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REVIEW ARTICLE

# Microalgae for microplastic removal from water and wastewater: a review

**Paulo M. S. Sousa**[1,2] · **Kerry A. Kinney**[3] · **Cátia A. Sousa**[1,2,4,5,6] · **Manuel Simões**[1,2,6]

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## Abstract

The worldwide microplastic pollution in waters requires efficient removal techniques, yet actual wastewater treatment methods are limited. Here we review the use of microalgae for microplastic removal, with focus on microplastics in aquatic systems and wastewaters, legislation and regulations, common removal techniques, and microalgae for microplastic removal. We describe the mechanisms involved in microalgae-microplastics aggregation. We also present the criteria for selecting adequate microalgae for microplastics removal from wastewater.

**Keywords** Aquatic contamination · Microplastic pollution · Microalgae-based system · Microalgae-microplastics interaction · Removal mechanism · Wastewater treatment

## Introduction

Microplastics are emerging contaminants of worldwide concern due to their negative impacts on aquatic ecosystems and human health [1]. Microplastics are defined as tiny solid plastic particles between 1 µm and 5 mm in diameter that have a potentially negative impact on aquatic environments and are harmful to all living organisms [1, 2]. The annual global production of plastics is enormous with 400.3 million tons generated in 2022 [3]. According to data collected in 2019 by the Organization for Economic Cooperation and Development (OECD), a massive 353 million tons of plastic waste was generated worldwide, with only 9% being recycled, and nearly 50% ending up in landfills [4]. Moreover, in 2019, of the global plastic waste generated, an estimated 6.1 million tons was discharged into water environments, and 1.7 million tons flowed into the oceans [4]. This poses a threat to the quality and availability of water on our planet. It is estimated that there are 30 million tons of plastic waste in seas and oceans (Fig. 1), with rivers being the primary locations for plastic waste in aquatic environments, around 109 million tons [4] Recently, Eriksen et al. [5] monitored the rapid increase of floating plastic waste estimating that there are about 82 to 358 trillion plastic particles weighing between 1.1 to 4.9 million tons.

Plastic waste introduced into the environment undergoes mechanical, biological, and chemical degradation processes, changing its physical and chemical properties and leading to fragmentation and the formation of microplastics [6, 7]. As a result, microplastics can reach the aquatic environment from a primary or a secondary source [8]. Primary sources directly release small particles into the environment from plastic pellets, personal care products containing microbeads, paint, household laundry wastewater, and vehicle tire

✉ Cátia A. Sousa
csousa@fe.up.pt

✉ Manuel Simões
mvs@fe.up.pt

1 LEPABE-Laboratory for Process Engineering, Environment, Biotechnology and Energy, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

2 ALiCE-Associate Laboratory in Chemical Engineering, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

3 Architectural, and Environmental Engineering, Department of Civil, The University of Texas at Austin, Austin, TX, USA

4 School of Engineering, ISEP/P.PORTO, Polytechnic of Porto, Rua Dr. António Bernardino de Almeida, 431, 4249-015 Porto, Portugal

5 School of Engineering, CIETI, Polytechnic of Porto, Porto, Portugal

6 Department of Chemical and Biological Engineering, Faculty of Engineering, ALiCE/LEPABE, University of Porto, Rua Dr. Roberto Frias, s/n, 4200-465 Porto, Portugal

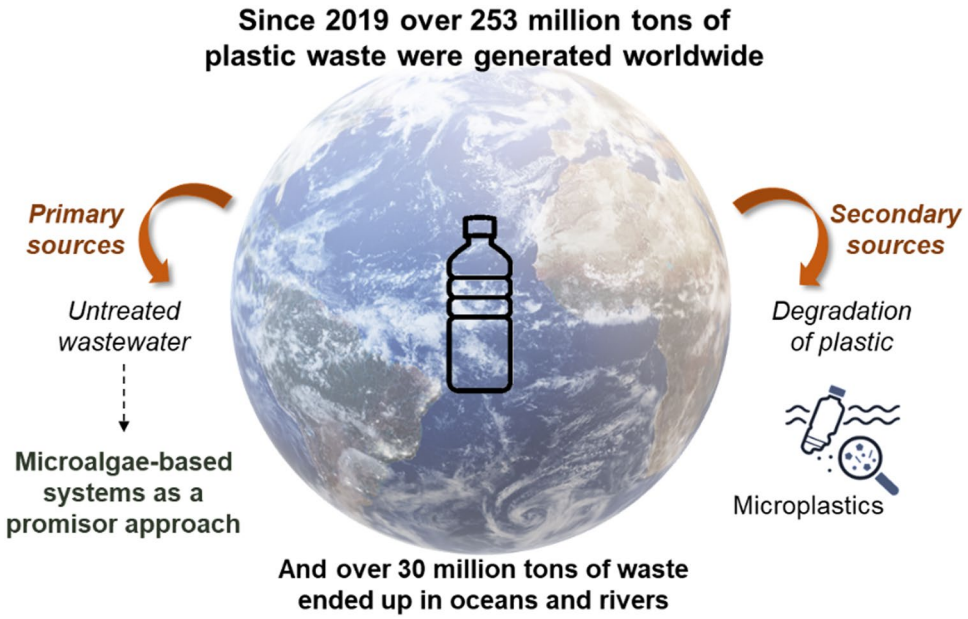


**Fig. 1** Global pollution of plastic and microplastics. Since 2019, an estimated 30 million tons of plastic waste currently pollutes the oceans, while rivers are the main spot for plastic waste in aquatic environments, containing approximately 109 million tons [Eriksen et al. [15], GESAMP [6], OECD [4], and Eriksen et al. [5]]. The primary and major source of plastics and microplastics contamination in aquatic environments is the ineffective wastewater treatment by current processes. As a result, a novel and sustainable approach using microalgae-based systems is gaining attention within the scientific community for removing these pollutants

wear, among others [6, 9–11]. Secondary sources of microplastics are generated by the degradation of larger plastic objects into smaller plastic fragments after exposure to specific conditions in aquatic ecosystems, such as plastic bags and bottles, fishing wastes, farming film, and other large-size plastic wastes [9].

Several recent studies have reviewed microplastics pollution in soils [12], oceans, freshwater, and drinking water [13–16]. However, wastewater represents a significant source of microplastics released into aquatic systems [17, 18] and warrants greater attention, particularly since current wastewater treatment processes are unable to remove microplastics efficiently. This work reviews the growing problem of microplastics pollution in aquatic environments and assesses the ineffectiveness of conventional wastewater treatment processes for its removal (Fig. 1). This work is further strongly focused on the high potential of biological systems for bioremediation processes, applying microalgae-based systems in particular. The feasible mechanisms, as well as the advantages of applying these microorganisms to remove microplastics from wastewater, were also reviewed.

## Categories of microplastics

From the million tons of plastic waste generated, all kinds of products are found with different polymers and chemical compositions. Plastics are beneficial in daily lives due to their wide applicability in many fields or industrial sectors, as well as their physical and mechanical characteristics, *e.g.*, elasticity, insulation, density, durability, waterproof, and corrosion resistance, among others, and their cost-effective production [17, 19–21]. They are synthesized from low-molecular organic units (monomers) [20] and the most common organic units found in different kinds of plastics are ethylene, propylene, styrene, phenol, formaldehyde, vinyl chloride, and acetonitrile. These monomers submitted to a polymerization process are responsible for the production of different classes of plastics. For example, propylene is the base constituent for polypropylene (PP) plastics, styrene for polystyrene (PS) polymers and vinyl chloride is a monomer for polyvinyl chloride (PVC), products widely used in our daily lives. However, other polymers require more complex syntheses, involving chemical reactions with alcohols, *e.g.*, ethylene glycol, acids, *e.g.*, terephthalic acid, or methyl methacrylate to develop complex polymers (Table 1).

The most common types of microplastics that are of worldwide environmental concern are the following, as summarized by Plastics Europe [22] and Plastic Oceans [23] (Table 1): i) polypropylene (PP); ii) polyethylene (PE) divided into two subtypes — iii) high-density polyethylene (HDPE) and iv) low-density polyethylene (LDPE); v) polyvinyl chloride (PVC); vi) polyethylene terephthalate (PET); vii) polystyrene (PS); and viii) polyurethane (PUR). Despite these eight different types of polymers, other types of microplastics can be found dumped into ecosystems, particularly polymethyl methacrylate (PMMA) and polyacrylonitrile (PAN) [24–26].

Also, microplastics derived from polypropylene (PP), polyethylene (PE) (high-density polyethylene and low-density polyethylene), and polyethylene terephthalate (PET) comprise approximately 78% of the estimated waste generated worldwide (Table 1). Moreover, these plastics have a long estimated degradation time, particularly high-density polyethylene (HDPE) products, which can require up to 1200 years to biodegrade [27]. Therefore, considering

**Table 1** The most polluting plastic waste, sources, and estimated degradation time

| Microplastics | Density ($g/cm^3$) | Chemical formula | The most common waste debris | Estimated degradation time (years) | Estimated waste worldwide generated (Million tons) | References |
|---|---|---|---|---|---|---|
| PP | 0.90–0.91 | $[CH_2–CH(CH_3)]_n$ | Microwave dishes, ice cream tubs, bottle caps, single-use face masks | Up to 450 | 62[a] | [4, 9, 28, 29] |
| HDPE | 0.95–0.97 | $(CH_2–CH_2)_n$ | Shampoo bottles, milk bottles, freezer bags, ice cream containers | Up to 1200 | 44.7[a] | [4, 9, 27, 30, 31] |
| LDPE | 0.92–0.93 | $(CH_2–CH_2)_n$ | Bags, trays, containers, food packaging film | Up to 1000 | 49.3[a] | [4, 9, 27, 30–32] |
| PVC | 1.3–1.6 | $(CH_2–CHCl)_n$ | Water pipes, packaging, wires and cables, blood bags | Up to 50 | 21.2[a] | [4, 9, 30, 33, 34] |
| PET | 1.3–1.4 | $(C_{10}H_8O_4)_n$ | Water bottles, dispensing containers, biscuit trays | approximately 450 | 24.9[a] | [4, 9, 27, 30, 35] |
| PS | 1.0–1.1 | $[CH_2–CH(C_6H_5)]_n$ | Cutlery, plates, cups | Between 500–900 | 15.2[a] | [4, 27, 30, 36, 37] |
| PUR | 1.05 | $[C_3H_8N_2O]_n$ | Footwear, thermal isolation | 20–30 | 11.3[a] | [4, 9, 30, 38, 39] |
| PMMA | 1.2 | $[CH_2–C(CH_3)CO_2CH_3]_n$ | Shatterproof windows, skylights, illuminated signs, and optical fibers | Not mentioned | ≈1 | [40, 41] |
| PAN | 1.18 | $(CH_2–CHCN)_n$ | Fibers in the hot gas filtration system, outdoor awnings, sail for yachts | Not determined | Not determined | [42] |

PP-polypropylene; HDPE-high-density polyethylene; LDPE-low-density polyethylene; PVC-polyvinyl chloride; PET-polyethylene terephthalate; PS-polystyrene; PUR-polyurethanes; PMMA-polymethyl methacrylate; PAN-polyacrylonitrile

[a]the values listed in the literature are relative to the year 2019

the characteristics of microplastics and their very extensive biodegradation timescale (Table 1), the scientific community has initiated research to understand the phenomena of microplastics accumulation in the environments, particularly in aquatic ecosystems.

## Microplastics in aquatic ecosystems

Microplastics have been increasingly accumulating in aquatic environments through anthropogenic action, prompting an emergent research area of "White Pollution". Over the last decades, numerous studies have been published investigating the presence of microplastics in oceans, revealing concerning numbers [6, 8, 15, 43, 44]. For example, Eriksen et al. [5] analyzed data on floating ocean plastics from various stations worldwide (approximately 12,000 stations) over 40 years, estimating that the global abundance of plastic particles floating in the oceans is approximately 82 to 358 trillion, with a weight of 4.9 million tons. The particles enter the marine environment via different primary or secondary pathways, through land-based human activity, or in the marine environment, *e.g.*, fishing [5]. Subsequently, they are dispersed and transported across the oceans by large-scale abiotic factors such as sea currents, waves, wind, geostrophic circulation, and weather events [6, 8, 15, 44, 45]. Other important variables are the density, shape, and size of microplastics (Table 1), which also affect the transportation and dispersion patterns [45].

Even though the majority of plastic debris accumulates in areas of the northern hemisphere (56%) [15], probably due to a higher density of human activity and population, microplastics are ubiquitous in global ocean regions, including in the frozen Arctic and Antarctic waters, in seabed sediments, beaches, in coastal waters, and throughout the water column [8, 15, 44, 46–55]. According to the International Maritime Organization (IMO) report [6], the polymers most frequently found in microplastics recovered from marine environments are polyethylene (PE) (79%), polypropylene (PP) (64%), and polystyrene (PS) (40%). The IMO report offers a comprehensive study, gathering information on the industrial synthesis of the different types of polymers, including some ordinary applications, sources (primary or secondary) of plastic waste

in the aquatic environment, environmental exposure to degradation or fragmentation into microplastics, and the factors influencing microplastics dispersion and accumulation in worldwide seas and oceans [6].

Microplastics pollution extends to freshwater environments, such as the dynamic natural ecosystems, *e.g.*, rivers, lakes, estuaries, ice and glaciers, among others, and terrestrial systems, *e.g.*, urban waters and wastewater [45, 56]. This pollution rapidly spreads, leading to numerous persistent plastic particles and fibers in worldwide freshwater ecosystems (Table 2), endangering their crucial chemical and microbiological quality for human subsistence [45, 56].

The abundance of microplastics in freshwaters depends on natural environments (*i.e.* dynamic or static ecosystems) and anthropogenic factors. In fact, in an open and dynamic ecosystem, like rivers, the abundance of microplastics can be conditioned by the river course, ending in the marine environment causing the dispersion of the particles. On the other side, static and stagnant environments, such as lakes, stimulate the accumulation or deposition of microplastics in the ecosystem [45, 118]. Moreover, microplastics enter into freshwaters through different sources: i) surface runoff (resulting from weather conditions), or wastewater effluents (both treated and untreated); ii) sewage overflows, industrial effluents (primary source); and iii) degraded plastic waste or atmospheric deposition (Fig. 2). Surface runoff and wastewater effluents are recognized as the main sources of pollution for freshwater systems [119]. According to Liu et al. [120], an average of 7.2 billion microplastic particles per day enter rivers from wastewater treatment plants (Fig. 2).

Based on data from different studies (Table 2), microplastics are omnipresent across worldwide water and their surroundings, stimulating the accumulation or deposition of microplastics in water ecosystems. Moreover, no pattern directly correlates the highest abundance of microplastics with a particular aquatic environment or geographical country. The concentrations of the different polymers are heterogeneous even in the same type of environment or country.

## Regulation and legislation on microplastics

One of the biggest gaps concerning microplastics is the lack of standard international regulations regarding microplastics discharge and monitoring in water, particularly wastewater [121]. As such, urgent actions are needed to establish policies and guidelines to minimize, or even ban, the production of certain plastics and mitigate the presence of microplastics in wastewater and not only their consumption. Although there are worldwide regulation gaps concerning plastic production, limited progress has been made in some countries to ban specific plastic products from being manufactured and marketed [122–125]. For instance, in Europe, at the request of the European Commission, the European Chemicals Agency proposed in 2019 a wide restriction on microplastics in products on the market in the European Union and European Economic Area to prevent or reduce their release into the marine environment, *e.g.*, single-use plastics (Directive 2019/904) [126]. More recently, in August 2022, the European Commission released a draft proposal to restrict intentionally added microplastics in daily-use products. The restriction would ban the use of synthetic polymer microparticles in a diverse range of consumer products, for example, in cosmetics, cleaning products, pesticides, and sports fields, among others-banning particles smaller than 5 mm and fiber-like particles smaller than 15 mm [122, 127].

Furthermore, the European Commission also revised and improved the Directive to handle microparticle pollution in wastewater treatment, providing a strong starting point for the implementation of measures to minimize the dispersion of microplastics in the environment. In the Urban Waste Water Treatment Directive (UWWTD) (Council Directive 91/271/EEC), new standards and goals were added to mitigate wastewater pollution, with the main focus on: i) reducing pollution and energy used in wastewater treatment plants (more technological development and recycling); ii) improving water quality; iii) making industry pay for the treatment of micro-pollutants; and iv) leading more to a circular sector [127].

Across the European regulatory landscape, different governmental regulations and laws are drafted in each country, in parallel with the European Commission Directives [123, 124, 126, 130, 131]. For instance, in 2019, the Portuguese government put into force the law No. 76/2019 to ban the use in commercial establishments or the commercial sale of "plastic tableware" and other materials made of polystyrene (PS), *e.g.*, cotton swabs, to reduce consumption by 90% before December 2030 [132]. More restrictive measures have been applied in France, Italy, Germany, and Belgium, among others, with complete bans on plastic bags and selling other single-use products made of different types of plastic [124, 133].

Great efforts have also been made beyond Europe as well to regulate the manufacture and sale of plastic products [130]. The United Nations has developed guidelines for controlling and preventing the generation of plastic waste, and there are also relevant studies outlining policies applied by several countries around the world (with different enforcement efforts) to reduce or ban plastic waste, avoiding reaching aquatic ecosystems [124, 130, 133].

Regulatory efforts to ban the manufacture or introduction of plastic microbeads in cosmetic and hygiene products (primary microplastics in waters) have been implemented by many countries such as the United States since December 2015 (“Microbead-Free Waters Act”), in Canada since 2016, in England since 2019, joining the European Union in this initiative [122, 123, 130]. But, looking at the US regulation,

**Table 2** Pollution by microplastics of water environments, with the respective concentrations and sizes of microplastics

| Country or Ocean region | Aquatic Environment | Most types of microplastics (shape) | The abundance of the microplastics | Size (mm) | References |
|---|---|---|---|---|---|
| Portugal | River–freshwater | PP (29%), PE (29.4%), PS (8.8%) and PET (8.8%)–foam, film and fibers | $\leq$1265 particles/m$^3$ | $\geq$0.055 | [57] |
| | Ocean coast–marine (surface water) | Predominantly pellets, fragments, and polymeric foams | 1908 $\pm$ 454 items/m$^2$ | 4.0–5.0 | [58] |
| China | | | | | |
| | Ocean–marine | PP, PE, PS–film, fiber, granule, pellet | 545 $\pm$ 282 particles/m$^3$ | $<$0.50 | [59] |
| | Urban Waters | Not determined | 1597 to 12,611 particles/m$^3$ | $<$1.00 | [60] |
| | Urban Waters | PP (34%), PE (29%), PS (23%)–Fibers | 911.57 $\pm$ 199.73 to 3395.27 $\pm$ 707.22 particles/m$^3$ | 0.50–1.00 | [61] |
| | Lake–freshwater (surface water) | 50–91% fibers, 5.67–33.33% beads, 2.63–20.00% fragments | 0.62 to 4.31 particles/m$^2$ | 0.9–0.333 | [62] |
| | River–freshwater | PP (35.7%), PE (28.6%) and PET (28.6%)–fibers (80.9%), fragments (18.9%) and films (2.2%) | 379 to 7924 items/m$^3$ | 0.02–1 mm (48%) and 1–2 mm (36.5%) | [63] |
| | River–freshwater | Fragment, fiber, film, and granules | 0.0158 $\pm$ 0.0098 items/ m$^3$ | 0.2–0.5 (56.4%) | [64] |
| | Ocean–marine | Fibrous rayon (67%) and PET (23%)–fibers (88 to 100%) | 0.0046 to 0.064 items/m$^3$ | 0.010 – 4.556 | [65] |
| USA | River–freshwater | Fibers (71%) and fragments (17%) | $5\times10^{-8}$ to $32\times10^{-5}$ particles/m$^3$ | 0.36 – 0.99 (72%) and 1.0 – 4.75 (26%) | [66] |
| | River–freshwater | Not determined | Average particles $2\times10^{-5}$ to $6\times10^{-5}$/m$^3$ | | [67] |
| | River–freshwater | Not determined | Average particles $1\times10^{-6}$/m$^3$ | 0.3 – 2.0 | [68] |
| | Ocean–marine | Fibers | 5.0 to 18.4 particles/m$^3$ | $<$0.10 | [69] |
| | Lake–freshwater | Not determined | Average $2.7\times10^{-6}$ particles/m$^3$ | 0.355–0.999 (81%) and 1.000 – 4.749 (17%) | [70] |
| | Sea–marine | PE (53%) and PP (43%), and also PS, PA, and PVC–fragments (86%) | $\leq$4.12 microplastics/m$^3$ (mean 0.34 $\pm$ 0.80 microplastics/m$^3$) | 0.5–5.0 | [71] |
| Indonesia | Sea–marine | PP | $7\times10^{-5}$ to $1.11\times10^{-3}$ particles/m$^3$ | 0.270 – 1.279 | [72] |
| | River–freshwater | Fibers, fragments, microbeads, and films | 5.77 $\pm$ 1.25 items/m$^3$ | 1.5 | [73] |
| Mongolia | Lake–freshwater | Fragments (40%), films (38%) and fibers (20%) | Average $1.2\times10^{-6}$ particles/m$^3$ | 0.333 – 5.0 | [74] |
| India | River–freshwater | Rayon (54%), PMMA (24%), PET (8%), PVC (6%) and PES (5%)–fiber (91%) and fragments (9%) | $3.8\times10^{-5}$ items/m$^3$ | 2.459 $\pm$ 0.209 | [75] |
| | Ocean–marine | PET, PE, rayon, PA and PVC | 2.3 $\pm$ 2.1 items/m$^3$ | 0.108 – 4.703 | [76] |

**Table 2** (continued)

| Country or Ocean region | Aquatic Environment | Most types of microplastics (shape) | The abundance of the microplastics | Size (mm) | References |
|---|---|---|---|---|---|
| | Ocean–marine | PE (23.89%), PP (15.93%), alkyd (13.29%), PS (8.85%)–fibers, fragments, films, and pellets | $1.25 \pm 0.88$ particles/$m^3$ | 0.30 – 4.75 | [77] |
| | Lake–freshwater | LDPE, HDPE, PET, and PP–fragments, films and fibers | $0.0088 \pm 0.0003$ particles/$m^3$ | 0.02 – 5.00 | [78] |
| | River–freshwater | PET and PA (38%), PE (26%), PP (18%), PVC (10%), PS (5%)–filaments, fragments and films | Average $206 \pm 31.9$ particles/$m^3$ | 0.10 – 2.00 | [79] |
| Italy | Lake–freshwater (surface water) | Fragments and fibers | Average of 3.0 particles/$m^2$ on Lake Chiusi surface water and an average of 2.5 particles/$m^2$ on Lake Bolsena surface water | 0.5 – 1.0 | [80] |
| France | River–freshwater | Fibers (48%) | Average 0.0003 particles/$m^3$ in plankton net | 0.1 – 5.0 | [81] |
| | River–freshwater | 2–D fragments and 3–D spherules | Average 0.00035 particles/$m^3$ in manta trawl | | |
| Switzerland | River–freshwater | PE (62%), PP (15%) and PS (12%)–films, fragments and foams | Average $7 \times 10^{-8}$ particles/$m^3$ | Not determined | [82] |
| Belgium | River–freshwater | PP (49%), PS (49%), and PVC (2%) | Up to 0.0048 particles/$m^3$ | 0.025–1.000 | [83] |
| Austria | River–freshwater | Pellets (17%), flakes (10.4%) and spherules (3.6%) | Average 0.0032 particles/$m^3$ | Not determined | [84] |
| Spain | Glacial | Fragments (59.7%), fibers (38.8%), and spheres (1.5%) | 0.0213 particles/$m^3$ | < 0.045 | [85] |
| | Sea–marine | HDPE (64.7%), PP (27%), and PS (0.2%) – fragments (77.2%), tar (15.7%), and films (3.9%) | From 0.27–136.70 items/$m^3$ | 0.5–1.0 (49.7%) and > 1.0 (33.6%) | [86] |
| Germany | Sea–marine | Granulates, fibers, and black carbon (BC) particles | 1770 particles/$m^3$ | Not determined | [55] |
| | River–freshwater | PE (20%), PP (16%), PVC, PET and polyester, polychloroprene, and PA–fragments | 28–134 particles/$m^3$ | 0.3–1 mm | [87] |
| Japan | Sea–marine | Spherical particle, microbead | 0.03 to 0.075 particles/$m^3$ | < 2.00 | [88] |
| Colombia | Lake–freshwater | Polyester (57.9%), PS (47.0%), and PET (35.3%) – fragments (20.8%), foams (0.2%), and pellets (0.1%) | Average 0.0019 particles/$m^3$ | 0.35 | [89] |
| South Africa | Sea–marine | Fibers (90%) | $257.9 \pm 53.36$ to $1215 \pm 276.7$ particles/$m^3$ | 0.08–5.00 | [90] |
| Brazil | Sea–coastline | Fibers, fragments, styrofoam and pellets | 12 to 1300 particles/$m^2$ | Not determined | [91] |

**Table 2** (continued)

| Country or Ocean region | Aquatic Environment | Most types of microplastics (shape) | The abundance of the microplastics | Size (mm) | References |
|---|---|---|---|---|---|
| | Sea–marine | PE (81.7%), PE (16.20%) – fragments, films | 1.4 to 21.3 particles/$m^3$ | 0.30–1.00 | [92] |
| | River–freshwater | PE (29%), polyester (26%), PA (19%), ethylene vinyl alcohol (9%), nylon (9%), and HDPE (8%) – fibers | 0.38 ± 0.14 – 0.71 ± 0.25 particles/$m^3$ | Not determined | [93] |
| Finland | Lake–freshwater | PE, PP, PET, PMMA, and PAN–fibers (64%) and fragments (36%) | Average concentrations 0.27 ± 0.18 microplastics/$m^3$ | 0.020–0.300 | [94] |
| Scotland | Sea–marine | PP (26%), PS (17%), PVC (12%), PE (10%)–fragments, fibers and beads | $9.113 \times 10^{-8}$ microplastics/$m^2$ | 0.30–5.00 | [95] |
| Denmark | Sea–marine | Fragment, fiber | 0.07 ± 0.02 particles/$m^3$ | 0.30–0.63 | [96] |
| | Sea–marine | PMMA, PA, PP, PE, and polyesters – fragments (54%) and fibers | 103 ± 86 items/$m^3$ | < 0.1 | [97] |
| Australia | Freshwater | PE, rayon–fibers | 0.004 ± 0.0027 items/$m^3$ | 0.036–4.668 | [98] |
| | Ocean–marine | Fragment, fiber | 0.031 particles/$m^3$ | < 2.00 | [88] |
| Iceland | Glacial | PUR, PVC, PA, and acrylonitrile butadiene styrene | Not determined | ≤ 3.00 | [56] |
| Norway | Sea–Artic | Polyester (15%), PA (15%), PE (5%), PMMA (10%), PVC (5%), cellulose–fibers (95%), fragment, films | 0.34 ± 0.31 particles/$m^3$ | 1.93 ± 1.22 | [99] |
| Sweden | Sea–marine | Not determined | ≤ 102 000 particles/$m^3$ | ≥ 0.30 | [100] |
| Malaysia | River–freshwater | PE, PS, polycarbonate, and PET–fibers (68.4%), film, and fragment | 0.060 to 0.128 items/$m^3$ | 0.10–5.00 | [101] |
| South Korea | River–freshwater | PE, PS (16.9%), silicone (23.1%), PTFE, polyester (13.8%), PP (15.4%)–fragments (73%), and fibers | Surface waters – 42.9 particles/$m^3$ and water column ≤ 180.0 particles/$m^3$ | mostly < 1.00 | [102] |
| | Jungnang stream–freshwater | PE, PP, and PET–fragments and fibers | 0.0098 ± 0.008 particles/$m^3$ | ≤ 0.2 | [103] |
| Vietnam | River–freshwater | Polyesters (70%), PET (9%), PE (7%), PP (4%) and rayon (4%)–fibers (92%) | Between 172 000 items/$m^3$ to 519 000 items/$m^3$ | 0.050–0.450 | [104] |
| Iran | River–freshwater | PE (36.6%), PA, and PS–fibers (53.5%), fragments and foams | 1 to 43 items/$m^3$ (mean 12.8 ± 10.5) | 0.10–5.00 | [105] |
| Pakistan | Lake–freshwater | PP, PE, Polyesters, PET, PVC–fibers (38.6%), sheets (2.5%), and foams (2.2%) | 2074 ± 3651 particles/$m^3$ | ≤ 1.00 | [106] |
| UK | Sea–marine (surface waters) | PP, rayon, polyester, PA, PET, and PMMA–fibers, fragments, and pellets | 0.26 to 0.68 items/$m^3$ | 0.053–3.00 | [107] |

**Table 2** (continued)

| Country or Ocean region | Aquatic Environment | Most types of microplastics (shape) | The abundance of the microplastics | Size (mm) | References |
|---|---|---|---|---|---|
| Artic | Sea–marine | Polyester, PAN, PA, and PVC–fibers (90%) and fragments | 0.7 particles/$m^3$ | 1.00–2.00 (62%) and 2.00–5.00 (38%) | [108] |
| | Chukchi Sea, Western Ocean | PE (34.9%), PP (18.6%), PUR (16.3%), silicone resin (7.0%), PET and PVC (4.7%) | $\leq$0.0188 pieces/$m^2$ | 1.0–2.0 (37.2%) | [109] |
| Switzerland, France, Germany, and Netherlands | River–freshwater | PS (29.7%), PP (16.9%), other types (13.6%), acrylate (9.3%), polyester (5.1%), and PVC (1.7%)–spherules (45.2%), fragments (37.5%), fibers (2.5%) | Average $5\times10^{-5}$ particles/$m^3$ | 0.3–1.0 | [110] |
| Open Ocean | North Eastern Mediterranean | Fibers (70%) | $42\pm46.7$ particles/$m^3$ | 0.1–2.5 | [111] |
| | Northwest Europe | Fragments (63%), film (14%), pellets (10%), foam (8%) | $\leq$1.5 particles/$m^3$ | 1.00–2.79 | [112] |
| | North East Pacific Ocean | Essentially fibers and fragments | 9 180 particles/$m^3$ | $0.60\pm0.22$ | [113] |
| | Southern Caspian Sea (surface water) | PP, PE, PS–fragments (38%), styrofoam (31%), film (20%) | $3.449\times10^{-8}$ particles/$m^2$ | 1.00–4.75 | [114] |
| | North and Central Adriatic Sea (surface waters) | PE (80.7%), PP (9.3%), PA (2.6%), PS (1.9%) and PET (1.4%)–fragments, filaments, films, pellets and granulates | $1.78\times10^{-8}$ to $1.55\times10^{-6}$ items/$m^2$ | Not determined | [115] |
| | Arabian Sea, Indian Ocean | PE, PP, PA, and PVC–fiber (77.14%), fragment (21.78%), and pellet (1.07%) | Average $0.013\pm0.002$ particles/$m^3$ | $0.864\pm0.074$ | [116] |
| | Northwestern Pacific Ocean, Indonesian seas | Nylon (15%), polyester (13%), polyvinyl alcohol (10%), PS (8%), PE (8%), PP (4%), | $<$0.018 particles/$m^3$ | 0.20–0.35 | [117] |

PE–polyethylene; PP–polypropylene; PLA–polylactide; PA–polyamide; PS–polystyrene; PUR–polyurethanes; PVC–polyvinyl chloride; PET–polyethylene terephthalate; PAN–polyacrylonitrile; PMMA–polymethyl methacrylate; PTFE–polytetrafluoroethylene

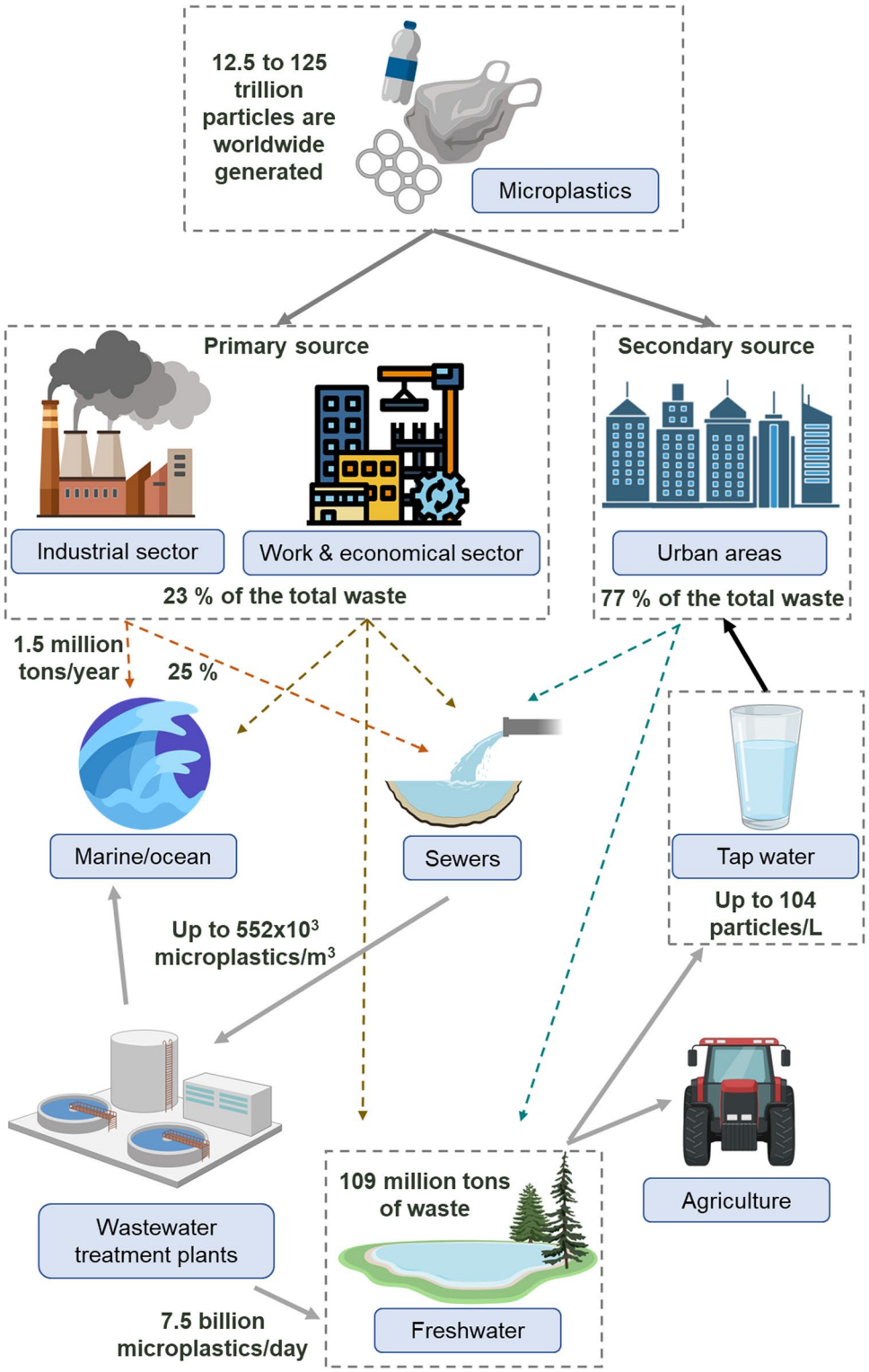


**Fig. 2** Pathways allowing microplastics to enter aquatic environments include industrial activities, the economic sector, and urban areas. These sources contribute to the contamination of aquatic environments with up to 125 trillion microplastic particles globally [4, 15, 120, 128, 129]. Aquatic ecosystems, such as freshwater bodies and oceans, are heavily impacted by microplastic–based pollution, primarily due to the inefficient wastewater treatment processes

Wang et al. [134] point to the concern for the lack of federal legislation (mostly state or city laws being enforced) on plastic products such as plastic bags or food containers, the lack of public investment for increased sustainability, and the gap in environmental and societal education on this issue. Still, some states such as California, Maine, Hawaii, and cities like New York have laws that ban the use of plastic bags, highlighting California as the only state with more

stringent regulation for the control of microplastics in wastewater and drinking water [134]. Moreover, Sorensen et al. [135] warn that although there are government policies and laws controlling the abundance of microplastics in the environment and food products, they are ambiguous and mostly unenforceable.

According to Costa et al. [130], almost 150 countries around the world already have some policies that reduce plastic usage. On the Asian continent, Bangladesh was one of the first countries worldwide to ban low-density polyethylene (LDPE) single-use items from the market (since 2002), India with the same guidelines (essentially for low-density polyethylene (LDPE) bags) in 2016, and more recently China banned certain products made from plastic microbeads and plastic bags [124, 130]. Also, African, and South and Central American countries, *e.g.*, Rwanda, Chile, and Costa Rica, have government laws to ban the consumption of single-use products made from plastic [124, 130, 133].

Overall, it is urgent to reinforce the regulations and guidelines currently in force to enhance the monitoring of microplastics in wastewater. Despite all legislative efforts to regulate the production and usage of plastics worldwide, there is still a need to deal with a considerable number of other sources or pathways of microplastics entering wastewater that are not controlled, *e.g.*, domestic laundry water or run-off.

## Microplastics in wastewaters

The wastewater environment is a significant source responsible for releasing microplastics into aquatic ecosystems, primarily through sludge, road runoff, and effluent discharges [17, 136, 137]. Microplastics stem from household items such as toothbrushes, cosmetics, cleaning products, personal care items, and synthetic fibers, among others [17, 138]. These particles vary in morphological and chemical properties and are consistently discharged in substantial quantities into receiving waters [17]. Reddy et al. [17] reported that the influx of microplastics into wastewater is influenced not only by household sources but also by pollutants from the industrial sector, human activities, demographic factors, and local conditions (Fig. 2). Plastic particles derived from construction materials, *e.g.*, insulation, medical equipment, tire wear, pipelines, automobiles, and the textile industry also contribute significantly to the considerable abundance of microplastics in wastewater. This is exacerbated by factors such as population density, societal habits, cultural practices, economic activities, and daily and seasonal weather fluctuations. The billions of plastic particles released daily into wastewater and other aquatic environments, eventually reach wastewater treatment plants (Table 3), depending not only on anthropogenic and abiotic factors but also on the annual wastewater inflow ($m^3$/year) to the wastewater treatment plants [137].

Microplastics in wastewater have diverse shapes and sizes that are influenced by the wastewater influent sources, the material degradation processes, and wastewater discharge sources. Synthetic fibers, *e.g.*, polyesters (PES), polyethylene (PE), or polyamide (PA), dominate in wastewater treatment plants due to household laundry and textile production. However, particles in various forms such as pellets, fragments, foams, flakes, and films are also identified [120, 137, 139, 140]. Several studies estimate that synthetic fibers constitute 40% to 89% of the microplastics found in wastewater, highlighting household washing as a major contributor [120, 137, 138, 140, 141]. These particles are typically smaller than 1 mm, often ranging between 0.15 and 0.33 mm [120, 137, 138, 140, 141]. Wastewater hosts a wide array of plastic polymers, including polypropylene (PP) (≈ 21%), polyethylene (PE) (≈ 23%), polyethylene terephthalate (PET) (≈ 7%), polyamide (PA) (≈ 2%), polystyrene (PS) (≈ 13%), polyvinyl chloride (PVC) (≈ 7%), polyurethanes (PUR) (≈ 5%), polyvinyl alcohol (PVAL) (≈ 3%), polyesters (PES) (≈ 2.5%), and acrylic (≈ 10%), frequently detected in both influent and effluent samples across wastewater treatment plant facilities [137, 139–141]. These polymers exhibit varying physicochemical characteristics independent of geographical location, wastewater treatment plant types and capacities, biotic and abiotic transport processes, and discharge sources (Table 3).

### Common techniques for microplastic removal in wastewater treatment plants

The presence of high amounts of microplastics in wastewater poses substantial environmental risks, not only because of the microplastics themselves but also due to their potential to adsorb various other pollutants [142, 143]. Owing to their hydrophobic surface properties, microplastics can interact with and adsorb heavy metals, *e.g.*, copper, zinc, lead, iron, chromium, cadmium, arsenic, persistent pollutants, and pharmaceuticals and personal care products (PPCPs). This includes harmful contaminant additives like polybrominated diphenyl ethers, phthalate esters, or polychlorinated biphenyls, originating from their chemical synthesis, raising concerns about the effective removal of these microparticles from aquatic environments [141–148]. Recent studies have also investigated the interaction between microplastics and oil in aquatic ecosystems, revealing evidence of heteroagglomeration between plastic particles and oil seeps or slicks on ocean water surfaces [149–151].

**Table 3** Microplastics wastewater samples, with the respective microplastics concentrations, particle size, and their removal efficiency

| Country | Sampling | WWTPs treatments | Most types of microplastics (shape) | Abundance in influent | Abundance in effluent | Efficient removal (%) | Size (mm) | References |
|---|---|---|---|---|---|---|---|---|
| Germany | WWTPs | Primary, Secondary, and Tertiary treatments | PE, PP, PS, PA, PVC, PUR, PET, ethylene vinyl acetate, polyvinyl alcohol, acrylonitrile butadiene styrene, polylactide, and paint | Not mentioned | > 500 µm: 0 to 50 microplastics/$m^3$; < 500 µm: 10 to ($9 \times 10^3$) microplastics/$m^3$ | 97.0 | < 0.5 or ≥ 0.5 | [204] |
| | WWTPs | Primary, Secondary, and Tertiary treatments – consist of a mechanical treatment stage, a biological stage with denitrification and nitrification, and chemical phosphorus precipitation with aluminum–based precipitants | PE (39.7%), PP (28.9%), PET (21.6%), and PS (9.8%) | $8.8 \times 10^2 \pm 2.7 \times 10^2$ microplastics/$m^3$ | 7.0 ± 2.2 microplastics/$m^3$ | 99.2 ± 0.29 | < 5.0 | [168] |
| Thailand | WWTPs | A conventional WTTPs and an underground WWTPs coupled with ultrafiltration | PET, PE, and PP (60% was fibers shape) | conventional – 0.01655 ± 0.00992 microplastics/$m^3$ and with UF – 0.0077 ± 0.00721 microplastics/$m^3$ | conventional – 0.00352 ± 0.00143 microplastics/$m^3$ and with UF – 0.01067 ± 0.003.51 microplastics/$m^3$ | Ultrafiltration–96.97% and Conventional–86.14% | 0.05–0.5 | [177] |
| | DWTP | Primary and Secondary treatments – (with chlorination) | PP (20%), PE (30–55%), PET (15–40%) – fragments (90%), fibers (10%) | $7.5 \times 10^{-4}$ particles/$m^3$ | $6.5 \times 10^{-4}$ particles/$m^3$ | 27.7 | 0.05–1.0 | [205] |
| | WWTPs | WWTP–A is a cyclic activated sludge system; WWTP–B is an oxidation ditch; and WWTP–C is a CAS system, which undergoes continuous operation | PET (18%), PE (13%), polyacrylate (12%), PP (9%) – fibers (57–61%), also fragments and sheet | 0.0122 pieces/$m^3$ | 0.0020 pieces/$m^3$ | 84.0 | Not mentioned | [115] |
| | Conventional municipal WWTPs | Primary, secondary, and pilot–scale tertiary treatment facility, with ultrafiltration with a pore size of 0.1 µm | PET (40%), PE (29%), PP (10%), PMMA (6%) and PS (3%)–Fibers, films and fragments | 0.077 ± 0.007 particles/$m^3$ | 0.0023 ± 0.0015 particles/$m^3$ | Conventional treatment–86.14%; and ultrafiltration–96.97% | 0.05–0.5 | [206] |
| Italy | Municipal WWTPs | Primary, secondary, and tertiary treatments (full–scale plant with CAS system versus UASB + anaerobic membrane bioreactor | PE (43–53%), PP (10–13%), polyesters (9–10%), PUR (9%), PS (4%), PA (2%), and PVC (2%)–fragments (27–36%), lines (9%) and films (55–73%) | $3.6 \times 10^{-3}$ microplastics/$m^3$–CAS and 0.00172 microplastics/$m^3$–UASB + AnMBR | $5.2 \times 10^{-4}$ microplastics/$m^3$–CAS and 0.0002 microplastics/$m^3$–UASB + AnMBR | Conventional process–86%; UASB + AnMBR–94% | 0.1–0.5 | [183] |
| | WWTPs | Primary, secondary, and tertiary treatments–articulated in screening, grit and grease removal stages, biological treatment, sedimentation (with recycled activated sludge), sand filter treatment, and disinfection | Polyesters (35%) and PA (17%)–films (73%), fragments (21%), and lines (6%) | $2.5 \times 10^{-4} \pm 3.0 \times 10^{-4}$ microplastics/$m^3$ | $4.0 \times 10^{-4} \pm 1.0 \times 10^{-4}$ microplastics/$m^3$ | 84.0 | < 1.0 | [178] |

**Table 3** (continued)

| Country | Sampling | WWTPs treatments | Most types of microplastics (shape) | Abundance in influent | Abundance in effluent | Efficient removal (%) | Size (mm) | References |
|---|---|---|---|---|---|---|---|---|
| Scotland | WWTPs | Primary, Secondary, and Tertiary treatments | PP (most abundant synthetic polymer–23%) in (fibers shape (67%)) | $8.1\times10^{8}$ particles/day | $2.2\times10^{7}$ particles/day | 97.0 | 0.060 and 2.8 | [205] |
| | Secondary WWTPs | Four stages of treatment (grit and grease effluent, primary effluent, and the final effluent) | Alkyds (28.7%), polystyrene–acrylic (19.1%), polyester (10.8%), PUR (8.9%), and PMMA (8.3%) (flakes (67.3%), fibers (18.5%), film (9.9%), beads (3.0%)) | 0.0157 (±0.00523) microplastics/$m^3$ | $2.5\times10^{-4}$ ($\pm4.0\times10^{-5}$) microplastics/$m^3$ | 98.41 | average 0.598 (±0.089) | [136] |
| France | WWTPs | Primary, Secondary, and Tertiary treatments | PS (37.5%) and PE (39.7%), PP, PVC, PET, PA, PUR (3–17%)–fibers and fragments | 0.244 items/$m^3$ | 0.00284 items/$m^3$ | 98.83 | 0.2–0.5 | [207] |
| | Four WWTPs with ultrafiltration as tertiary treatment | WWTP–A–the main process is MBR (0.02 µm UF);<br>WWTP–B–MBR (0.1 µm UF);<br>WWTP–C–Physico–chemical with biofiltration;<br>WWTP–D–activated sludge | PE, PA | 4.203–42.00 microplastics/$m^3$ | Not mentioned | WWTP–A and B–88–99.8%<br>WWTP–C–98–99.9%<br>WWTP–D–72% | Not mentioned | [208] |
| | WTTP | Primary, Secondary, and Tertiary treatments (with screening, then grit and oil removal, settled in a primary settling tank before undergoing biological treatment that consists of biofilters) | Fibers (≥90%) | 260–320 × $10^3$ particles/$m^3$ | 14–50 × $10^3$ particles/$m^3$ | 84.38–94.62 | 0.1–5.0 | [81] |
| USA | Tertiary WWTPs | Primary, Secondary, and Tertiary treatments | Not mentioned | 0.001 particle/$m^3$ | $8.8\times10^{-7}$ microplastics/m3 | 99.9 | 0.1–0.6 | [209] |
| | WWTPs | Primary and Secondary treatments | Essentially PE and PMMA (≈ 70%)–microfibers, | 0.1–0.25 Microplastic /$m^3$ | <0.027 Microplastic /$m^3$ | 75 to 99 | 0.060–0.418 | 210 |
| | WWTPs | Primary, Secondary, and Tertiary treatments (development of AnMBR) | fibers (55–62%), fragments (22–26%), and microbeads (11–16%) | 0.133 ± 0.0356 microplastics/$m^3$ | <0.005 microplastics/$m^3$ | AnMBR–99.4%, while in the other two WWTPs–61–73% | 0.58 | [182] |
| | Municipal WWTPs | Different types of WTTPs facilities, populations, and advanced filtration types | Fibers (59%), followed by fragments (33%), films (5%), foams (2%), and pellets (1%) | Not mentioned | $4.0\times10^{-6}$ to $1.95\times10^{-1}$ microplastics/$m^3$ | Not determined | 0.125–0.355 (57%) | [211] |
| China | DWTPs | Primary, Secondary, and Tertiary treatments (Coagulation through aluminum and iron–salts, sedimentation, and ultrafiltration) | PE | Not mentioned–synthetic solution | Not mentioned | 45.34 ± 3.93 | <0.5 | [212] |
| | Conventional WWTPs | Primary and Secondary treatments (Sedimentation and Aerated grit chamber) | PA (54.8%), PE (9.0%), PP (9.6%), PVC (2.5%), and polycarbonate (1.0%)–fibers (34–57%) and fragment (31–46%) | 0.0799 microplastics/$m^3$ | 0.0284 microplastics/$m^3$ | 64.4 | 0.02–0.3 (45–80%) | [213] |

**Table 3** (continued)

| Country | Sampling | WWTPs treatments | Most types of microplastics (shape) | Abundance in influent | Abundance in effluent | Efficient removal (%) | Size (mm) | References |
|---|---|---|---|---|---|---|---|---|
| | WWTPs | Three stages of treatments (with anaerobic–anoxic–oxic and MBR or cyclic activated sludge technology and fiber rotary filter) | PE (34.95–46.26%), PP (31.07%), PET (22.45%), phenolic resin (18.45%), and PS (15.53%) – fragments (34–38%) and granulates (28–29%) | $1.03–2.205\times10^{-2}$ microplastics/$m^3$ | $2.4–3.4\times10^{-4}$ microplastics/$m^3$ | 97.67–98.46 | < 0.7 | [188] |
| | Municipal WWTPs | Primary, Secondary, and Tertiary treatments (oxidation ditch versus MBR) | PET (47%), PS (20%), PE (18%), and PP (15%)–fragments (65%), fibers (21%), which mainly were PET, with limited films (12%) and foams (2%) | $2.8\times10^{-4}\pm2\times10^{-5}$ microplastics/$m^3$ | $5\times10^{-5}\pm1\times10^{-5}$ microplastics/$m^3$ | 99.5% in the membrane system versus 97% in oxidation ditch | 0.0625–0.5 | [181] |
| | Urban WWTP | Primary treatment includes a course, thin, cyclone, and aeration grit; Secondary treatment includes the sequencing batch reactor activated sludge process, and CAS; and tertiary treatment includes high–efficiency sedimentation tanks, activated sand filters, denitrification filters, and disinfection tanks | PP, PE, PMMA, PET, and PVC–fragment, fiber, and thin film | $0.0325\pm0.001$ items/$m^3$ | $5.0\times10^{-3}\pm4.0\times10^{-4}$ items/$m^3$ | 84.6 | Mainly 0.03–0.10 | [214] |
| | Municipal sewage treatment plants | Until Tertiary treatment (include an aerated grit chamber, primary sedimentation tank, and secondary sedimentation tank following treatments (anaerobic, anoxic, and aerobic), and denitrification, ultra–filtration, ozonation, and ultraviolet) | PET (42.25%), PES (19.09%), and PP (13.05%) – more than 70% of microplastics | $0.1203\pm0.0013$ items/$m^3$ | $5.9\pm2.2\times10^{-4}$ items/$m^3$ | $95.16\pm1.57$ | Average $0.682\pm0.529$ | [187] |
| | Wastewater | Electrocoagulation–anode material made of aluminum and iron metal | PE, PMMA, cellulose acetate, and PP (granulates) | Synthetic solutions using controlled concentration of microplastics–0.05; 0.10; 0.20; 0.50; 0.80; 1.00 g/L | | 91–99.9 | 0.0063–0.287 | [173] |
| | Freshwater | Tertiary treatments (a novel mechanism based on electrostatic–force–induced aggregation and flotation) | PE, PS, PVC, and fiber mixture | $0.026\pm0.006$ microplastics/$m^3$ | Not mentioned | 90.2–95.7 | < 1.0 | [174] |
| | WWTPs (only filtration system) | Dynamic membrane filtration and transmembrane pressure | Not determined | Synthetic solutions using controlled concentration of microplastics–0.1; 0.20; 0.40; 0.60; 0.80; 1.00 g/L | | Not determined | < 0.09 | [215] |
| | Advanced DWTPs | Coagulation and flocculation combined with sedimentation, sand filtration, and filter combined with ozonation | PET (55.4–63.1%), PE (15.1–23.8%), PP (8.4–18.2%), and polyacrylamide–fiber, spheres, and fragments | $\approx 6.614\pm1132$ microplastics/$m^3$ | $\approx 0.930\pm72$ microplastics/$m^3$ | 82.1–88.6 | 0.001–0.010 (85%) | [175] |

**Table 3** (continued)

| Country | Sampling | WWTPs treatments | Most types of microplastics (shape) | Abundance in influent | Abundance in effluent | Efficient removal (%) | Size (mm) | References |
|---|---|---|---|---|---|---|---|---|
| Spain | WWTPs | Four stages of treatment | LDPE (52.4%), PP (11.3%), HDPE (9.0%) (fragments (46.9%), films (34.0%), beads (11.5%), fibers (7.4%), and foam (0.2%)) | $3.20\times10^{-3}$ ($\pm6.7\times10^{-4}$) microplastics/$m^3$ | 3.1 ($\pm0.6$)$\times10^{-4}$ microplastics/$m^3$ | 90.3 | 0.4–0.6 | [166] |
| | DWTPs | Primary, and secondary treatments in urban and industrial waste | PVC, HDPE, PE | 0.64503 ± 0.18224 microplastics/$m^3$ to 1.56749 ± 0.41318 microplastics/$m^3$ | 0.01640 ± 0.00785 microplastics/$m^3$ to 0.13135 ± 0.09536 microplastics/$m^3$ | 91.0–97.0 | 0.100–0.355 | [216] |
| | Urban WWTP | Constituted by a pre–treatment (sieving, grit remover, degreaser), primary treatment, and secondary treatment (biological reactor, gravity thickener, floatation, anaerobic stabilization, dehydration, and co-generation | PE (8–79%), synthetic cellulose (0–26%), PP (0–39%), PVC (0–17%), synthetic polymeric resin (0–91%), PA (0–21%), PAN (0–13%) and polyester (0–12%)–fragments (42%), fibers (44%) and films (10%) | 0.365 to 1.058 microplastics/$m^3$ | 0.032 to 0.178 microplastics/$m^3$ | 96–99 | 0.02–2.0 | [217] |
| | Municipal WWTP | Primary and secondary treatments | Polyester fibers, PE, dyed cotton, PP and cellophane fibers, PET (51% were fragments and 49% fibers) | 0.171 ± 0.042 particles/$m^3$ | 0.0107 ± 0.0052 particles/$m^3$ | 94.0 | 0.025–0.104 (54%) | [178] |
| | Municipal WWTP | Primary, secondary (one with oxidation ditch) and the other with integrated fixed film activated sludge, and two tertiary treatments | PE (30%), PET (29%), PP (11%), and PS (7%)–fragment, foam, film, fiber, and granulate | 0.0155 ± 0.0035 particles/$m^3$ and 0.0385 ± 0.0025 particles/$m^3$ | $2.0\times10^{-4}\pm1.0\times10^{-4}$ particles/$m^3$ and $1.0\times10^{-4}\pm1.0\times10^{-4}$ particles/$m^3$ | With oxidation – 90% and with integrated fixed film activated–97% | 0.05–0.2 (41%) and 0.2–0.5 (27%) | [218] |
| | DWTPs | Primary, and Secondary treatments (with chlorine dioxide and carbon dioxide are added as initial disinfection, followed by the coagulation and flotation step, and ozonation followed by granular activated carbon filtering. The advanced membrane technology | PE and PP – fibers (45–60%) and fragments (40–55%) | $9.6\times10^{-4}\pm4.6\times10^{-4}$ microplastics/$m^3$ | $6\times10^{-5}\pm4\times10^{-5}$ microplastics/$m^3$ | 93 ± 5 | 0.02–0.50 | [184] |
| UK | WWTP | Primary, secondary, and tertiary treatment processes (primary settlement, activated biological anoxic treatment, and activated biological aerobic treatment) | PE (50%), PVC (42%), nylon (4%), and PP (4%) | 0.034 microplastics/$m^3$ | 0.0015 microplastics/$m^3$ | 76.9 | 0.392 (±0.027) | [219] |
| | Synthetic wastewater | Electrocoagulation treatment–electrode made of aluminum | PE | Synthetic solution using a controlled concentration of PE–0.10 g/L | | 99.24 | 0.3–0.355 | [172] |
| England and Wales | Treatment Plants | A wide range of applied techniques, until tertiary processes | PS and acrylonitrile butadiene styrene | 0.0049 microplastics/$m^3$ | $1.0\times10^{-6}$ microplastics/$m^3$ | 99.99 | ≥0.025 | [220] |

**Table 3** (continued)

| Country | Sampling | WWTPs treatments | Most types of microplastics (shape) | Abundance in influent | Abundance in effluent | Efficient removal (%) | Size (mm) | References |
|---|---|---|---|---|---|---|---|---|
| Denmark | Conventional WWTP | First, Secondary treatments (applying several levels of filtration through biofilters) | PE dominated the particle numbers (34%), followed by PP, PVC, PS, PA, and PMMA. PUR was rare and below 1% | 917 items/$m^3$ | ≈ 200 items/$m^3$ | 79.0 | < 0.3 | [221] |
| | WWTPs | First, Secondary and Tertiary treatments | Acrylic (27%), PE (27%), PP (39%) | 7.216 microplastics/$m^3$ | 0.054 items/$m^3$ | 98.0 | 0.010–0.50 | [222] |
| | DWTPs | First, Secondary and Tertiary treatments | PA, PVC, PS, PE, PU, PP, PES–fibers (19%) | Detected 174 ± 405 microplastics/$m^3$ | | | 0.008–0.374 | [223] |
| Hong Kong | WWTPs | Until tertiary treatments, including chemical–enhanced primary treatment | Fibers 55–71%; fragments 25–26% and sheet 19% | $1.01–2.06 \times 10^{-3}$ microplastics/$m^3$ | $2.7–4.0 \times 10^{-4}$ microplastics/$m^3$ | 60.4–86.9 | 1.0–5.0 (≈ 60–64% of the particle) | [224] |
| | Tap Water | | Fibers (98.7%), film (2.2%) | Quantification – An average of $2.18 \times 10^{-3} \pm 1.65 \times 10^{-4}$ particles/$m^3$ | | | 0.05–4.83 | [225] |
| Netherland | Wastewater | Primary and secondary treatments (by conventional or membrane reactor) | Fibers, spheres, and foils | 0.068–0.910 particles/$m^3$ | 0.009–0.091 particles/$m^3$ (average of 0.052 particles/$m^3$) | 72.0 | 0.010–5.0 | 180 |
| Finland | Municipal WWTPs | Primary and secondary treatments | PE and PET (79.1%), PE (11.4%), PA (3.7%), and PP (< 0.1%) | 0.0576 (± 0.0124) microplastics/$m^3$ | 0.0004 (± 0.0001) microplastics/$m^3$ | 99.4 | < 1.0 | 167 |
| | Secondary WWTPs | Primary and secondary treatments (include coagulation and flocculation (using ferric chloride, polyaluminum chloride, and cationic polyamine) | PS–spheres | $5.0 \times 10^2$ microplastics/$m^3$–$182 \times 10^3$ microplastics/$m^3$ | $0.5 \times 10^3$–$13.2 \times 10^3$ microplastics/$m^3$ | for 0.001 mm–95.0%; and for 0.0063 mm–76.0% | 0.001–0.0063 | 171 |
| | Wastewater | Membrane bioreactor; rapid sand filter; dissolved air flotation; disc filter | PE (≈ 60%), followed by PE (≈ 14%), polyacrylates (av. 7%), PVC (≈ 5%), PS (≈ 4%), and PP (≈ 3%) | $6.9 \times 10^{-3}$ ($\pm 1.0 \times 10^{-3}$) microplastics/$m^3$ | $5.0 \times 10^{-6}$ ($\pm 4.0 \times 10^{-6}$) microplastics/$m^3$ | MBR–99.9%; RSF–97%; DAF–95%; DF–98.5% | 0.020–0.100 | 169 |
| Israel | WWTPs | Primary, Secondary, and Tertiary treatments (consist of bar screens, grit removal, primary clarifiers, biological nutrient removal, activated sludge reactors, final clarifiers, effluent filtration, and disinfection | PE (13.9%), PVC (5.9%), PP (2.0%), polycarbonate (1.5%), PFTE (1.0%), polyolefin elastomer (0.5%), PS (0.5%), PUR (0.5%) and nylon 66 (0.5%)–most of the fragments are fibers (74%) | 0.065 microplastics/$m^3$ | 0.00197 microplastics/$m^3$ | 97.0 | 0.2 to 0.45 (with a peak abundance at 0.35) | 226 |
| Australia | Municipal WWTPs | Primary and advanced secondary treatments, which include screening (mesh size of 3 mm) and sedimentation, biological treatment, flocculation, disinfection and de–chlorination processes, ultrafiltration, reverse osmosis, and de–carbonation | PE (10%), PET (80%), PP (10%) | WWTP A – 0.092 microplastics/$m^3$, WWTP B – 0.098 microplastics/$m^3$ and WWTP C – 0.055 microplastics/$m^3$ | WWTP A – 0.00096 microplastics/$m^3$, WWTP B – 0.00098 microplastics/$m^3$ and WWTP C – 0.00091 microplastics/$m^3$ | WWTP A – 97.6%, WWTP B – 90.2%, and WWTP C – 80.4% | 0.10–0.19 | 185 |

**Table 3** (continued)

| Country | Sampling | WWTPs treatments | Most types of microplastics (shape) | Abundance in influent | Abundance in effluent | Efficient removal (%) | Size (mm) | References |
|---|---|---|---|---|---|---|---|---|
| Republic of Korea | WWTPs | Tertiary treatments–used inorganic coagulant followed by ozone (WWTP–A); membrane disc–filter (WWTP–B) and rapid sand filtration (WWTP–C) | Microbeads, fibers, fragments, and sheet | 4.2–31.4 microplastics/$m^3$ | 0.033–0.297 microplastics/$m^3$ | WWTP–A–99.2%; WWTP–B–99.1%; WWTP–C–98.9% | Not mentioned | [170] |
| | Municipal WWTP | Primary, Secondary, and Tertiary treatments, *e.g.*, most of them apply anaerobic–anoxic–aerobic or modified treatment processes | PP (39.6%), PE (25.6%), PET (21.3%), also PS, PMMA, PA, PUR, and polyether–fragments (68.2%), fibers (31.8%) | 0.010 to 0.470 items/$m^3$ | $4\times10^{-6}$ to $5.1\times10^{-4}$ items/$m^3$ | 98.7 to 99.99 (in 31 WWTPs) | 0.045–5.00 | [186] |
| | WWTPs | Until Tertiary treatments, with first physical processes (bar screening, grit removal, and primary clarifier), biological processes, and finally advanced treatment (coagulation and disc filter) | Microbeads, fibers, and fragments | 2.223–10.044 microplastics/$m^3$ | 0.029–0.447 microplastics/$m^3$ | 98–99 | Not mentioned | [227] |
| Sweden | WWTPs | Primary, Secondary, and Tertiary treatments – mechanically, chemically, and biologically (conventional process) | Fibers, fragments, and flakes | $15.1\pm0.89\times10^3$ particles/$m^3$ | $8.25\pm0.85$ particles/$m^3$ | $\approx 99.9$ | $\geq 0.3$ | [100] |
| Canada | Secondary WWTPs | Primary and Secondary treatments (applying oil extraction followed by digestion and vacuum filtration)–Sedimentation | 89.2% of synthetic fibers–made of PS, PES, and PA–fibers (65.6%), fragments (28.1%), and pellets (5.4%), while a small abundance of foam, granules, and sheets (0.22%, 0.45% and 0.20%, respectively) | $0.032\pm0.007$ microplastics/$m^3$ | $5.0\times10^{-4}\pm2.0\times10^{-4}$ microplastics/$m^3$ | 98.3 | $<1.0$ | [228] |
| | Freshwater | Magnetic extraction with coated iron–nanoparticles | PE, PS, PUR, PVC, and PP | Synthetic solution using controlled concentrations of microplastics–0.005, 0.010 particles/L | | 84.0 | $<0.2$–1.0 | [229] |
| Czech Republic | DWTPs | Primary, Secondary, and Tertiary treatments–coagulation and flocculation, flotation, sand filtration, and granular activated carbon filtration | PS ($\leq$68%), PP (16–26%), PE (24%), PAN, polybutylacrylate, PVC, and PMMA ($\leq$5%) | $1.473\pm0.034$ to $3.605\pm0.497$ particles/$m^3$ | $0.338\pm0.076$ to $0.628\pm0.028$ particles/$m^3$ | 70.0 | 0.001–0.01 | [230] |
| India | DWTPs | Primary and Secondary treatments–chlorination, coagulation, pulse clarification, and sand filtration | PE (33%), PET (56%), PP (4%), PS (3%)–fibers (52–59%), films/fragments (41–48%) | 0.0179 items/$m^3$ | 0.0028 items/$m^3$ | 85.39 | 0.025–0.10 | [176] |

**Table 3** (continued)

| Country | Sampling | WWTPs treatments | Most types of microplastics (shape) | Abundance in influent | Abundance in effluent | Efficient removal (%) | Size (mm) | References |
|---|---|---|---|---|---|---|---|---|
| Iran | WWTP | Primary and Secondary treatment processes, including screening (mesh size of 8 mm), grit chamber, and primary sedimentation, followed by aeration, secondary sedimentation, and chlorination process | fibers (73%), film (9%), and granule (17.6%) | $9.2\times10^{-4}$ microplastics/$m^3$ | $8.4\times10^{-4}$ microplastics/$m^3$ | 90.9 | < 0.84 | 231 |
| | Conventional WWTPs | Primary and Secondary treatments–its main units are a bar screen, an aerated grit chamber, a flow metering, a primary settling tank, an anoxic tank, an aeration basin, a clarifier, and a disinfection unit | PET and polyester (73–91%), PMMA, PA, PE, and PP (10%)–essentially fibers | 12,667 microplastics/$m^3$ | $423\pm44.9$ microplastics/$m^3$ | 96.7 | < 0.5 | 232 |
| | Municipal WWTP | Not mentioned | Not mentioned | Average of $0.0545\pm0.0377$ microplastics/$m^3$ | $1.8\times10^{-3}\pm2.0\times10^{-3}$ microplastics/$m^3$ | 96.7 | 0.025–0.3 | 233 |
| Poland | Municipal WWTP | Consists of a mechanical part, a biological part, and a sludge treatment line with a biogas installation | PET (44%), PE (14.15%), PP (8.56%), PS (2.93%), and PUR (2.69%)–fragments (33%), film (12.3%), foam (8.31%) and beads (3.42%) | $4.09\times10^{-3}$ particles/$m^3$ | $2.5\times10^{-4}$ ($\pm4.0\times10^{-5}$) particles/$m^3$ | > 90 | < 1.0 (50.12%) and 0.1–0.2 (30.81%) | 234 |
| Slovenia | Municipal Lab–scale WWTP | Primary (mechanical and biological)–sequencing batch reactor | Microbeads from cosmetics | Synthetic solution with an Microplastic concentration of $5\times10^{-4}$ g/$m^3$ | 21 particles/$m^3$ | 52.0 | ≈ 0.1 | 235 |
| Turkey | WWTPs | Primary and Secondary treatments | PP (13.8%), PET (50%), PE (29%)–fibers (55–88%), film (2.5–18%), fragment (10–27%) | Seyhan WWTP (4 825 697 ± 575 630 microplastics per day); Yüreğir WWTP (2 040 639 ± 343 859 microplastics/day) | Seyhan WWTPs (1 249 102 ± 146 373 microplastics per day); Yüreğir WWTPs (351 019 ± 26 800 microplastics/day) | Yüreğir WWTPs (79.0%) and Seyhan WWTPs (73.0%) | < 5.0 | 236 |
| | Municipal WWTP | Primary and Secondary treatments–including screens, aerated grit chambers, and conventional activated sludge | PE (54.5%), EVA (37.84%)–essentially fibers (41.78–60.77%) | 4.80 particles/$m^3$ | 0.14 particles/$m^3$ | 97.08 | 0.1–0.5 (58.57–80.07%) | 237 |
| | WWTPs | Primary, Secondary and Tertiary treatments–including anaerobic oxidation and membrane bioreactor | PE (28%) and PET (28%), PA (21%), PP (9%), PVC (8%) and PES (6%)–fiber, fragment and fiber | 0.040 to 0.079 particles/$m^3$ | 0.0004 to 0.0056 particles/$m^3$ | Membrane bioreactor (99%); trickling filter (98%) and activated sludge process (91%) | 0.5–1.0 | 238 |
| Vietnam | Four Municipal WWTPs | Primary, Secondary, and Tertiary treatments (including CAS treatment, a sequencing batch reactor coupled with a UV channel, and trickling filters followed by aerated lagoons and maturation ponds) | Fragments and fibers | 1860 items/$m^3$ to 125 000 items/$m^3$ | 140 items/$m^3$ and 813 items/$m^3$ | 69–99 | Average 1.0 | 239 |

**Table 3** (continued)

| Country | Sampling | WWTPs treatments | Most types of microplastics (shape) | Abundance in influent | Abundance in effluent | Efficient removal (%) | Size (mm) | References |
|---|---|---|---|---|---|---|---|---|
| Indonesia | Municipal WWTP | Primary and Secondary treatments–including Moving Bed Biofilm Reactor and a High Rate Clarifier | fibers (68–70.17%), fragments (23.68–26.24%), films (0.71–2.9%), microbeads (0.4–1.4%) and foams (1.4–2.8%) | 0.017 (±0.006) items/$m^3$ | 0.0014 (±0.0001) items/$m^3$ | Setiabudi WWTP–91.29 | 0.1–5.0 | [240] |
| Bangladesh | 3 DWTPs | Primary, Secondary, and Tertiary treatments | PP (48%), PE (35%), PET (11%), and PS (6%)–fragments were (90%), fibers (10%) | DWTP–A and DWTP–B–$2.6\times10^{-2}\pm1.0\times10^{-2}$ items/$m^3$ and DWTP–C–$6.2\times10^{-3}\pm1.6\times10^{-3}$ items/$m^3$ | DWTP–A and DWTP–B–$3.0\times10^{-4}\pm3.0\times10^{-5}$ and DWTP–C–$4.0\times10^{-4}\pm1.0\times10^{-5}$–$5.0\times10^{-4}\pm2.0\times10^{-4}$ items/$m^3$ | Up to 99% | 0.02–5.0 | [241] |
| Lithuania | Secondary WTTP | Primary and Secondary treatments | PP, PE, and PS, being essentially fibers and fragments | 0.08 to 0.34 particles/$m^3$ | 0.012–0.025 particles/$m^3$ | 55.4±3.9 | 0.02–1.0 | [242] |
| Fiji | Two municipal WWTPs–Kinoya and Natabua | Primary and Secondary treatments (including simple secondary clarifier, trickling filter, and Anaerobic pond) | Cellophane, PP, polyester, and polyvinyl acetate–ethylene–fibers and fragments (both 44%) | Kinoia–$3.45\pm0.3\times10^{-3}$ particles/$m^3$ Natabua–$2.9\pm1.1\times10^{-3}$ particles/$m^3$ | Kinoia – $0.3\pm0.26\times10^{-3}$ particles/$m^3$ Natabua–$0.53\pm0.42\times10^{-3}$ particles/$m^3$ | Kinoia–91% Natabua–81% | 0.25 (67%) and 2.0 (33%) | [243] |
| Marocco | Urban and Industrial WWTPs | One WWTP, utilized lamellar decantation and a submarine emissary, and the other used activated sludge | PE (29–20%), PET (21–24%), PP (10–8%), PVC (11–9%), PS (9–12%), PA (10–6%), ethylene–vinyl acetate (8–13%), and HDPE (2–8%)–fibers, fragments, films, and pellets | 1.114±0.090 particles/$m^3$ | 0.607±0.101 particles/$m^3$ | 46 | 0.1–0.5 | [244] |
| Kazakhstan | Municipal WWTP | Constituted with mechanical treatment, primary and secondary sedimentation, biological treatment (Oxidation process), subsequent coagulation, floatation, granular filtration, and UV disinfection | PE, PET, PS, PVC, PA, PP, polyester, and ethylene–acrylic acid copolymer–fibers, fragments, and films | 0.0471±0.0376 microplastics/ $m^3$ to 0.0694±0.0400 microplastics/ $m^3$ | 0.0041±0.0031 microplastics/ $m^3$ to 0.0054±0.0035 microplastics/ $m^3$ | Between 88.6–93.0 | 0.1–0.5 (66.45–75.13%) | [245] |
| Oman | Three Municipal WWTPs | Until tertiary treatments–WWTP–A (with CAS); WWTP–B (Sequencing Batch Reactor); WWTP–C (with MBR) | PP, LDPE, PUR, PET, and PVC–fiber (60.7%) | WWTP–A–$3.6–8.5\times10^{-3}$ particles/$m^3$, WWTP–B – $4.6–8.7\times10^{-3}$ particles/$m^3$, and WWTP–C–$3.6–7.1\times10^{-3}$ particles/$m^3$ | WWTP–A–$1.0\times10^{-3}$ particles/$m^3$, WWTP–B–$1.4\times10^{-3}$ particles/$m^3$, and WWTP–C–$1.0\times10^{-3}$ particles/$m^3$ | WWTP–A (82.5%), WWTP–B (77.4%), and WWTP–C (79.2%), | Average 0.045–0.425 | [246] |
| Nepal | WWTPs | Primary and Secondary treatments (including secondary aeration tank) | Essentially PE and PS–fiber, fragments, foam, and pellets | 0.0312±0.0173 particles/$m^3$ | $8.50\times10^{-3}\pm5.60\times10^{-3}$ particles/$m^3$ | 72.5 | Most common 0.15–5.0 | [247] |
| Kuwait | Three municipal WWTPs | Primary, Secondary, and Tertiary treatments (including reverse osmosis, ultrafiltration membranes, an oxidation ditch system for secondary treatment, sand filtration, UV, and chlorination as tertiary treatment) | PA (≈ 55%), PP (≈ 30%), and PE (≈ 15%)–fiber (78–84%), fragment (13–20%), and films (2–4%) | 0.119 to 0.230 particles/$m^3$ | 0.001 to 0.012 particles/$m^3$ | 81.3% | Essentially 0.063–0.333 | [248] |

Regarding the potential adsorption of microplastics with toxic heavy metals and other emerging contaminants, recent research indicates an increased risk to human health, as these particles may enter the food and water supply chain [13, 142, 146, 147, 152, 153]. The aggregation of microplastics in various environmental media (freshwater, soils, and so on) highlights their role as vectors for the persistence of other emerging contaminants [144]. Moreover, the prevalence of microplastics in agricultural drainage water, in groundwater supplies, and in drinking and tap water [12, 13, 119, 154–159] directly impacts human health. Several polymers have been detected in human tissues or blood [30, 160, 161]. Certain microplastics, *e.g.*, polypropylene (PP), polyethylene (PE), polyethylene terephthalate (PET), and polyamide (PA) have also been reported in bottled water, whether in plastic, glass, or cardboard bottles [13, 154, 162–164]. Hence, the efficient removal of microplastics from wastewater is crucial, despite the lack of high-efficiency treatments in wastewater treatment plants or drinking water treatment plants (DWTPs) (Table 3).

In some conventional or municipal wastewater treatment plants, performing a primary, secondary, and often advanced tertiary treatment is necessary to remove microplastics efficiently [137, 165]. Pretreatment processes can remove between 35 and 59% of the plastic particles in conventional wastewater treatment plants, but, when combined with primary treatment, are responsible for the removal of the majority of microplastics (estimated between 50 and 98%), with only the smallest particles remaining in the wastewater [137, 165]. Secondary treatment yields an additional removal of 0.2–14%. Finally, tertiary treatments can contribute to a high-efficiency elimination of the smallest particles [137, 165].

In recent years, numerous techniques have been developed or improved in wastewater treatment plants to remove microplastics, depending on the design of the wastewater treatment plant and its location or population density (Table 3). These techniques include grit chamber and primary sedimentation [136, 166, 167], precipitation [168], dissolved air flotation [169], coagulation [170, 171], electrocoagulation [172, 173], electrostatic forces [174], sand filtration [175], rapid (gravity) sand filter (RSF) [170, 176], ultrafiltration [177], activated sludge process [178, 179], membrane bioreactor (MBR) [167, 169, 180–183], reverse osmosis [184, 185], anaerobic-anoxic-aerobic ($A^2O$) treatments [186–188], and ozonation [175]. The efficiency of wastewater microplastics removal (Table 3) is very uneven, with lower rates obtained in conventional wastewater treatment plants [189], contrasting with high-efficiency removal rates of 99.9% obtained in tertiary wastewater treatment plants that have implemented new methodologies, *e.g.*, implemented MBR [169, 186]. Chemical precipitation, *e.g.*, with aluminum, ultrafiltration, and $A^2O$ treatments can also eliminate the microplastics most commonly found in wastewater, with removal percentages of 99.2%, 97%, and 98.5–99.9%, respectively. It should also be noted that electrocoagulation treatment can be another alternative method (91–99.24%), but the studies performed so far have been on synthetic solutions with controlled microplastics concentrations [172, 173, 190].

On the other hand, in terms of biological treatments, MBR is considered one of the methods that can lead to high microplastics removal yields (between 94 and 99.9%). For instance, Talvite et al. [169] achieved 99.9% efficiency of the treatment compared to other methodologies applied in wastewater treatment plants, such as RSF (97%), dissolved air flotation (DAF, 95%), and disc filter (98.5%). Moreover, by comparing the performance of MBR against two conventional wastewater treatment plants, a 99.4% yield was obtained [182]. A cost-effectiveness analysis by Vuori et al. [190] concluded that treating wastewater by MBR to mitigate microplastics pollution provides higher cost savings in both private and social costs, compared to the implementation of conventional activated sludge (CAS) or RSF, which have a lower removal efficiency (88% to 97.1%, respectively) and a higher environmental impact [190]. Even so, despite proving to be an efficient method for lower-capacity wastewater treatment plants (with tertiary treatments implemented), the incorporation of MBR into tertiary treatment in wastewater treatment plants entails prohibitive energy costs and difficulties in controlling fouling. Moreover, there are gaps related to the low cleaning efficiency of the membranes, the failure to obtain ecological status, and, above all, the absence of specificity for microplastics removal [191–193].

Overall, the methods currently used in wastewater treatment plants have several limitations, *e.g.*, process costs, modest removal efficiency, lack of environment-friendly status, and the absence of specificity regarding the microplastics problem, boosting the necessity of developing new technologies and approaches. As such, efforts are underway to enhance existing water treatment processes and develop new, cost-effective, and efficient technologies for sustainable water treatment. These efforts focus on using advanced materials and technologies such as protein nanofibrils, metal–organic frameworks (MOFs), covalent organic frameworks, nanocomposites, fluorous oligoamide nanorings, and bio-based materials (such as agricultural residues, algae, bacteria, and fungi) [194, 195].

Given the necessity for sustainable and cost-effective methods to remove microplastics from aquatic environments, the use of microorganisms has gained attention in the scientific community for biodegradation and retention of microplastics present in wastewater, considering their abundance in wastewater [196, 197]. Biostimulation and bioaugmentation, mainly involving fungi and bacterial species, are being explored as bioremediation strategies for microplastics.

These bioremediation approaches are influenced by a wide range of biotic (the species of microorganisms and the number of living cells, the interactions in microbial consortia, cell hydrophobicity, and enzymatic diversity) and abiotic factors (UV light, pH, temperature, and oxygen ($O_2$) concentration, among others) [198, 199].

Some microorganisms can biodegrade microplastics in aquatic environments by breaking down the complex polymerized structure of plastics into smaller molecules (into their monomers), through the secretion of intracellular or extracellular enzymes, such as polyhydroxybutyrate (PHB), poly(3–hydroxybutyrate–co–3–hydroxyvalerate) (PHBV), or poly(3–hydroxyalkanoate) (PHA), among others [200]. This biodegradation process involves the first stage where biofilms form on the plastic fragment, followed by biofragmentation which involves the secretion of enzymes by the microorganisms surrounding the plastic particles [201, 202]. The third step is the assimilation (polymer degradation to monomers) and culminates in the mineralization process, with the synthesis of secondary metabolites such as carbon dioxide ($CO_2$), water ($H_2O$), and methane ($CH_4$) [198–200, 203]. For instance, Miloloža et al. [199] underlined that biodegradation of microplastics by microorganisms depends on many factors, such as the metabolic versatility of microorganisms, environmental factors, and the physicochemical characteristics of the polymers that constitute the plastics (Table 1).

The concentration of microplastics entering municipal wastewater treatment plants ranges from very low to extremely high concentrations-from $2.8 \times 10^{-4}$ microplastics per $m^{-3}$ to very high concentrations of $55 \times 10^4$ microplastics per $m^3$ (Fig. 2). The abundance of plastic particles in the influent is influenced by the type and capacity of wastewater treatment plant, but more importantly, by the population density (Table 3). In the effluent, the concentrations are much lower, ranging from $1.0 \times 10^{-6}$ microplastics per $m^{-3}$ to $14–50 \times 10^3$ microplastics per $m^{-3}$, depending on the treatment stages (pretreatment, primary, secondary, and tertiary processes) that yield the overall efficiency of the method. The morphology (shape and size) as well as PE–polyethylene; PP–polypropylene; PLA–polylactide; PA–polyamide; PS–polystyrene; PUR–polyurethanes; PVC–polyvinyl chloride; PET–polyethylene terephthalate; PAN–polyacrylonitrile; PMMA–polymethyl methacrylate; PTFE–polytetrafluoroethylene; LDPE–low–density polyethylene; HDPE–high–density polyethylene; EVA–Ethylene–vinyl acetate; WWTPs–wastewater treatment plants; DWTPs–drinking water treatment plants; CAS–conventional activated sludge; AnMBR–anaerobic membrane bioreactor; MBR–membrane bioreactor; UF–ultrafiltration; UV–ultraviolet; UASB–pilot–scale up flow granular sludge blanket; WWTPs–A, B, C or D–different WWTPs in the same city or country the type of plastic polymer also affects the performance of the remediation methods. The fibers are the most common shape detected in wastewater treatment plant systems, and the sizes of microplastics are on average less than 0.5 mm, being polyethylene (PE), polypropylene (PP), polystyrene (PS), polyesters (PES), and polyethylene terephthalate (PET) as the most commonly detected polymers (Table 3). As such, the currently implemented wastewater treatment processes are not properly designed to remove microplastics, showing a lack of specificity for microplastics structures and shapes [137, 249]. These lack specificity for microscopic-sized particles, making them environmentally unfriendly and economically unsustainable due to their reliance on complex multi-step processes and chemical treatments, as reviewed by several authors [17, 176, 249, 250]. Moreover, the energy used in conventional wastewater treatment operations is remarkable (represents an estimation of 2% to 4% of a country's electricity consumption) [196, 251]. Given the current limitations in removing microplastics from wastewater, alternative processes, such as the use of microalgae-based systems, have gained attention as more sustainable and efficient options [252–254].

## Microalgae potential for microplastic removal

While numerous well-explored studies focus on the advantages of using microorganisms for the bioremediation of microplastics in soils and aquatic environments, predominantly marine, they primarily concentrate on employing various species of bacteria, some fungi, and other larger eukaryotic organisms for the biodegradation of plastic particles [198, 200, 255]. Several studies have emerged exploring the potential of these microorganisms for biological treatment within wastewater treatment plants, targeting heavy metals, organic pollutants, and, more recently, microplastics [165, 196, 256, 257]. For instance, Nyika et al. [196] discussed the role of specific microorganisms, mainly bacteria and fungi, in wastewater bioremediation, to eliminate heavy metals, dyes, or persistent organic pollutants. The authors covered general factors that influence these treatments, such as the physicochemical bioavailability of contaminants, the nature of the contaminant (chemical structure, concentration, solubility, and toxicity), environmental and microbial properties (enzyme induction, level of mutation), and co-metabolism versus growth substrate (associated to predation, succession, and competition during microbial interaction). In the same line, Tang and Hadibarata [202] discussed the potential and limitations of applying bioremediation as a secondary or tertiary treatment in wastewater treatment plants, but with the main purpose of microplastics removal. That study focused on bacteria, *e.g.*, *Vibrio*, *Bacillus*, *Acetobacteriodes*, *Saccharomonospora*, *Rhodococcus*, and *Pseudomonas*, and

fungi, *e.g.*, *Penicillium*, *Aspergillus*, and *Fusarium*, with the potential to degrade polymers, exhibiting efficiencies ranging between 8.46% and 36.4%, depending on the type of plastic, the conditions employed, and microbial species [202]. Though, these processes are time-consuming, more than 40 days are necessary before any degradation or removal of these polymers occurs [202].

In addition to bacterial and fungal species, microalgae possess a high potential for the removal and biodegradation of microplastics in wastewater [258]. When compared to bioremediation systems relying on bacteria, microalgae offer several advantages in wastewater treatment. Microalgae exhibit remarkable adaptability to their environment, efficiently removing nutrients, displaying high seasonal tolerance, and showcasing superior metabolic performance concerning nutrients commonly found in wastewater [202, 251, 256]. Furthermore, microalgae generate less sludge and demonstrate significantly better tolerance to other emerging contaminants, such as pharmaceuticals and personal care products [125, 251, 259]. The exploration of microalgae-based systems for wastewater biological treatment is novel and has the potential to yield environmentally friendly and sustainable processes [254]. These systems yield high-value end products and use relatively straightforward microorganisms to integrate into existing wastewater systems (Fig. 3) [251].

Microalgae are a diverse category of photosynthetic microorganisms, either eukaryotic or prokaryotic, which can use the sunlight that illuminates the surface of wastewater as an energy source, coupled with the capture of atmospheric carbon dioxide ($CO_2$) for their basic metabolism and growth [254, 261, 262]. Active green (*Chlorophyta*), red (*Rhodophyta*), and brown (*Phaeophyta*) algae are commonly identified as belonging to the category of photosynthetic microorganisms, as well as cyanobacteria [263]. These microorganisms are metabolically flexible with photoautotrophic, mixotrophic, or heterotrophic metabolism and can adapt to a variety of water environments, even those with extreme growth conditions (*i.e.* highly saline water) [258, 264]. Furthermore, the biomass derived from microalgae in wastewater holds substantial potential for diverse applications in sustainable product development. It can serve as a source for extracting high-value compounds like proteins, polysaccharides, fatty acids, and vitamins, among others, catering to various biotechnological uses [254, 263, 265]. For instance, in the green industry, this biomass can contribute to the production of biofuel or biogas. Additionally, it finds utility as feed for fish and animals, biofertilizers, food ingredients, bioplastics, cosmetics, and biopharmaceutical drugs, and aids in carbon dioxide ($CO_2$) mitigation, promoting industrial sustainability and embracing the concept of a circular economy with its "zero-waste" concept (Fig. 3) [254, 263, 265, 266]. Hence, microalgae not only extract nutrients (such as nitrogen and phosphorus) from wastewater for their growth and metabolism but also exhibit remarkable resilience to highly toxic wastewater conditions. This versatility highlights microalgae as efficient biological systems capable of effectively treating various types of effluents within wastewater treatment plants.

Moreover, microalgae have a high potential to remove different types of emerging contaminants found in wastewater [267], including heavy metals (by adsorption and uptake), persistent organic pollutants (by bioaccumulation, biosorption, and metabolization), and controlling pathogen growth (by increasing pH and temperature, and excreting growth inhibitory metabolites) [254] and more recently microplastics [200, 268]. As such, microalgae-based biological treatment systems offer lower capital and operational costs, short growth cycles, ease of operation, and environmentally friendly processes (Fig. 3) [258, 269, 270].

More recently, a novel biotechnological approach has emerged, focusing on studying microalgae capacity to stimulate the synthesis of specific enzymes, *e.g.*, polyethylene terephthalate (PET) hydrolase (PETase), superoxide dismutase, mono(2-hydroxyethyl) terephthalic acid hydrolase (MHETase), cutinases, esterases, and lipases, among others, for plastic decomposition and disposal. These enzymes can be further genetically modified for that purpose [201, 271–276]. Synthetic enzymes represent a promising application in the bioremediation of microplastics, potentially playing a pivotal role in the removal or elimination of microplastics from wastewater [201].

On the other hand, microalgae, with their uncomplicated genetic structure, are amenable to genetic manipulation to produce and secrete enzymes responsible for breaking down or eliminating microplastics [201]. This genomic and post-genomic approach, known as Algomics, is highly important for understanding algal cellular mechanisms [201, 277]. *C. reinhardtii* and *Phaeodactylum tricornutum* are microalgae that, despite inhabiting different aquatic environments, can express specific enzymes to degrade microplastics by being genetically manipulated [273, 275]. Kim et al. [273] demonstrated that *C. reinhardtii* strain CC-124 was able to synthesize a PETase, which is responsible for hydrolyzing polyethylene terephthalate (PET). After a period of 4 weeks of catalytic activity of PETase, through the interaction between *C. reinhardtii* and the microplastic, it was possible to detect the release of terephthalic acid, one of the metabolites of polyethylene terephthalate (PET) polymer degradation, a process which was corroborated by scanning electron microscopy (SEM) inspections that confirmed morphological changes on the surface of the microplastic. This was the first report showing the success of a microalga-based PETase in microplastic degradation. Moreover, in Moog et al. [275], *P. tricornutum* was used as a microbial cell factory to produce and secrete engineered PETase under

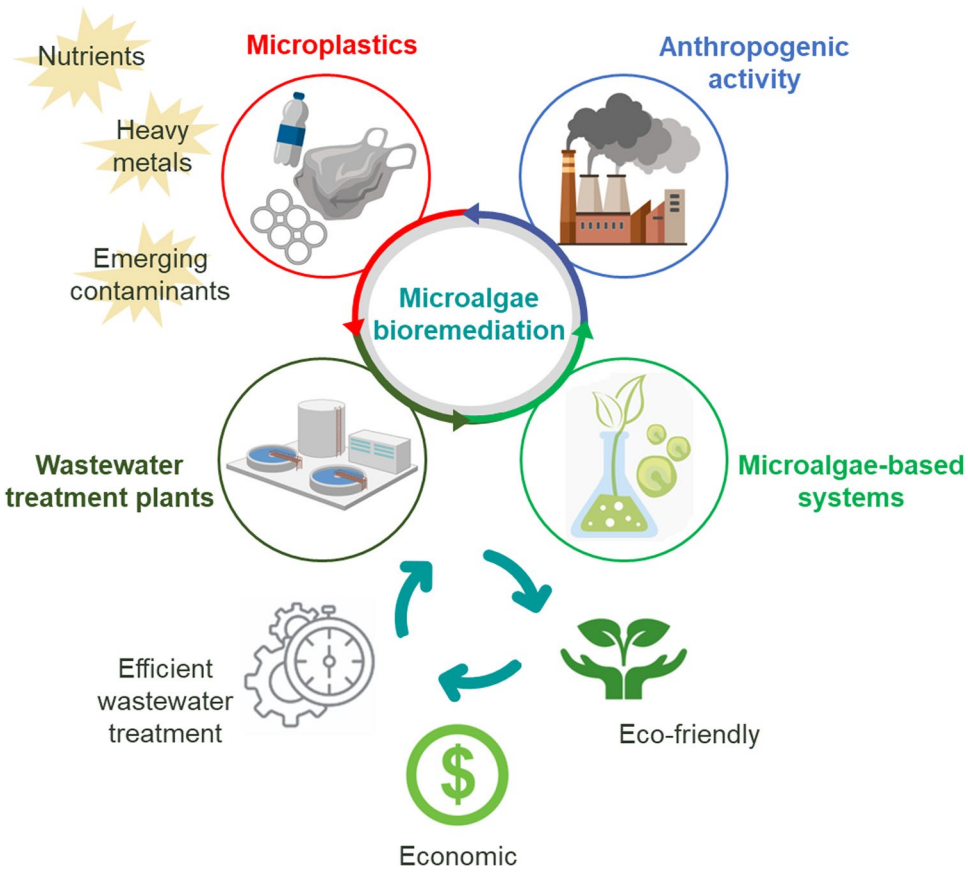


**Fig. 3** "Zero waste" concept where microalgae–based bioremediation is evolving as a promising strategy for removing emerging contaminants, including microplastics, from wastewater. This approach offers advantages over traditional approaches like low costs, fast growth, and eco–friendly processes. Microalgae use the contaminants as a carbon source necessary for microalgal growth, resulting in high–value biomass or compounds (*i.e.* vitamins and lipids). By incorporating these systems into wastewater treatment, the industry can move closer to the zero–waste concept, promoting both sustainability and improving water quality [adapted from Srimongkol et al. [260]]

saltwater mesophilic conditions. The approach consisted of adapting the gene sequence encoding PETase$^{R280A}$ (previously sequenced in the bacteria *Ideonella sakaiensis* [278]) and transferring it to *P. tricornutum* (PETase$^{R280A}$-FLAG) to study its biodegradation of polyethylene terephthalate (PET) and the copolymer polyethylene terephthalate glycol. After 5 weeks of incubation of the microplastic fragments with the marine diatom, it was observed that the enzyme was actively biodegrading the polymer, and products from the polyethylene terephthalate (PET) substrate degradation process, TPA and mono(2-hydroxyethyl) terephthalic acid, were detected. This study proposed that microalgae can be an alternative model for the synthetic biology of polyethylene terephthalate (PET) degradation enzymes compared to bacteria from aquatic environments [275].

The metabolic engineering of microalgae to produce specific enzymes presents a promising approach to develop proficient microorganisms for microplastics removal from aquatic environments. Other studies assessing the potential of microalgae to transform microplastics include the use of *Spirulina* sp. which was able to synthesize extracellular enzymes to degrade or adsorb polyethylene terephthalate (PET) and polypropylene (PP) microparticles [276, 279], while *C. vulgaris* was found to be able to degrade bisphenol-A, an additive compound present in polycarbonate, polyacrylates, and polyesters [280, 281], without estrogenic activity [271, 276].

## Selecting microalgae species for wastewater treatment

The selection of suitable microalgae species for wastewater treatment involves crucial criteria, particularly their ability to grow in a diversity of process conditions and to form harmless algal blooms [282]. Wastewater is a complex mixture of various substances that can vary widely in composition and typically includes organic matter, inorganic compounds (such as metals), nutrients (namely nitrogen and phosphorus), and other pollutants, *e.g.*, personal care and pharmaceutical products, and plastics [254, 283]. As such, the wastewater complex composition can be toxic to microalgae and/or unsuitable for their growth [260, 263].

Out of the thousands of known microalgae strains (approximately 300,000), the initial screening process should be focused on selecting strains that predominantly thrive in freshwater environments and can adapt to growth in the wastewater [284]. Also, microalgae require nutrients (namely nitrogen and phosphorus) and specific oligoelements, *e.g.*, iron, manganese, copper, and zinc, to replicate [254] and these are readily available in wastewater. However,

high concentrations of heavy metals can be present in wastewater which can inhibit microalgae growth [285]. For example, copper, when present at high concentrations in wastewater, can significantly decrease the biomass concentration, chlorophyll, and carotenoid content [286]. In fact, according to a toxicological study performed by Cid et al. [287], concentrations of copper above 0.1 mg/L in aquatic environments can be toxic to microalgae, reducing their growth by 50%, and at concentrations higher than 1.0 mg/L, it can inhibit completely their growth. Also, other factors characteristic of wastewater have to be considered since different microalgae have specific process requirements: pH levels (with ideal values ranging between 6 and 9, but some species survive in an acidic pH), organic matter availability, irradiation duration, and intensity (directly related to photosynthesis), the concentration of atmospheric carbon dioxide ($CO_2$), turbulence, and the water temperature [254, 263].

An essential criterion in choosing strains for phytoremediation processes is avoiding the formation of harmful algal blooms (HABs) [254, 288]. According to the Environmental Protection Agency (EPA) [289], the excessive abundance of nitrogen and phosphorus (the main nutrients) in the receiving water can lead to eutrophication, causing a rapid overgrowth of microalgae in a short time. This overgrowth consumes significant amounts of oxygen ($O_2$) in the environment, making it inhospitable for other life forms to survive. In some cases, there is a production of chemicals, metabolites, or toxic compounds that are harmful to aquatic life and human health (through contaminating the drinking water), causing significant negative impacts on the environmental health, ecosystems, and economy [290]. Therefore, microalgae species must selected based on their harmless to the surrounding environment character and incapability to form HABs [254, 288]. Considering these criteria, microalgae typically tested for wastewater bioremediation belong to the genera *Chlorella*, *Scenedesmus*, *Desmodesmus*, *Neochloris*, *Nitzschia*, *Cosmarium*, and *Chlamydomonas* [254].

## Toxicological profile

While microalgae can endure harsh conditions in wastewater [254, 265, 291], it is crucial to consider the influence of microplastics on their growth and metabolic activity. A wide variety of studies analyzing the microplastics toxicity and ecotoxicity have been done involving different microalgae species, including freshwater strains (as environmental model organisms), with different types and concentrations of microplastics [142, 274, 292–301]. According to Prata et al. [298], microplastics have negative impacts on microalgae metabolism, photosynthesis, and morphology. In fact, microplastics can decrease the growth of some microalgae, potentially inhibiting growth when high concentrations of microplastics or nanosized particles are present [296].

For instance, the presence of polystyrene (PS) decreased the growth of *Scenedesmus obliquus* (about 2.5% at 1000 mg/L), *Pseudokirchneriella subcapitata* (concentrations between 1 and 100 mg/L), *C. reinhardtii* (an $EC_{50}$ of 0.54 mg/L), *Chlorella pyrenoidosa* (until 22 days) [298], and *Chlorella vulgaris* (26.9% at 35 particles/L) [301]. According to Rani-Borges et al. (2021), 78 days after contact with these emerging contaminants (PS, polypropylene (PP), polyvinyl chloride (PVC), polyethylene (PE), polyethylene terephthalate (PET), and polyamide (PA)), growth was reduced in most microalgae species, *e.g.*, *P. subcapitata*, *C. reinhardtii*, *Chlamydomonas pyrenoidosa*, and *Scenedesmus obliquus*. Their interaction can also lead to a subsequent decrease in chlorophyll content and photosynthetic activity (affecting the photosynthetic efficiency), either by acting as inhibitors of microalgae growth, or by the shadow effect they can cause in the aquatic environment (by decreasing the amount of light falling on the microalgae), or by the potential to decrease the expression of photosynthetic genes [201]. It is worth noting the capacity of polystyrene (PS) to decrease the polysaccharide content of extracellular polymeric substances (EPS) per cell of *C. vulgaris*, its total CYP450 content, and total CYP450 activity, as well as completely downregulating the expression on key genes related to algal cell metabolic activity, *e.g.*, *psbA*, *psaB*, and *rbc* [301]. Also, microplastics can exert adverse effects on different stages of the photosynthesis process in microalgae-from the electron donor site to the electron transport chain, leading to oxidative stress. At the morphological level, severe consequences can occur, *e.g.*, including unclear pyrenoids, plasma detached from the cell wall, deformed thylakoids, and cell wall thickening, and modulated energy metabolism [201, 296, 298]. Similarly, polystyrene microplastics were responsible for a 40% decrease in chlorophyll content in *S. obliquus* (at a concentration $\geq$ 100 mg/L [302]) and *C. pyrenoidosa* (up to 10 days, at a concentration of 50 mg/L) [292]. Other microplastics have been studied for their ecotoxicological impact on microalgae, including polypropylene (PP), high-density polyethylene (HDPE), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyethylene (PE), and polyacrylonitrile (PAN) [296, 299, 303, 304] which were found to inhibit growth, reduce photosynthetic activity, affect enzymatic activity, and alter cell morphology [296, 299, 303, 304].

The toxicological effects of microplastics on microalgae depend on a diversity of factors such as the size and shape of the plastic particles, polymer type, exposure time, and even the surrounding environment [298, 299]. These toxicological studies show that smaller particles tend to be more toxic to microalgae, due to the capacity for adsorption to the cell surface [296]. It is noteworthy that the toxicological impacts on microalgae may be temporary, with an initial high vulnerability followed by adaptive responses to the adverse

conditions [296, 305]. The hypothetical mechanisms for their detoxification can be via homo-aggregation or hetero-aggregation to microplastics as well as the development of biofilms on the surface of the microplastics to enhance nutrient use in the aquatic environment [296, 298, 305].

Therefore, choosing the most suitable microalgae for specific bioremediation treatments to eliminate microplastics from wastewater demands a thorough consideration of this toxicological profile and the aforementioned selection criteria. This selection process requires an understanding of how these microorganisms interact with the surfaces of microplastics, along with a keen awareness of the toxic effects these pollutants may have on the microalgae species selected.

## Microalgae-microplastics interaction

Regarding the removal of microplastics, an important characteristic of these microorganisms when interacting with the surface of microplastics (Fig. 4) is the ability to form hetero-aggregates, by secreting extracellular polymeric substances, as part of the biofouling formation process [296, 306]. Manzi et al. [201] found that the most common mechanisms to remove microplastics using microalgae entail colonization, aggregation, and adsorption processes. Aggregation is the most plausible mechanism for application to wastewater treatment plants since it entails reduced adverse effects on the microalgae [201]. These authors further verified the ability of microalgae to aggregate on microplastics to form hetero-aggregates and the ability to colonize the surface of the microplastics inducing changes in the chemical structure of the plastic and initiating the removal process by aggregation [201]. Moreover, Cunha et al. [307] reported the interaction between freshwater microalgae (*Microcystis paniformis* and *Scenedesmus* sp.) and microplastics, and found that microalgae were able to colonize microplastics of polystyrene (PS) and polymethyl methacrylate (PMMA), leading to the formation of hetero-aggregates. *C. reinhardtii* was able to form aggregates on polypropylene (PP) microparticles after 20 days of exposure [303]. However, no hetero-aggregate formation occurred on high-density polyethylene (HDPE) surfaces. These authors hypothesized that microalgae can produce different types of extracellular polymeric substances depending on the type of polymer, resulting in higher affinity and cohesion for certain microplastics [303]. Other studies also support the high aggregation ability of freshwater microalgae to the surface of diverse microplastics, such as low-density polyethylene (LDPE) [308], polystyrene (PS) [268, 309], polymethyl methacrylate (PMMA) [309], and polylactide (PLA) [309].

Regarding the removal of plastics from wastewater, Kumar et al. [310] and Sarmah et al. [311] investigated the effectiveness of different species of photosynthetic microorganisms (such as *Scenedesmus dimorphus*-a green microalga, *Anabaena spiroides*-a blue-green alga, and *Navicula pupula*-a diatom) to degrade low-density polyethylene (LDPE) and high-density polyethylene (HDPE). These three photosynthetic microorganisms were more prone to form hetero-aggregates on the surface of low-density polyethylene (LDPE) fragments than on the high-density polyethylene (HDPE) surface, with *A. spiroides* being the most prone of the three species to colonize low-density polyethylene (LDPE) [310]. Through SEM analysis and mass balance of the polyethylene (PE) fragments, the highest biodegradation efficiency was achieved by *A. spiroides* ($8.18 \pm 0.07\%$), followed by *N. pupula* contributing ($4.44 \pm 0.82\%$) and *S. dimorphus* ($3.74 \pm 0.26\%$). However, a higher biodegradation performance of low-density polyethylene (LDPE) was obtained by the two cyanobacteria, *Phormidium lucidum* and *Oscillatoria subbrevis* [311]. After 42 days of exposure, a 30% weight loss of low-density polyethylene (LDPE) was estimated by Fourier-transform infrared spectroscopy (FTIR) analysis, demonstrating a decrease in intensity of some characteristic peaks of polyethylene (PE), *e.g.*, 2364 $cm^{-1}$, after being incubated with these two cyanobacteria. With complimentary thermogravimetric-differential scanning calorimetry (TGA–DSC) analysis and carbon/hydrogen/nitrogen elemental analysis, it was possible to verify that in the particles degraded the total carbon percentage was reduced (3%–4%) and the melting point of the polymer decreased [310]. This could mean that the microplastics are used as a carbon source for their growth and metabolic activity, leading to the biodegradation of the polymers. *Chlorella* sp. in a consortium with a cyanobacterium also showed the potential to degrade low-density polyethylene (LDPE) bag particles [308]. The microalgae can colonize, aggregate, and adhere to the surface of low-density polyethylene (LDPE) microparticles, with support from *Cyanobacteria* sp. through the production of extracellular polymeric substances that facilitates the adhesion of *Chlorella* sp. Through field-emission scanning electron microscopy-energy dispersive X-ray (FESEM-EDX) analysis, complemented with FTIR, carbon analysis, and differential scanning calorimetry (DSC), Govindan et al. [308] estimated that approximately 38% of the amount of carbon decreased after hetero-aggregation of the consortium of these two microorganisms.

For the same type of microplastic source, the green microalgae *Uronema africanum* Borge also demonstrated to be of interest to biodegrade these polymers in a laboratory-scale context [313]. Although the biodegradation efficiency of microplastics in the 30-day trial (by carbon proportion) was not estimated, atomic force microscopy (AFM) and SEM analyses, along with gas chromatography-mass spectrometry (GC–MS) and FTIR, revealed that the microalgae can initiate the colonization and degradation of low-density polyethylene (LDPE) bags. In overview, this aggregation

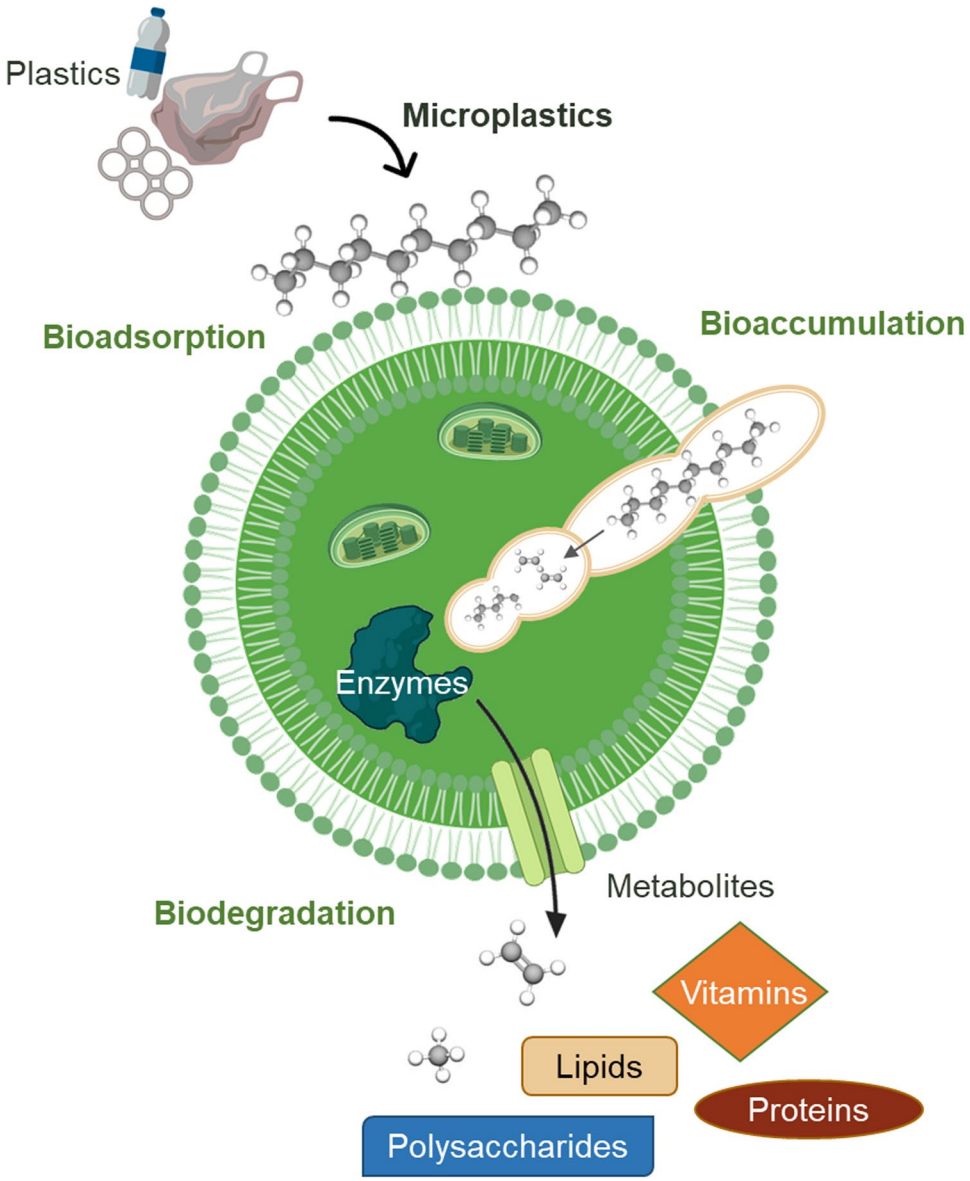


**Fig. 4** Three mechanisms used by microalgae to remove microplastics: bioadsorption, biodegradation, and bioaccumulation. Through microalgae metabolism, several metabolites can be formed by microplastic degradation (*i.e.* microplastic monomers, including propylene, phenol, and ethylene) along with high–value products such as lipids, vitamins, proteins, and polysaccharides [adapted from Rempel et al. [312]]

process enables the microalgae to act as a flocculant, causing precipitation or sedimentation of microplastics in the water system [306, 314]. So, from a treatment point of view, this strategy may hold the potential to be applied in wastewater treatment plants to remove microplastics, causing the microplastic-algal flocks to sediment and subsequently be removed through simple physical techniques, *e.g.*, settling.

Other removal mechanisms of emerging contaminants from wastewater by microalgae-based systems include bioaccumulation, bioadsorption, biodegradation, photolysis, hydrolysis, and volatilization [265, 269, 270, 282, 315]. Concerning bioremediation, three process pathways are feasible: bioadsorption, biodegradation, and bioaccumulation (Fig. 4). Bioadsorption, occurs when the contaminant is adsorbed to the cell wall or other substances excreted by the cell via interaction with the surface of the contaminant (a physical and passive process) [265, 269, 270]. For this biological process, the chemical structure of the contaminant is a key factor, but other aspects like temperature, solubility, and pH can influence microalgae interaction [315].

Nolte et al. [316] studied the adsorption of microplastics to *P. subcapitata*, where atomic force microscopy (AFM) and depletion measurements demonstrated that positively or neutrally charged polystyrene (PS) microplastics were adsorbed more efficiently than negatively charged microplastics, mainly due to particle–particle (inter-particles) and particle-cell membrane interactions. In addition, both the physicochemical properties of the microplastics and environmental conditions (the cation concentration in the freshwater media) were found to be crucial factors involved in the absorption of the microalgae to the microplastic [316]. Another work was also developed to study the adsorption of

polystyrene (PS) microplastics to *Fucus vesiculosus* [317]. The adsorption of polystyrene (PS) microplastics was highly efficient (circa 95% of the particles remained adsorbed). *F. vesiculosus* has phaeophycean hairs, rich in alginate, that allow an easy adhesion of polystyrene (PS) microplastics [317]. Peller et al. [318] used *Cladophora* sp. to remove synthetic textile microfibers (MFs) and other microplastics (namely polyethylene (PE), polyethylene terephthalate (PET), and polyacrylonitrile (PAN)) from freshwater (in Laurentian Great Lakes), observing high rates of MFs adsorption to the alga [318]. This phenomenon was attributed to the chemical composition of the cell wall and the high surface area. More recently, Kiki et al. [319] reported the adsorption of polyethylene (PE), polyvinyl chloride (PVC), and polyamide (PA) microplastics to *C. vulgaris* over a 30-days exposure period, observing that the microalga colonized the microplastics and induced structural damage, fractures, and aging. A decrease in intensity of characteristic peaks was observed, *e.g.*, 3300 $cm^{-1}$, 1641 $cm^{-1}$, and 686 $cm^{-1}$ for polyamide (PA); 1245 $cm^{-1}$ and 1093 $cm^{-1}$ for polyvinyl chloride (PVC); 2920 $cm^{-1}$ and 1463 $cm^{-1}$ for polyethylene (PE) [319]. That study proposes that the aging of microplastics can alter the physicochemical properties of the polymers, resulting in decreased hydrophobicity, which enhances the adsorption of organic micropollutants from microplastics to the cell wall of *C. vulgaris* [319]. Compounds such as bisphenol-A, bisphenol-S, bisphenol-F, and parabens (propyl–paraben, PPBen, and benzyl–paraben, BPBen), among others, form hydrogen bonds to strengthen the microalgae multicellular structure, particularly the extracellular polymeric substances matrix [319]. It is noteworthy that when the experiments were submitted to a river freshwater environment, biofouling by algae considerably increased the adsorption capacity of polyethylene (PE) and polyvinyl chloride (PVC) and weakened the adsorption of the amide group on polyamide (PA) [319].

Moreover, a combination of mechanisms can also occur. According to Cheng et al. [309], microplastics removal by microalgae can be stimulated by two mechanistic pathways: i) hetero-aggregation between *S. abundans* and microplastics, promoting the formation of extracellular polymeric substances that stimulates mutual aggregation; ii) microplastics adsorption by the cell wall of microalgae. Comparing the two mechanisms, hetero-aggregation coupled with prolonged exposure to microplastics (enhancing the synthesis of binding extracellular polymeric substances) in the medium, stimulates the removal of microplastics compared to the adsorption approach, a finding that was corroborated by SEM analysis. However, in the same study, the PLA microparticles were only efficiently removed in the water system by short-period adsorption to the microalgae cell wall in the presence of extracellular polymeric substances. This means that the ability of microalgae to remove microplastics, as well as the associated mechanisms (including the production of specific extracellular polymeric substances), depends on the type of plastic the microalgae will try to adapt to and the period of exposure to the contaminant [309].

On the other hand, bioaccumulation, unlike bioadsorption, is an active process and consists of the transport of the emerging contaminants into exclusively living cells, crossing the cell wall, and binding to intracellular proteins or other cell substances [265, 270]. Maia et al. [269] argue that bioadsorption and bioaccumulation processes are not sustainable solutions for emerging contaminants removal, because the contaminants remain inside the living microalgae cells, transforming them into possible toxic biomass, hindering the valorization into high-value products.

Lastly, biodegradation is considered the most promising pathway because it allows the fragmentation of emerging contaminants macromolecules into simple non-toxic, or less hazardous breakdown molecules via microalgae catalytic activity for their growth [265, 269, 270, 315]. Furthermore, it is a process that can occur intracellularly and also extracellularly (or a combination of both) through the secretion of ligninolytic enzymes or extracellular polymeric substances. In biodegradation, the emerging contaminants can be used as a carbon source or an electron donor or acceptor for algal metabolic activity, or for co-metabolism, in which the emerging contaminants are degraded by enzymes [265, 320] (Abdelfattah et al. 2023; Anand et al. 2023). It is worth noting that the metabolites resulting from biodegradation must be identified and quantified, as they may prevail in the environment even though the contaminant has been degraded [269].

Regarding the removal of microplastics by biodegradation, it was found in freshwater environments that the microalga *Spirulina* sp. can also biodegrade microplastics [321]. Hadiyanto et al. [321] despite the initial aim of evaluating the toxicological effects of polyethylene (PE) and polypropylene (PP) microparticles on *Spirulina* sp., found by FTIR and energy dispersive X-ray analysis that the total carbon content after 30 days of experimentation had decreased by 1.62% and 1.08% in the polyethylene (PE) and polypropylene (PP) particles, respectively. There was a decrease in the intensity of some peaks in the spectrum of the microplastics of polyethylene (PE) and polypropylene (PP) that were in contact with the microalgae (the most evident at 3281 $cm^{-1}$). By complementary SEM analysis, it was also visualized that cracks have been formed on the surface of the microplastics by interaction with the microalgae [321]. *Spirulina* sp. was also evaluated in the biodegradation efficiency of polyethylene terephthalate (PET) and polypropylene (PP)

microparticles after 112 days [279]. After the long period of interaction between the microplastics and the microalgae, it was observed by EDX analysis that the carbon content in the polyethylene terephthalate (PET) and polypropylene (PP) microplastics decreased by 48.61% and 36.7%, respectively. The biodegradation of these polymers by *Spirulina* sp. was also corroborated by FTIR analysis. The infrared spectra of the polyethylene terephthalate (PET) particles after contact with the microalgae were characterized by the decrease in intensity of the peaks in the band located between 1613 and 1505 $cm^{-1}$, associated with carbon (C=C) bonds. In polypropylene (PP) particles, new peaks appeared essentially between 1599–1534 $cm^{-1}$ and 1731 $cm^{-1}$, which indicates the presence of by-products (carbonyl groups in esters and ketones) resulting from the polypropylene (PP) oxidation process. Morphological analysis was also carried out by Khoironi et al. [279] using SEM and tensile strength. Throughout the 112 days, the structure of the microplastics was losing its hardness and elasticity, observing the appearance of cavities and erosion on the surface of microplastics. *Scenedesmus abundans* was also used for efficiently removing polystyrene (PS), polymethyl methacrylate (PMMA), and poly(lactic acid) (PLA) microparticles, obtaining an average removal rate of 84% [309]. Among the three types of polymers, *S. abundans* showed the highest removal efficiency for polymethyl methacrylate (PMMA) microparticles (with a removal efficiency of 98%), while for polystyrene (PS) and PLA microplastics, the removal was 84% and 87%, respectively [309].

Indirect photolysis, hydrolysis, and volatilization are less-studied processes applied by microalgae in microplastics bioremediation treatments [304, 315]. Indirect photolysis can be applied to more resistant pollutants in the medium, through the production of reactive oxygen species (ROS) by the microalgae [315]. This process depends on the photosynthetic capacity of the microalgae, and the process pH and temperature [251]. Hydrolysis and volatilization, on the other hand, are much more application-specific, for example, in organic pollutants with ester or amide groups [322].

Overall, all these potential bioremediation mechanisms that can be applied to different types of water contaminants, as described above, are equally applicable to microplastics [267]. As such, microalgae can be implemented as a tertiary treatment, for wastewater polishing, since the water may contain less toxic chemicals and heavy metals at this stage, which does not threaten the microalgae metabolic activity in the wastewater environment and does not impact microplastics removal [201]. However, it will be necessary to further explore these microalgae-microplastics interactions in a wastewater context and understand the influence that biotic and abiotic factors, *e.g.*, temperature, pH, concentration of organic matter, and nutrients, have on the biodegradability of microplastics.

## Conclusion

Bioremediation processes are starting to be recognized as promising strategies to be applied to remove these emerging contaminants, specifically the use of microalgae-based systems, bridging the current gaps, *e.g.*, low-efficiency rates, in municipal wastewater treatment plants. Microalgae demonstrate the ability to form hetero-aggregates with plastic microparticles. They possess mechanisms capable of degrading the polymeric molecules into simpler and safer compounds through enzymatic activity or extracellular polymeric substances secretion. This process results in biomass with high-value, contributing to the development of more environmentally friendly approaches, which will also result in a more sustainable industry. In fact, by applying microalgae-based systems in wastewater bioremediation, there is an opportunity to advance the concept of zero-waste, thereby improving the sustainability of ecosystems and water quality. However, additional in-depth studies will be necessary to identify the mechanisms of microplastics removal from wastewater by microalgae, whether through bioflocculation or biodegradation processes, taking into account the limitation of current scientific studies highlighting the removal capacity of these micropollutants in a wastewater context. It is crucial to consider the specific parameters characterizing wastewater, as they influence the metabolic function and growth of performance microalgae, as well as the microbiome present in the aquatic environment, which can facilitate hetero-aggregation and consortia between different microbial species. This comprehensive understanding of the interactions and potential mechanisms associated with the removal of microplastics from wastewater will contribute to the development of more effective and environmentally sustainable strategies for mitigating microplastics pollution.

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## Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

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