were between 0.051±0.036

Table 1. The density and uses of the most common microplastic polymer types observed in aquatic habitats (Yurtsever, 2015).

Microplastic type	Density	Usage area
High Density Polyethylene (HDPE)	0.94-0.96 g/cm^3	Bottles, stretch film
Low Density Polyethylene (LDPE)	0.91-0.93 g/cm^3	Plastic bags
Polypropylene (PP)	0.83-0.90 g/cm^3	Automotive industry, bottle caps, cooking utensils
Polystyrene (PS)	0.96-1.05 g/cm^3	Plastic sheets, paper, toys, houseware
Polyvinyl Chloride (PVC)	1.16-1.58 g/cm^3	Electric cables, packaging industry, pipe, and plumbing materials
Polyethylene Terephthalate (PET)	1.37-1.45 g/cm^3	Food and pharmaceutical industry, machine manufacturing

Table 2. The amount of microplastics observed in various freshwater bodies, the examined water compartment, sampling and detection methods, and sampling locality.

Locality and sampled compartment	Sampling and detection methods	Microplastic quantity	References
Water			
Antua River (Portugal)	Water pump FT-IR	58-1265 items/m³	Rodrigues et al., 2018
Teltow Canal (Germany)	Niskin bottle SW-IR	0.01-95.8 items/L	Schmidt et al., 2018
Citarum River (Indonesia)	125 µm manta trawl FT-IR	0.057±0.025 particles/m³	Sembiring et al., 2020
Surface Waters			
Hudson River (USA)	Metal bucket micro FT-IR	0.625-2.45 fibers/L	Miller et al., 2017
Sub-alpine Lake (Italy)	300 µm plankton net FT-IR	4000-57.000 particles/km²	Sighicelli et al., 2018
Saigon River (Vietnamese)	300 µm plankton net FT-IR	172.000-419.000 items/m³	Lahens et al., 2018
Pearly River (China)	Stainless steel sieve FT-IR	379-7924 items/m³	Lin et al., 2018
Hong Lake (China)	Water pump Stainless steel sieve Raman Spectroscopy	1250-4650 items/m³	Wang et al., 2018
Dongting Lake (China)	Water pump Stainless steel sieve Raman Spectroscopy	900-2800 items/m³	Wang et al., 2018
Rhine River (Germany)	300 µm manta trawl SEM FT-IR Raman Spectroscopy	0.05-8.3 particles/m³	Mani et al., 2019
Nakdong River (South Korea)	Stainless steel beaker FT-IR	293-4760 particles/m³	Eo et al., 2019
Pearl River Basin (China)	160 µm plankton net FT-IR Raman Spectroscopy	0.051±0.036 mg/L	Fan et al., 2019
Kallaandsi Lake (Finland)	20-100-300 and 333 µm Manta trawl Water pump Stereomicroscope FT-IR	0.27 particles/m³	Uurasjarvi et al., 2019
Carpathian Basin (Europe)	Water pump FT-IR	3.52-32.05 particles/m³	Bordos et al., 2019
Rainwater Pond (Denmark)	Glass bottle FPA-FT-IR	2.7x10⁵ items/m³	Olesen et al., 2019
Ofanto River (Italy)	Plankton net (333 µm) Py-GC-MS	0.9-13 particles/m³	Campanale et al., 2020
Manas River (Asia)	Stainless steel drum micro FT-IR, SEM	21-49 items/L	Wang et al., 2020a
Dutch River (Holland)	Water pump ATR-FT-IR	67-11532 MP/m³	Mintenig et al., 2020
Kızılırmak River Karasu River Yeşilırmak River Melet River Aksu River Değirmendere River Fırtına River	333 µm manta trawl Niskin bottles Stereomicroscope FT-IR SEM	1.783 and 40.03 particles/m³	Aytan et al., 2020
Vistula River (Poland)	55 µm plankton net SEM, FT-IR Raman Spectroscopy	1.6-2.55 particles/L	Sekudewicz et al., 2021
Saskatchewan River (Canada)	53 µm plankton net Stereomicroscope Raman Spectroscopy	4.6-88.3 particles/m³	Bujaczek et al., 2021

Table 2. Continue.

Locality and sampled compartment	Sampling and detection methods	Microplastic quantity	References
Kızılırmak River (Turkey)	200 µm steel sieve Stereomicroscope	Not available	Özkor, 2022
Asi River (Hatay, Turkey)	333 µm manta trawl Stereomicroscope	281 items	Şahutoğlu, 2022
Sediments			
Vembanad Lake (India)	Van-Veen grab Micro Raman Spectroscopy	252.80 particles/m^2	Sruthy & Ramasamy, 2017
Shanghai River (China)	Spade micro FT-IR	802 items/kg (dry weight)	Peng et al., 2018a
Tame River (England)	Stainless steel scoop FT-IR	165 particles/kg (dry weight)	Tibbetts et al., 2018
Yangtze River Delta (China)	Stainless steel spatula micro FT-IR	35.76-3185.33 items/kg	Hu et al., 2018
Antua River (Portugal)	Van-Veen grab FT-IR	100-629 (March) items/kg 18-514 (October) items/kg	Rodrigues et al., 2018
Po River Delta (Italy)	Metal spatula ATR-FT-IR	2.92-23.30 particles/kg	Piehl et al., 2019
Kelvin River (Scotland)	Spade SEM-EDS Light and Electron microscope	161-432 particles/kg	Blair et al., 2019
Rainwater Pond (Denmark)	Glass corer with a diameter of 5 cm FPA-FT-IR	9.5x10^5 items/kg	Olesen et al., 2019
Carpathian Basin (Europe)	Van-Veen Grab FT-IR	0.46-1.62 particles/kg	Bordos et al., 2019
Pearl River Basin (China)	Bucket FT-IR Raman Spectroscopy	174±115 mg/kg	Fan et al., 2019
Bizerte River (Tunisia)	Stainless steel spatula ATR-FT-IR	2340-6920 items/kg (dry weight)	Toumi et al., 2019
Riva River Alacalı River Kumbala River Kurfalli River Ağva River	Metal spoons	20.7 particles/kg (dry weight)	Şener et al., 2019
Rhine River (Germany)	Steel spade micro FT-IR	0.26-11.07 particles/kg	Mani et al., 2019
Citarum River (Indonesia)	Ekman grab FT-IR	16.66±0.577 particles/100 g	Sembiring et al., 2020
Kızılırmak River Karasu River Yeşilırmak River Melet River Aksu River Değirmendere River Fırtına River	Box core FT-IR SEM	74.1 and 1778.8 particles/m^2	Aytan et al., 2020
Brisbane River (Australia)	Stainless-steel grab sampler ATR-FT-IR	0.18-1290 mg/kg	He et al., 2020

Table 2. Continue.

Locality and sampled compartment	Sampling and detection methods	Microplastic quantity	References
Yongfeng River (China)	Peterson grab ATR-FT-IR FESEM, EDS	0.5-16.75 mg/kg	Rao et al., 2020
Shuangtaizi River (China)	Steel grab FT-IR	170±96 particles/kg	Xu et al., 2020
Daliao River (China)		237±129 particles/kg	
Solimoes, Negro and Amazon River (Brazil)	Van-Veen grab Stereomicroscope	417-8178 particles/kg	Gerolin et al., 2020
Lawrence River (Canada)	Ponar grab Fluorescent microscope	65-7562 particles/kg	Crew et al., 2020
Vistula River (Poland)	Stainless steel spade SEM FT-IR Raman Spectroscopy	190-580 particles/kg	Sekudewicz et al., 2021
Danube River (Romania)	Spade Microscope Py-GC-MS	87 particles/kg	Pojar et al., 2021

Py-GC-MS; Pyrolysis-Gas Chromatography-Mass Spectrometry, FT-IR; Fourier Transform Infrared Spectroscopy, FPA-FT-IR; Focal Plane Array Fourier-Transform Infrared Spectroscopy, ATR-FT-IR; Attenuated Total Reflection-Fourier Transform Infrared Spectroscopy, micro FT-IR; micro Fourier Transform Infrared Spectroscopy, SW-IR; Short-wave Infrared, SEM; Scanning Electron Microscope, FESEM; Field Emission Scanning Electron Microscopy, EDS; Energy Dispersive Spectroscopy

mg/L to 172.000-419.000 items/m³, and in the sediments it was between 0.18-1290 mg/kg to 9.5x10^5 items/kg. Clearly indicates that microplastic particles are observed almost in all sampling localities reviewed and were quite abundant both in water column and sediments.

Microplastic Pollution in the Marine Ecosystems

The data, including the examined water compartment sampling and detection methods and sampling locality, gathered from the studies focusing on the amount of microplastics observed in various marine habitats are given in Table 3. According to the data summarized, we found that the amount of microplastic particles found in surface water samples were between 4.38x10^4-1.46x10^6 particles/km^2 to 0.018 items/m^2, and in the sediments it was between 0.58 and 1154.4 items/kg. This data clearly indicates that the quantity of microplastic particles are quite high both in water column and sediments. On the contrary to freshwater habitats which are isolated to a certain degree, seas are under greater threat since they are exposed to microplastic entrance from various non-point sources.

The Effects of Microplastics on Aquatic Organisms

Several aquatic organisms, either freshwater or marine, including zooplankton, corals, lobsters, sea urchins, mussels, aquatic birds and aquatic mammals are exposed to microplastics (Browne et al., 2008). Those microplastic particles are either selectively ingested or mistaken as a prey or involuntarily ingested during respiration (Gregory, 1996; Derraik, 2002). Several studies demonstrated that many aquatic animals are usually not able to distinguish plastic from their natural food (Crawford & Quinn, 2017). The physicochemical characteristics of microplastics such as size, density and particularly color are important factors misleading aquatic animals (Wright et al., 2013; Alomar & Deudero, 2017). Once they enter an aquatic animal's digestive tract they can easily reach higher trophic levels through the food chain (Lusher et al., 2016).

Microplastics are observed in the digestive tract of several aquatic animals including zooplankton (Setala et al., 2014), macroinvertebrates (Van Cauwenberghe et al., 2015), fish (Foley et al., 2018), aquatic birds (Nelms et al., 2018), and even aquatic mammals (Lusher et al., 2015). There is also evidence that plastic microparticles can pass across biological barriers through endocytotic processes such as phagocytosis and persorption (Wright et al., 2013; Wright & Kelly, 2017). Persorption is a paracellular mechanical process in which particles penetrate into the underlying tissues through the epithelial layer (Wright & Kelly, 2017). These processes are dependent on the particle size; very small particles can passively pass through cell membranes, while large particles should be taken by endocytosis (Kettiger et al., 2013).

Microplastics ingested as a food particle can block the digestive tract of the animal and eventually may cause death, or lead to behavioral changes, or leading to a pseudo sense of satiety and thus leading to a weakening of the animal and making it an easy prey for other animals (Derraik, 2002; Wright et al., 2013; Jovanovic, 2017). In addition, microplastics can cause oxidative stress, cellular damage, damage to DNA, inflammation and also trigger various immune reactions (Yong et al., 2020).

Microplastics observed in freshwater aquatic organisms, the polymer type recorded, particle quantity and the detection methods are reviewed in Table 4. The studies focusing on the toxic effects of microplastic particles, the polymer type, particle size and quantity, and their effects on some freshwater organisms are summarized in Table 5.

Table 3. The amount of microplastics observed in various marine habitats, the examined water compartment, sampling and detection methods, and sampling locality.

Locality and sampled compartment	Sampling and detection methods	Microplastic quantity	References
Water			
Bandar Abbas Coastline	ATR-FT-IR	3252 particles/m²	Nabizadeh et al., 2019
Antarctic Peninsula	330 µm manta trawl FT-IR	755-3524 items/km²	Lacerda et al., 2019
Surface Waters			
Antarctic Ocean	Neuston net Stereomicroscope	3.1×10^{-2} particles/m³	Isobe et al., 2017
Arabian Gulf	300 µm neuston net FT-IR	4.38×10^4-1.46×10^6 particles/km²	Abayomi et al., 2017
Iskenderun Bay (Adana, Turkey)	333 µm manta trawl Stereomicroscope	1.067.120 items/ km²	Gündoğdu, 2017
Mediterranean Coastal Water (Israel)	333 µm manta trawl Stereomicroscope	7.68 particles/m³	Van der Hal et al., 2017
Marmara Sea	333 µm manta trawl Stereomicroscope ATR FT-IR	1.263 items/m²	Tunçer et al., 2018
Faafu Coral Island (Maldives)	200 µm neuston net Stereomicroscope ATR FT-IR	0.32 particles/m³	Saliu et al., 2018
Kingston Port (Jamaica)	330 µm manta trawl Stereomicroscope FT-IR	0-5.73 particles/m³	Rose & Webber 2019
Tyrrhenian and Ligurian Seas	330 µm manta trawl Stereomicroscope ATR-FT-IR	1009-122817 particles/km²	Caldwell et al., 2019
North Sea	100 µm neuston net ATR-FT-IR	0.1-245.4 particles/m³	Lorenz et al., 2019
Pacific Ocean	330 µm manta trawl micro Raman Spectroscopy SEM	640-42000 items/km²	Pan et al., 2019
White Sea, Barents Sea and Black Sea	330 µm manta trawl FT-IR	28000-963000 particles/km²	Tošić et al., 2020
Macaronesia	200 µm manta trawl Stereomicroscope	15283-1007872 particles/km²	Herrera et al., 2020
Greenland and Northern Canada	335 µm manta trawl Stereomicroscope FT-IR	0.018 items/m²	Liboiron et al., 2021
Dalyan-Iztuzu Beach (East Mediterranean, Turkey)	Manta trawl Stereomicroscope	0.148±0.07 particles/m²	Zilifli & Tunçer, 2021
Southern coast of the Black Sea	FT-IR	18.68±3.01 particles/m³	Terzi et al., 2022
Sediments			
North Pole, Hausgarten observation station	Stereomicroscope micro FT-IR ATR FT-IR	4356 particles/kg	Bergmann et al., 2017
Terra Nova Bay (Antarctica)	Van-Veen grab FT-IR	1-90 items/m²	Munari et al., 2017
Strait of Hormuz, Persian Gulf	Stainless steel spoon FT-IR	2-1258 particles/kg	Naji et al., 2017
North Bering and Chukchi Seas	Stainless steel box micro FT-IR	0-68.88 items/kg	Mu et al., 2018

Table 3. Continue.

Locality and sampled compartment	Sampling and detection methods	Microplastic quantity	References
East Coast of Hong Kong	Stainless steel shovel ATR-FT-IR	0.58-2116 items/kg	Lo et al., 2018
Mariana Trench	Stereomicroscope Raman Spectroscopy	200-2200 particles/L	Peng et al., 2018b
Antarctica	Microscope FT-IR	31 particles/kg	Reed et al., 2018
Aegean Sea (Datça, Turkey)	Stainless steel shovel ATR-FT-IR	1154.4 items/kg	Yabanlı et al., 2019
Iskenderun Bay (Adana, Turkey)	Quadrate Stereomicroscope	3.4-658 items/kg 40.2-6354.1 items/m^2	Çevik & Gündoğdu, 2019
Sidi Mansour Port (Tunisia)	Core tube ATR-FT-IR	11242 particles/m^2	Chouchene et al., 2019
North Sea	Van-Veen grab ATR-FT-IR	2.8-1188.8 particles/kg	Lorenz et al., 2019
Tenerife Beach (Spain)	Stainless steel vessel ATR-FT-IR	2-115.5 items/m^2	Alvarez-Hernandez et al., 2019
Lanzarote Island	ATR-FT-IR Raman spectroscopy	36.3 g/m^2	Edo et al., 2019
Northwest Mediterranean	Steel trowel FT-IR	33-798 and 12-187 items/kg	Constant et al., 2019
New Zealand Coasts	FT-IR	459 particles/m^2	Bridson et al., 2020
Marmara Sea	Van-Veen grab FT-IR	0.3-85.6 g/kg	Baysal et al., 2020
Mediterranean (France, Toulon)	Remotely Operated Vehicle grab Stereomicroscope micro Raman Spectroscopy	80 particles/L	Cutroneo et al., 2022
Southern Coast of the Black Sea	FT-IR	64.06±8.95 particles/m^3	Terzi et al., 2022

FT-IR; Fourier Transform Infrared Spectroscopy, ATR-FT-IR; Attenuated Total Reflection-Fourier Transform Infrared Spectroscopy, micro FT-IR; micro Fourier Transform Infrared Spectroscopy, SEM; Scanning Electron Microscope

Microplastics observed in marine organisms and the polymer type recorded, particle quantity and the detection methods are reviewed in Table 6. The studies focusing on the toxic effects of microplastic particles, the polymer type, particle size and quantity, and their effects on some marine organisms are summarized in Table 7.

CONCLUSIONS

The plastic wastes released, either intentionally or unintentionally, into the environment, break into smaller pieces when exposed to meteorological events such as wind, precipitation, UV radiation and abrasion. The recent studies indicated that the amount of microplastic particles are increasing in all compartments of the aquatic ecosystems. Thus, they are considered a serious health concern both for aquatic biodiversity and human health through the food chain. There are numerous studies demonstrating the toxic effects of various plastic polymers on several aquatic organisms. However, it is not easy to achieve a precise decision on the potential risks of microplastic pollution.

In this study, we reviewed the polymer type, particle size and quantity of microplastics observed in freshwaters and marine ecosystems. The data reviewed here clearly indicates that microplastics are present almost in all freshwater and marine ecosystems, both in surface waters and sediments. Studies on the toxic effects of microplastic particles on aquatic organisms demonstrate that alterations are common in the biochemical and behavioral characteristics of the organisms exposed to microplastics. Furthermore, mortality is reported to be a prevalent consequence of microplastic exposure.

The microplastic particles ingested have a great potential to reach higher trophic levels through the food chain. Therefore, future studies should focus on the mechanisms that can be responsible for the transmission of these particles through food chains and their potential risks for human beings and other organisms consuming fish and shellfish.

Conflict of Interest: The author has no conflicts of interest to declare.

Table 4. Microplastics observed in some freshwater aquatic organisms and the polymer type recorded, detection method and particle quantity.

Location	Species	Target tissue	Polymer type	Detection method	Particle quantity	References
Invertebrates						
Dutch River (Amsterdam)	*Gammarus* spp.	Digestive tract	Not available	NaOH 30% H_2O_2 FT-IR	11-105 particles/g	Leslie et al., 2017
Dutch River (Amsterdam)	*Carcinus maenas* *Littorina littorea* *Mytilus edulis* *Crassostrea gigas*	Stomach, intestine	Not available	NaOH 30% H_2O_2 FT-IR	11-105 particles/g	Leslie et al., 2017
Lawrence River (New York)	*Dreissena polymorpha* *D. bugensis*	Digestive tract	Not available	Dissection microscope	No microplastics were found.	Schessl et al., 2019
Melet River Yeşilırmak River	*Donax trunculus* *Chalelea gallina* *Abra alba* *Anadara inaequivalvis* *Pitar rudis*	Soft tissue	Not available	10% KOH Strereomicroscope	92 items	Şentürk et al., 2020
Grand River (Canada)	*Lasmigona costata*	Soft tissue	PP, PE	20% protease enzyme 70% ethanol Raman Spectroscopy	0-7 particles/ind.	Wardlaw & Prosser, 2020
Fish						
Citarum River (Indonesia)	*Chanos* sp.	Intestine, gill	PP, PE	30% H_2O_2 FT-IR	1.33±0.57 particles/fish	Sembiring et al., 2020
Akora River (Ghana)	*Oreochromis niloticus* *O. aureus* *O. mosssambicus* *Sarotherodon melanotheron* *Clarias anguillaris*	Digestive tract	PE, PS	KOH Light microscope	12-24 particles/m^3	Adu-Boahen et al., 2020
Fengshan River (Taiwan)	*Oreochromis niloticus,* *Pterygoplichthys pardalis* *Carassius auratus* *Leiognathus equulus* *Pomadasys argenteus*	Digestive tract	PE, PP, PS, PVC	KOH ATR-FT-IR	14-94 items/fish	Tien et al., 2020
Lijiang River (China)	*Cyprinus carpio* *Pelteobagrus fulvidraco* *Mystus macropterus* *Pelteobagrus vachelli*	Digestive tract	PVC, PA, PS, PP, PE, PET	30% H_2O_2 micro FT-IR	0.6±0.6 particles/fish	Zhang et al., 2021a

Table 4. Continue.

Location	Species	Target tissue	Polymer type	Detection method	Particle quantity	References
Other Aquatic Vertebrates						
Yangtze River (China)	*Microhyla ornata* *Rana limnochari* *Pelophylax nigromaculatus* *Bufo gargarizans*	Not available	PES, PP	1.2 g/cm^3 30% H_2O_2 ATR-FT-IR	0-2.73 items/individual	Hu et al., 2018
Ticino River (Italy)	*Alcedo atthis*	Pellet*	PE, PUR, PP	NaCl 0,0616 M Fe (II) micro FT-IR SEM-EDS	3 items/individual	Winkler et al., 2020

PP; Polypropylene, PE; Polyethylene, PET; Polyethylene Terephthalate, PVC; Polyvinyl Chloride, PA; Polyamide, PS; Polystyrene, PUR; Polyurethane, PES; Polyether sulfone) (FT-IR; Fourier Transform Infrared Spectroscopy, micro FT-IR; micro Fourier Transform Infrared Spectroscopy, ATR-FT-IR; Attenuated Total Reflection-Fourier Transform Infrared Spectroscopy, SEM-EDS; Scanning Electron Microscope-Energy Dispersive Spectroscopy

*Undigested parts of the food that the bird eats. These parts may include the exoskeleton of insects, claws, teeth, vegetable matter. The birds throw the pellet out by vomiting.

Table 5. Studies on the toxic effects of microplastics on some freshwater organisms.

Target organism	Microplastic			Experimental duration and exposure method	Effects	References
	Polymer type	Size	Concentration			
Plankton						
Daphnia magna	PET	62-1400 µm (length) 31-528 µm (width) 1-21,5 µm (diameter)	12.5-25-50-100 mg/L	48 hours Added to water	Mortality was observed. Microplastic particles were observed in digestive tract.	Jemec et al., 2016
Brachionus koreanus	PS	0.05-0.5-6 µm	10 µg/ml	24-48 hours Added to water	Mortality was observed depending on the size and conc. of microplastics. Microplastics were found in gut. ROS conc. and GPx, GST, SOD activities increased.	Jeong et al., 2016
Ceriodaphnia dubai	PE PES	1-4 µm	0.5-1-2-4-8-16 mg/L PE 0.125-0.25-0.5-1-2-4 mg/L PES	48 hours 8 days Added to water	LC_{50} was found as 2,2 mg/L for PE and 1,5 mg/L for PES. Growth rate, number of juveniles and reproductive rates decreased. Abnormal swimming behavior was observed. Microplastics were found in gut.	Ziajahromi et al., 2017
Daphnia magna	PS PS-COOH	201.5 nm (PS) 191.3 nm (PS-COOH)	1-5-10-20-30 mg/L	48 hours Added to water	Immobilization was observed. PS-COOH type particles were found to be more toxic.	Kim et al., 2017

Table 5. Continue.

Target organism	Microplastic			Experimental duration and exposure method	Effects	References
	Polymer type	Size	Concentration			
Brachionus koreanus	Fluorescence microbead	0.05-0.5-6 μm	10 μg/ml	24 hours Added to water	Microplastics were found in gut. It was observed that microplastics can pass through the through cell membrane.	Jeong et al., 2018
Daphnia magna	Fluorescent PE microbead	63-75 μm	25-50-100 mg/L	5-21 days Added to water	Microplastics was observed in gut. No effect on mortality and reproductive rates.	Canniff & Hoang, 2018
Chlorella pyrenoidosa *Microcystis flos-aquae*	PP, PVC	64 μm PP 172 μm PP 236 μm PP 111 μm PVC 157 μm PVC 216 μm PVC	5-10-50-100-250-500 mg/L	11 days Added to water	Altered chlorophyll-a synthesis Microplastic internalization was observed.	Wu et al., 2019
Spirulina sp.	PP PET	1-2 μm	150 mg/500 ml 250 mg/500 ml 275 mg/500 ml	112 days Added to water	Decreased growth rate.	Khoironi & Anggoro, 2019
Daphnia magna	PS	1.25 μm	2-4-8 mg/L	10 days Added to water	The transcription of AK, TrxR and permease increased. No mortality was observed	Tang et al., 2019
Scenedesmus quadricauda	PS	1-2-3-4-5 μm	10 mg/L	24-48-72-96 hours Added to water	Microplastics internalization was observed. Population density decreased on a time dependent manner. No effect on photosystem II. Retarded growth.	Chen et al., 2020
Chlorella sorokiniana	PS	<70 μm	240 mg/L	30 days Added to water	ALA concentration decreased. Cell size decreased. Lipid accumulation, saturated myristic and palmitic acid levels increased.	Guschina et al., 2020
Chlamydomonas reinhardtii	PS	300-600 nm	5-25-50-100 mg/L	1-3-6-10 days Added to water	Decreased chlorophyll-a conc. Increased MDA conc.	Li et al., 2020
Chlamydomonas reinhardtii	PVC	50-100 μm	1-10-20-30-40-50 mg/L	24-48-72-96 hours Added to water	Decreased chlorophyll conc. Reduced growth and population density. Increased MDA and SOD activity.	Wang et al., 2020b

Table 5. Continue.

Target organism	Microplastic			Experimental duration and exposure method	Effects	References
	Polymer type	Size	Concentration			
Euglena gracilis	PS	0.1-5 μm	0.5-1-10-20-30-40-50 mg/L	24-96 hours Added to water	Reduced growth. Damage to cell membrane and chloroplasts. Decreased signal transduction and carbohydrate metabolism rate.	Xiao et al., 2020
Scenedesmus armatus *Microcystis aeruginosa*	PE	200 to 300 μm	250-500-1000 μg/ml	3-7-14-21-28 days Added to water	Decreased growth rate and photosynthetic activity.	Sanchez-Furtun et al., 2021
Acutodesmus obliquus	HDPE PP PVC	<100 μm	5-10-15-25-100-125-200-250 mg/L	21 days Added to water	Microplastics internalization was observed. Growth rate and photosynthetic activity decreased. Microplastics accumulation on the cell surface.	Ansari et al., 2021
Daphnia magna	PE	3.43±17.23 μm PE 13.09±34.43 μm PE 9.74±39.54 μm PE	5 mg/L	21 days Added to water	Microplastics was observed in gut. Body length, survival rates, reproductive rates, carbohydrate and protein reserves decreased.	An et al., 2021
Brachionus calyciflorus	PS	1 μm	0-1x10^4-1x10^5-1x10^6-1x10^7 particles/ml	2 days Added to water	Reproductive rates and PHGPx activity decreased. ROS conc. increased. SOD, MnSOD, CuZnSOD and CAT activities did not change.	Liang et al., 2021
Chlorella sp.	PE, PS, PP, PVC, PET	100-2000 μm	10-1000 mg/L	3 days Added to water	Microplastic internalization was observed. Retarded growth.	Miloloza et al., 2021
Brachionus calyciflorus	PE	10-22 μm	0.5x10^3-2.5x10^3-1.25x10^4 particles/ml	24 hours Added to water	NA$^+$-K$^+$-ATPase activity and SOD activity decreased GPx activity increased.	Xue et al., 2021
Euglena gracilis	PS	75-1000 nm	1-5-25 mg/L	4-8 days Added to water	Microplastics internalization was observed. No effect on growth mobility.	Sun et al., 2021
Spirulina sp.	PE PP	0.5-1 mm^2	500 mg/500 ml	30 days Added to water	Phycocyanin and protein conc. decreased. PES (extracellular polymeric substance) production rate increased.	Hadiyanto et al., 2021
Microcystis aeruginosa	Nylon	1-3 μm	25-50-100 mg/L	6-12-18-24-30 days Added to water	GPx and SOD activity increased. MDA conc. increased. Energy reserves, carbohydrate and lipid synthesis increased Regulation of *por*, *petE*, *petF*, *petH* and *cyt b6/f* genes decreased.	Zheng et al., 2022

Table 5. Continue.

Target organism	Microplastic			Experimental duration and exposure method	Effects	References
	Polymer type	Size	Concentration			
Daphnia magna	PVC	2±1 and 50±10 μm	10-20-40-80-160 mg/L	4-7-14-21 days Added to water	The reproductive rate, CAT activity and MDA conc. varied depending on the size of microplastic particles. SOD activity, GSH conc. and *vtg* gene regulation decreased.	Liu et al., 2022
Invertebrates						
Potamoryrgus antipodarum	PA, PET, PC, PS, PVC	118±105 μm	30%-70%	8 weeks Added to food	Mortality was observed. Number of juveniles did not change	Imhof & Laforsch, 2016
Gammarus fossarum	PS PA	500x20 μm PA 1.6 μm PS	100-540-2680-13380 PA fibers/cm^2 500-2500-12500-60000 PS beads/ml	0.5 hours to 28 days Added to food	Microplastics were found in the digestive tract. Mortality was observed.	Blarer & Burkhardt-Holm, 2016
Palaemonetes pugio	PS, PP, PE	30-34-35-59-75-83-93-116 μm	50000 particles/L	3 hours Added to water	Microplastics were found in intestines and gills. Mortality was observed.	Gray & Weinstein, 2017
Sphaerium corneum	PS	20-500 μm	0 to 40% dry weight of sediment	28 days Added to sediment	No mortality was observed.	Redondo Hasselerharm et al., 2018
Dreissena polymorpha	PS	1-10 μm	Mixture 1 (5x10^5 1 μm and 5x10^5 10 μm) Mixture 2 (2x10^6 1 μm and 2x10^6 10 μm)	6 days Added to water	Microplastics were present in intestinal lumens, hemolymph and on hemocyte surface. SOD, GPx activities did not change. Antioxidant conc. decreased.	Magni et al., 2018
Corbicula fluminea	Red fluorescent polymer	1-5 μm (ort 2 μm)	0.2 and 0.7 mg/L	96 hours Added to water	No mortality was observed. Microplastic were present in the digestive tract, gill surface and hemolymphatic sinuses.	Guilhermino et al., 2018
Corbicula fluminea	Fluorescent microspheres	1-5 μm	0.13 mg/L	8-14 days Added to water	No mortality was observed. Microplastics were found in the digestive tract. LPO conc. increased ChE activity decreased	Oliveira et al., 2018

Table 5. Continue.

Target organism	Microplastic			Experimental duration and exposure method	Effects	References
	Polymer type	Size	Concentration			
Lumbriculus variegatus *Tubifex* spp.	PS	20-500 µm	0 to 40% dry weight of sediment	28 days Added to sediment	Mortality was observed.	Redondo Hasselerharm et al., 2018
Gammarus pulex	PET	10-150 µm	0.8-4.000 particles/ml	24 hours to 48 days Added to water	Microplastics were present in gut. No changes were observed in feeding activities, energy reserves, and molting.	Weber et al., 2018
Gammarus pulex *Hyalella azteca*	PS	20-500 µm	0 to 40% dry weight of sediment (PS microplastics were added to the sediment mixture at the specified rates.)	28 days Added to sediment	No mortality was observed.	Redondo Hasselerharm et al., 2018
Hydra attenuata	PE	<400 µm	0-0.01-0.02-0.04-0.08 g/ml	3-24-48-96 hours Added to water	Microplastics were found in digestive tract. Morphological changes were observed.	Murphy & Quinn, 2018
Eriocheir sinensis	PS	5 µm	40-400-4000-400000 µg/L	7-21 days Added to water	Survival rates did not change, HSI level decreased. CAT, GPx, SOD and GST activities increased. *p38* gene expression increased Growth reduced. Microplastics were found in liver, gill and digestive tract.	Yu et al., 2018
Asellus aquaticus	PS	20-500 µm	0 to 40% dry weight of sediment	28 days Added to sediment	Mortality was observed.	Redondo Hasselerharm et al., 2018
Chironomus tepperi	PE	1-4 µm 10-27 µm 43-54 µm 100-126 µm	500 particles/kg	5-10 days Added to water	Survival rates decreased. The number of juveniles, larval growth rates and antenna length decreased. Microplastics were found in the digestive tract.	Ziajahromi et al., 2018
Eriocheir sinensis	PS	5 µm	0.04-0.4-4-40 mg/L	7-14-21 days Added to water	The hemocyanin conc. and AKP activity initially increased and then decreased. Lysozyme activity decreased. PO activity increased.	Liu et al., 2019

Table 5. Continue.

Target organism	Microplastic			Experimental duration and exposure method	Effects	References
	Polymer type	Size	Concentration			
Caenorhabditis elegans	PS	1 μm	0-0.1-1-10-100 μg/L	72 hours Added to water	Mobility decreased, growth rate reduced. ROS conc. increased. The expression of *daclk-1, ctk-1, ctk-2, ctk-3, gst-4, isp-1, skn-4, sod-1, sod-2, sod-3, sod-4* and *sod-5* genes increased. Microplastics were present in the intestinal lumen, intestinal cells and in the body cavity.	Yu et al., 2020
Dreissena bugensis	PE	10-45 μm	0.1-0.4-0.8 g/L	25 days Added to water	Microplastics were found in the intestines and gills. Oxygen consumption rate decreased. Mortality rate increased.	Pedersen et al., 2020
Dreissena polymorpha	PS	2-60 μm	6.4-160-4000-100000 particles/ml	14 days Added to water	No changes in energy reserves and lipid peroxidation rates. Mortality increased.	Weber et al., 2020
Chironomus riparius	PA	<80 μm <100 μm <160 μm <180 μm	10.100 particles/kg	28 days Added to water	Number of larvae increased. Altered egg shape.	Khosrovyan & Kahru, 2020
Chironomus riparius	PS microrubber	38.9±28.6 μm 82.3±40 μm	1-10 mg/L	36 hours Added to water	*glycoprotein93, hsp90, hsc70, hsp60, hsp40* and *hsp17* (heat shock proteins) gene expression rate increased.	Carrasco-Navarro et al., 2021
Corbicula fluminea	PS	5-10-45-90 μm	12 particles/ml (5-10-95 μm) 2 particles/ml	6-96 hours 28 days Added to water	Microplastics were present in gut. Energy reserves, oxidative stress level and reproductive rates did not change.	Weber et al., 2021b
Potamoryrgus antipodarum	PS	0.01-514 μm	100-500-1000 mg microplastics/kg (dry weight of sediment) 2000 and 4000 mg microplastics/kg (dry weight of sediment)	31 days Added to sediment	Mortality was observed. Reproductive rates decreased.	Romero-Blanco et al., 2021

Table 5. Continue.

Target organism	Microplastic			Experimental duration and exposure method	Effects	References
	Polymer type	Size	Concentration			
Lymnaea stagnalis	PS	5-10-45-90 µm	12 particles/ml (5-10-95 µm) 2 particles/ml	6-96 hours 28 days Added to water	Microplastics were present in gut. Energy reserves, oxidative stress level and reproductive rates did not change.	Weber et al., 2021b
Dreissena polymorpha	PS	5-10-45-90 µm	6.4-100000 particles/ml	6-96 hours 7-28 days Added to water	Microplastics was observed in gut. No changes in energy reserves and lipid peroxidation levels.	Weber et al., 2021a
Caenorhabditis elegans	PS	1.002±0.005 µm	0.1-10-100 µg/L	24 hours Added to water	ROS conc. increased. Microplastics were found in gut. Expression of oxidative stress-related genes (*clk-1*, *ctl-1*, *sod-3*, *sod-4* and *sod5*) increased.	Chen et al., 2021
Neocaridina palmata	PE PVC PS	41 and 87 µm PE <63 µm PVC 11 µm PS	20-200-2000-20000 particles/L	4-24 hours Added to food	Microplastics were present in gut. The reproductive rates decreased. Microplastic uptake decreased when exposed to higher concentrations.	Klein et al., 2021
Chironomus riparius	PET	50 µm	500-5000-50000 particles/kg dry weight of sediment	28 days Added to sediment	No mortality was observed. Microplastics were found in digestive tract.	Setyorini et al., 2021
Chironomus riparius	PE	32-63 µm 63-250 µm 125-500 µm	1.25-5-20 g/kg	48 hours Added to water	Microplastics were present in gut. ETS activity and lipid conc. decreased. Lipid peroxidation rates increased. No changes were observed in sugar and protein conc. There did not different seen in sugar and protein content. CAT and GST activities decreased.	Silva et al., 2021
Fish						
Danio rerio larvae	PS	0.7 µm	5 mg/ml	1-2-3-4 days Injected into embryos	Microplastics were found in digestive tract. Lipid metabolism rate and oxidative stress increased.	Veneman et al., 2017

Table 5. Continue.

Target organism	Microplastic			Experimental duration and exposure method	Effects	References
	Polymer type	Size	Concentration			
Danio rerio larvae	PE	10-45 μm	5-20 μg/L	2-7-14 days Added to water	No effect on brain, eye and embryo development. Oxidative stress, steroid synthesis and muscle development decreased.	LeMoine et al., 2018
Symphysodon aequifosciotus	PE	70-88 μm	0-200 μg/L	30 days Added to water	Survival rate, body length, ETC and lipase activities did not change. Trypsin, ALP and AChE activities decreased. Amylase, CS, COX and LDH activities increased.	Wen et al., 2018
Pimephales promelas larvae	PE (Green sphere) PE (White sphere)	425-500 μm (Green sphere) 180-212 μm (White sphere)	35.0-0.069-70.0-0.137-140.0-0.274 mg/L	7-14 days Added to water	No adverse effects were observed.	Malinich et al., 2018
Oreochromis niloticus	PS	0.1 μm	1-10-100 μg/L	0-1-3-6-10-14 days Added to water	Mortality was observed. AChE activity decreased. MDA conc. did not change.	Ding et al., 2018
Carassius auratus	EVA, PS, PA	<500 μm	0.96%-1.36%-1.94%-3.81%	6 weeks Added to food	Weight decreased Oral cavity damaged. Microgranuloma and inflammation were observed.	Jabeen et al., 2018
Barbodes gonionotus	PVC	0.1-1000 μm	0.2-0.5-1.0 mg/L	96 hours Added to water	Mortality has been observed. Microplastics were found in the intestine. Trypsin and chymotrypsin activities increased.	Romano et al., 2018
Acanthurus dussumieri	PE, PVC, PE, PS	9 particle PE (film), 5 particle PVC, 1 particle PE (pellet) and A mixture was prepared by mixing 1 particle PS. (1000-250 μm)	0.051 g	95 days Added to food	Mortality was observed. Microplastics were present in the digestive tract. Body length and weight decreased.	Naidoo & Glassom, 2019
Danio rerio larvae	PS	5-50 μm	100-1000 μg/L	7 days Added to water	Microplastics were found in digestive tract. Transcription of genes related to glycolysis and lipid metabolism decreased. GSH conc. and CAT activity decreased. SOD activity did not change.	Wan et al., 2019

Table 5. Continue.

Target organism	Microplastic			Experimental duration and exposure method	Effects	References
	Polymer type	Size	Concentration			
Danio rerio	PS	1 µm	0-10-100-1000 µg/L	120 hours Added to water	Microplastics were present in stomach and intestine Larvae development did not change, but the free swimming performance has decreased. Inflammation and oxidative stress (CAT, SOD activities) increased.	Qiang & Cheng, 2019
Danio rerio	PS	1 µm	10-100-1000 µg/L	21 days Added to water	Microplastics were found in intestines and gills. The reproductive rate, estradiol and testosterone conc. did not changed.	Qiang et al., 2020
Fundulus heteroclitus	Recycled rubber particles produced from scrap automotive tires	38-355 µm	0-0.3-1.9-6.0 g/L 0-0.1-0.33-1.0 g/L	7 days Added to water	Microplastic particles were found in the digestive tract. GST activity did not change.	Laplaca & van den Hurk, 2020
Prochilodus lineatus	PE	10-90 µm	20 µg/L PE	24-96 hours Added to water	No mortality was observed DNA damage was observed in liver cells. GSH conc. and AChE activities decreased.	Roda et al., 2020
Oncorhynchus mykiss	PE	180-212 µm 425-500 µm	50 particles/L 100 particles/L 500 particles/L	15-30 days Added to food	No mortality was observed. No microplastics were observed on the outside of the intestine, which indicated that microplastics were not transported from the intestine to other parts of the body.	Kim et al., 2020
Cyprinus carpio	PVC	Not available.	45.55-91.1-136.65 µg/L (10%-20%-30%)	30-60 days Added to food	Mortality was observed. MDA conc. decreased. SOD, CAT and GST activities decreased.	Xia et al., 2020
Carassius auratus	PS	5 µm	10-100-1000 µg/L	1-3-7 days Added to water	Retarded growth. Decreased CAT and GPx activities, increased SOD activity. Increased hearth beat rate. Enlarged intestinal cavity. Disturbance of the intestinal mucosa.	Yang et al., 2020

Table 5. Continue.

Target organism	Microplastic			Experimental duration and exposure method	Effects	References
	Polymer type	Size	Concentration			
Clarias gariepinus	PVC	95.41±4.23 μm	0.5% 1.5% 3.0%	45 days Add to food	Hb, MCH, RBC and LPO level increased. Neutrophil count, MCV and WBC counts decreased. GPx, SOD, AChE and CAT activities decreased. No changes were observed in monocyte and lymphocyte counts.	Iheanacho & Odo, 2020
Danio rerio larvae	Red fluorescent microspheres (MP)	1-5 μm	2 mg/L	2-6-10-14 days Added to water	Mortality was observed. Heart beat rates, GSH and ROS conc. and LDH, AChE, CAT activities increased.	Santos et al., 2021
Danio rerio	PS	1 μm	0-10-100-1000 μg/L	21 days Added to water	ROS conc. increased. Cell apoptosis rates increased in the testicle.	Qiang & Cheng, 2021
Danio rerio	PS	0.10-0.12 μm	10-100 μg/L	7-14-21-28-35 days Added to water	ROS production and lipid peroxidation increased. LDH, ALT and AST activities increased. GPx, CAT and SOD activities decreased. GST activity did not change. Inflammation, hepatic necrosis, eosinophilic granuloma, cytoplasmic degeneration were observed.	Umamaheswari et al., 2021
Danio rerio	PP	50-200 μm	10-100 μg/L	21 days Added to water	Microplastics were present in the intestine. Physical damage to the intestines was observed. Oxidative stress led to inflammation. Lipid conc. decreased.	Zhao et al., 2021
Danio rerio	50% PE 25% PP 15% PS 10% PVC	Not available.	5-100 mg/L	21 days Added to water	Circulation rate slowed. Swimming performances initially increased and then decreased. AChE activity decreased.	Hanslik et al., 2022
Danio rerio	PP PS	230 μm (PP) <100 μm (PS)	12.5-25-50-100 mg/L	24-48-72-96 hours Added to water	Mortality was observed. Heart beat rate decreased. Body length of the larvae reduced.	Prata et al., 2022

Table 5. Continue.

Target organism	Microplastic			Experimental duration and exposure method	Effects	References
	Polymer type	Size	Concentration			
Danio rerio	PS	MPI MPII	$4x10^6$-$4x10^4$	5 days Added to water	GSH conc. increased. CAT, SOD and AChE activities increased.	Guimaraes et al., 2021
Oreochromis niloticus	PS	0.9-0.35 µm	5 mg/L	28 days Added to water	No mortality was observed. SOD and GPx activities decreased. MDA conc. decreased.	Ahmadifar et al., 2021
Cyprinus carpio	PVC	>100 µm 100-300 µm 300-1000 µm	1-10-100-1000 µg/L	10 days Added to water	Mortality was observed. Abnormal swimming behavior, irregular movements were noted. Mucus secretions increased. Structural abnormality in the intestinal wall and lesions in villi, liver and stomach inflammation were observed.	Ebrahimpour et al., 2021
Danio rerio	PE	146.20±8.86 µm	5-50 µg/L	10-20 days Added to water	CAT, GST, Na^+/K^+ATPase activities and LPO conc. increased.	Rangasamy et al., 2022

PP; Polypropylene, PE; Polyethylene, HDPE; High Density Polyethylene, PET; Polyethylene Terephthalate, PVC; Polyvinyl Chloride, PA; Polyamide, PS; Polystyrene, PS-COOH; Polystyrene, monocarboxy terminated, PUR; Polyurethane, PES; Polyether sulfone, PC; Polycarbonate, EVA; Ethylene-vinyl acetate copolymer). (SOD; Superoxide dismutase, MnSOD; Manganese superoxide dismutase, CuZnSOD; Copper and zinc superoxide dismutase, GPx; Glutathione peroxidase, CAT; Catalase, GSH; Glutathione, ROS; Reactive oxygen species, BaP; Benzo(a)piren, HSI; Hepatosomatic index, GSI; Gonadosomatic index, ETS; Electron transport system, Hb; Hemoglobin, MCH; Mean corpuscular hemoglobin, RBC; Red blood cell, LPO; Lipid peroxidation, MDA; Malondialdehyde, ALA; Alpha-lineoic acid, EPS; Extracellular polymeric substance, MCV; Mean corpuscular volume and WBC; White blood cell, AK; Arginine kinase, TrxR; Thioredoxin reductase, NA^+-K^+-ATPase; Sodium-potassium adenosine triphosphatase, GST; Glutathione S-transferase, AChE; Acetylcholinesterase, ChE; Cholinesterase, AKP; Alkaline phosphatase, PO; Phenoloxidase, ALT; Alanine aminotransferase, AST; Aspartate aminotransferase, LDH; Lactate dehydrogenase, ALP; Alkaline phosphatase, CS; Citrate synthase, COX; Cytochrome c oxidase, PHGPx; Phospholipid hydroperoxide glutathione peroxidase

Table 6. Microplastics observed in some marine organisms and the polymer type recorded, detection method and particle quantity.

Location	Species	Target tissue	Polymer type	Detection method	Particle quantity	References
Invertebrates						
Black Sea, Marmara and Aegean Sea Coasts	*Mytilus galloprovincialis*	Soft tissue	PET, EVA, PA, PAC, PC, PE, PAN, PS, PP, PVC, PVF, CA	30% H_2O_2 Stereomicroscope FT-IR	0.06 and 2.47 items/mussels	Gedik & Eryaşar, 2020
Izmir Bay (Aegean Sea)	*Mytilus galloprovincialis* *Ruditapes decussatus*	Soft tissue		30% H_2O_2 1.2 g/cm^3 NaCl Stereomicroscope	1682 items	Yozukmaz, 2021
Çesme/Ildır (Izmir, Aegean Sea)	*Pinctada imbricata radiata*	Digestive tract	PET, PE, PP	10% KOH 1.2 g/ml NaCl micro FT-IR	65 items	Aksakal et al., 2021
Terengganu (Malaysia)	Calanoida Cladocera Cyclopoida Harpacticoida Mysids Decapoda	Digestive tract	Not available	65% HNO_3 Stereo microscope	Microplastics were found in 47%, 2%, 11%, 6%, 2%, 1% of the samples, respectively.	Taha et al., 2021
Liaohe Estuary (China)	*Mactra andneriformis* *Sinonovacula constricta* *Neandrita didyma* *Rapana andnosa* *Oratosquilla oratoria* *Portunus trituberculatus*	Digestive tract	PE, LDPE, HDPE, PET	30% KOH micro FT-IR	0.83±1.97 items/individual	Wang et al., 2021
Fish						
Tokyo Bay (Japan)	*Engraulis japonicus*	Digestive tract	PE, PP, PS	FT-IR	2.3±2.5 items/individual	Tanaka & Takada, 2016
Kwazulu-Natal (Dayey Africa)	*Mugil cephalus*	Digestive tract	Not available	Dissection microscope	3.8±4.7 items/individual	Naidoo et al., 2016
Mallorca Island (Spain)	*Galeus melastomus*	Digestive tract	PET, PE, PP, PA, Cellophane, PAN, Polyacrylate	Stereomicroscope FT-IR	0.34±0.07 items/individual	Alomar & Deudero, 2017

Table 6. Continue.

Location	Species	Target tissue	Polymer type	Detection method	Particle quantity	References
South China Sea	*Rexea solandri* *Synagrops japonicus* *Centroneryx lineatus* *Malakichthys griseus* *Lepidotrigla guentheri* *Antigonia capros* *Chlorophthalmus agassizi* *Diaphus watasei* *Benthodesmus tenuis* *Polymetme elongata* *Neoscopelus microchir* *Borostomias pacificus* *Chlorophthalmus albatrossis*	Stomach and intestine	PARA, PA, PET PAE	69% HNO_3 Optical microscope micro FT-IR	1.96±1.12 items/individual (stomach) 1.77±0.73 items/individual (intestine)	Zhu et al., 2019
Bosphorus and Golden Horn (Marmara Sea) Izmir Bay (Aegean Sea) Iskenderun Bay (Mediterranean Sea)	*Chelon saliens* *Mullus barbatus barbatus* *Mullus surmuletus* *Trachurus mediterraneus* *Lithognathus mormyrus*	Digestive track	PP, PE	KOH: NaClO KI Stereomicroscope Micro-Raman Spectroscopy	283 items	Gündoğdu et al., 2020
Rize (Black Sea)	*Engraulis encrasicolus* *Trachurus mediterraneus* *Sarda sarda* *Belone belone* *Pomatotus saltatrix* *Merlangius merlangus* *Mullus barbatus barbatus*	Digestive tracks	PAN, PP, PET, PE, PS	63% HNO_3 Stereomicroscope ATR-FT-IR	352 items	Aytan et al., 2022
Other Aquatic Vertebrates						
New Zeland	*Delphinus delphis*	Stomach	PP, ABS, PET, Nylon,	Enzymatic digestion FT-IR	117 items	Stockin et al., 2021
Qaqaluit and Akpait Islands (Canada)	*Uria lomvia* *Fulmarus glacialis*	Digestive tract	PE, PA, PES	10% KOH micro Raman Spectroscopy	61 particles/ individual	Bourdages et al., 2021

ABS: Acrylonitrile Butadiene Styrene, HDPE: High Density Polyethylene, LDPE: Low Density Polyethylene, PA: Polyamide, PAN: Polyacrylonitrile, PE: Polyethylene, PES: Polyester, PET: Polyethylene Terephthalate, PARA: Polyacrylamide, PAE Polyarylether PP: Polypropylene, PS: Polystyrene, PVC: Polyvinyl Chloride FT-IR: Fourier Transform Infrared Spectroscopy, micro FT-IR: micro Fourier Transform Infrared Spectroscopy

Table 7. Studies on the toxic effects of microplastics on some marine organisms.

Target organism	Microplastic			Experimental duration and exposure method	Effects	References
	Polymer type	Size	Concentration			
Bacteria						
Halomonas alkaliphila	PS	55-nm and 1 µm	20-40-80-160-320 mg/L	2 hours Added to water	Mortality increased depending on microplastic quantity. ROS conc. was higher when exposed to nanoplastics.	Sun et al., 2018
Uronema marinum	PS	0.5, 1.07, 2.14 and 5 µm	2×10^5, 4 × 105, 6×10^5, 8×10^5, and 1×10^6 microplastic/L	96 hours Added to water	Number of individuals, body size and biomass decreased. Decrease in biomass is not dependent on the size of microplastics.	Zhang et al. 2021b
Plankton						
Amphibalanus amphitrite *Artemia franciscana*	PS	0.1 µm	0.001-0.01-0.1-1-10 mg/L	24-48 hours Added to water	No mortality was observed. Swimming performances decreased with increasing conc. Neurotoxic effects were observed.	Gambardella et al., 2017
Skeletonema costatum	PVC	1 µm and 1 mm	1-5-10-50 mg/L	96 hours Added to water	Growth decreased. Photosynthesis rate and chlorophyll conc. decreased.	Zhang et al., 2017
Brachionus plicatilis *Tigriopus fulvus* *Acartia clausi*	PE	1-6 µm	0-30 mg/L	48 hours Added to water	LOEC= 1 LOEC>10 LOEC>30	Beiras et al., 2018
Calanus finmarchicus	Nylon granule Nylon fibers	10-30 µm 10x30 µm	50 microplastic/ml	6 days Added to water	Algae consumption decreased and molting rate increased when exposed to microplastic fibers.	Cole et al., 2019
Artemia parthenogenetica	PS	10 µm	0.1-1-10-100-1000-10000 microplastic/ml	24 hours and 14 days Added to water	Anomalies were observed in intestinal epithelial tissue.	Wang et al., 2019
Acartia tonsa	PE	7.73 µm	20-200-2000 microplastic/L	24-48 hours Added to water	No effect on the mortality, nutrition, egg production and incubation period.	Bellas & Gil 2020
Tigriopus japonicus	PS	50 nm and 10 µm	For 50 nm particle: 2.9×10^{11} particles/ml, For 10 µm particle: 3.6×10^4 particle /ml	24-48 hours Added to water	ROS production showed an inverse relationship with the size of microplastics and a linear relationship with exposure duration. Expression of oxidative stress related genes and enzymes activities increased.	Choi et al., 2020
Calanus finmarchicus *C. glacialis* *C. hypolietilenrboreus*	PE	20.7 µm	200-20000 particles/L	6 days Added to water	No effect on the defecation rate. Fecundity increased.	Rodríguez-Torres et al., 2020

Table 7. Continue.

Target organism	Microplastic			Experimental duration and exposure method	Effects	References
	Polymer type	Size	Concentration			
Phaeodactylum tricornutum	PE	5-60 µm 61-499 µm 500-3000 µm	0.1 mg/ml	72 hours Added to water	The species was found to be tolerant to microplastic exposure.	Piccardo et al., 2020
Karenia mikimotoi	PS	For PS 65 nm, 100 nm and 1 µm	10 mg/L	3-13 days Added to water	Nanoplastics had worse effects on cell mortality, cell membrane integrity and DNA conc. compared to microplastics.	Zhao et al., 2020
Brachionus rotundiformis	PS	5 µm	10-100-1000 µg/L	24 hours Added to water	Number of individuals decreased. MDA conc. and SOD activity increased.	Chen et al., 2022
Artemia salina	PP	11.86–44.62 µm	1-25-50-75-100 µg/ml	2-7-14 days Added to water	LC_{50} was found as 40.95 µg/ml and 51.95 µg/ml for nauplius and meta nauplius larvae respectively. SOD, CAT, GST and AChE activities increased. Epithelial cells damaged.	Jeyavani et al., 2022
Invertebrates						
Mytilus galloprovincialis	PS	2 and 6 µm	32 µg/L/day	7 days Added to water	ROS production increased. Antioxidant conc. and GR activity increased. Mortality was observed in hemocytes.	Paul- Pont et al., 2016
Perna sp.	New and PP collected from the beach	Not available	2 ml	48 hours Added to water	Embryonic development altered.	de Silva et al., 2016
Crassostrea gigas	PS	2 µm	0.023 mg/L	2 months Added to water	Oxidative activity increased in hemocytes. Number and diameter of oocytes decreased.	Sussarellu et al., 2016
Nephrops norvegicus	PP	0.3 mm length, 0.2 mm diameter	360 piece	8 months Added to food	Feeding activity, body weight, the protein and stored lipid conc. in the blood decreased with increasing exposure duration.	Welden & Cowie 2016
Scrobicularia plana	PS	20 µm	1 mg/L	14 days Added to water	Microplastic particles were found in the digestive gland, gill and hemolymph. LPO conc., SOD, CAT, GPx and GST activities increased in the gills and digestive gland. CAT, GST and AChE activities decreased in digestive gland.	Ribeiro et al., 2017

Table 7. Continue.

Target organism	Microplastic			Experimental duration and exposure method	Effects	References
	Polymer type	Size	Concentration			
Paracentrotus lividus	PE	1–40 μm	0-100 mg/L	48 hours Added to water	NOEC=30 LOEC=100	Beiras et al., 2018
Scrobicularia plana	PE	11-13 μm	1 mg/L	3-7-14 days Added to water	BaP concentrations, hemocyte size and CAT activity increased. No changes on AChE activity	O'Donovan et al., 2018
Mytilus galloprovincialis	PE	1-40 μm	0-100 mg/L	48 hours Added to water	LOEC>100	Beiras et al., 2018
Mytilus galloprovincialis	HDPE	1-50 μm	4.6E+5 microbeads/L	18 days-64 days Added to water	Retarded growth. Microplastic particles were observed in gut.	Detree & Gallardo-Escarate, 2018
Mytilus galloprovincialis	PS	3 μm	50-10000 particles/ml	24-48 hours 3-6-9 days Added to water	Microplastic uptake rate increased with increasing particle conc.	Capolupo et al., 2018
Mytilus galloprovincialis	PS	1-10-90 μm	Not available.	3 hours-40 days Added to water	Microplastics were observed in gut. Microplastics were also found in feces.	Kinjo et al., 2019
Paracentrotus lividus	PE	5-60 μm 61-499 μm 500-3000 μm	0.1 mg/ml	72 hours Added to water	Anomalies observed during larval development increased with increasing particle size.	Piccardo et al., 2020
Mytilus galloprovincialis	PE, PS	20 and 75 μm	10^4 particles/L and 5×10^4 particles/L	7 days Added to water	Amylase and xylanase activities decreased, cellulose activity increased, with PS being more prominent.	Trestrail et al., 2021
Mytilus galloprovincialis	PE	40-48 μm	1-10-100-1000 μg/L	7-14 days Added to water	GST and CAT activity decreased. LPO level decreased.	Abidli et al., 2021
Perna viridis	PE	<32 μm 32-43 μm	1 μg/L 2 μg/L 3 μg/L	30 days Added to water	Byssus production decreased. CAT activity decreased. LPO conc. increased.	Hariharan et al., 2021
Crassostrea gigas	PE PET	36.72±24 μm (PE) 31.11±14.36 μm (PET)	10-1000 μg/L	21 days Added to water	SOD activity increased in digestive glands. MDA conc. did not change. CAT activity decreased in the digestive gland.	Teng et al., 2021

Table 7. Continue.

Target organism	Microplastic			Experimental duration and exposure method	Effects	References
	Polymer type	Size	Concentration			
Fish						
Dicentrarchus labrax	PVC	<0.3 mm	0.1% (w/w)	30-60-90 days Added to food	Morphological changes and hyperplasia observed	Peda et al., 2016
Pomatoschistus microps	PE	1-5 μm	0.184 mg/L	48 hours Added to water	Lipid oxidation was observed. AChE activity was altered.	Ferreira et al., 2016
Sparus aurata	PVC	40–150 μm	100 and 500 mg/kg	15 and 30 days Added to food	Creatine kinase, aspartate aminotransferase, albumin and globulin conc. in serum decreased. IgM conc. in the skin mucosa increased. *prdx5* gene expression decreased, *prdx1* and *prdx3* genes.	Espinosa et al., 2017
Dicentrarchus labrax	Thermoset amino formaldehyde polymer	1–5 μm	0.26 mg/L 0.69 mg/L	96 hours Added to water	AChE activity and lipid peroxidation in brain tissue showed alterations. ChE activity, LPO, LDH and LDH conc. in the muscle tissue changed	Barboza et al., 2018
Oryzias melastigma	PE	4-6 μm	0-1-10 mg/L	12 days Added to water	LOEC>10	Berias et al., 2018
Sparus aurata *Dicentrarchus labrax*	PVC, PE	40-150 μm	1-10-100 mg/ml	1-24 hours Added to water	Phagocytosis rate of the anterior kidney lymphocytes and respiratory burst rate increased. Expression of the *nrf2* gene increased.	Espinosa et al., 2018
Sebastes schlegelii	PE	15 μm	10^6 particles/L	14 days Added to water	Weight gain and specific growth rate decreased.	Yin et al., 2018
Pomatoschistus microps	PE	1-5 μm	0.18 mg/L	96 hours Added to water	AChE and GST activities decreased.	Miranda et al., 2019
Sparus aurata	LDPE	Not available	10%	21 days Added to food	CAT, SOD, GST, GPx activities increased in liver. CAT and SOD activities increased in brain. No changes were observed in MDA conc.	Rios-Fuster et al., 2021
Sparus aurata	PE	10-20 μm	5±1 μg	35 days Added to food	Survival rates decreased. Alanine, glucose, mannose, inosine phenyl alanine, valine, ATP, N-asetlaspartat, creatine, glycine, taurine, GABA, glutamate, asetamid and glutamine conc. increased.	Jacob et al., 2021

Table 7. Continue.

Target organism	Microplastic			Experimental duration and exposure method	Effects	References
	Polymer type	Size	Concentration			
Oryzias melastigma	PS	2-μm	2-20-200 μg/L	28 days Added to water	Diversity and quantity of the intestinal microflora decreased.	Wang et al., 2022
Oryzias melastigma	Primary PVC Secondary PVC	53–106 μm	10^3 particles/L and 10^6 particles/L	25 days Added to water	Anomalies observed during embryonal development.	Xia et al., 2022
Pagellus bogaraando	Irradiated microspheres	1–5 μm	0.3 mg/L	9 days Added to water	ROS production increased. AChE activity decreased.	Santos et al., 2022

HDPE: High Density Polyethylene, LDPE: Low Density Polyethylene, PE: Polyethylene, PP: Polypropylene , PS: Polystyrene , PVC: Polyinyl Chloride , UPVC: Unplasticised Polyvinyl Chloride) AChE: Acetylcholinesterase, CAT: Catalase, ChE: Cholinesterase, COX-2:Cyclooxygenase-2, GPx: Glutathione Peroxidase, GR: Glutathione Reductase, GRd: Glutathione-disulfide Reductase, GSH: Glutathione, GST: Glutathione S-Transferase, HIF-1α: Hypoxia-Induced Factor-1, IDH: Isocitrate dehydrogenase, IgM: Immunoglobulin M, LC_{50}: Lethal concentration, LDH: Lactate dehydrogenase, LOEC: Lowest observed effect concentration, LPO: Lactoperoxidase, MDA: Malondialdehyde, NOEC: No observed effect concentration, nrf2: Nuclear factor erythroid 2-associated factor 2, prdx1: Peroxiredoxin-1, prdx3: Peroxiredoxin-3, prdx5: Peroxiredoxin-5, SOD: Superoxide Dismutase.

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