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Tackling Marine Microplastics Pollution: an Overview of Existing Solutions

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Abstract Microplastics pollution is one of the main environmental challenges of our time, even though microplastics were observed for the first time almost 50 years ago. Microplastics—little plastic fragments smaller than 5 mm in size—are released from bigger plastic objects during their use, maintenance, or disposal. As their release is uncontrolled and mostly uncontrollable, microplastics end up in the environment and are easily transported across the world, polluting nearly every ecosystem, especially the aquatic ones. Hence, microplastics represent a huge menace for many living species: they are ingested unintentionally by smaller animals and transferred along the food chain up to human beings, even threatening our health. It is therefore vital to take action against microplastics and many technologies have been designed in recent years with this purpose in mind. This paper provides an overview of the main solutions developed thus far to reduce further microplastic emissions and to collect those already released.

Keywords Microplastic · Microplastic removal · Plastic pollution · Plastic interception · Water quality

1 Introduction

Water pollution is a widespread problem nowadays. It is related to the presence of chemical, physical or biological components, or other factors that interfere with the beneficial use or the natural functioning of ecosystems of a given water body (Schweitzer and Noblet, 2017). Among water bodies, oceans represent the ultimate receptacle of all pollutant substances, which reach them through rivers, runoff, atmospheric deposition, and direct discharges (Landrigan et al., 2020). Covering more than 70% of the earth's surface and holding 97% of the world's water, oceans provide many important ecosystem and economic services, which are threatened by increasing pollution. There are various sources of pollution, most of which come from human land-based activities. Hence, oceans contain a complex mixture of toxic metals, manufactured

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chemicals, petroleum, urban and industrial waste, pesticides, fertilizers, pharmaceutical chemicals, agricultural runoff, sewage, and plastics.

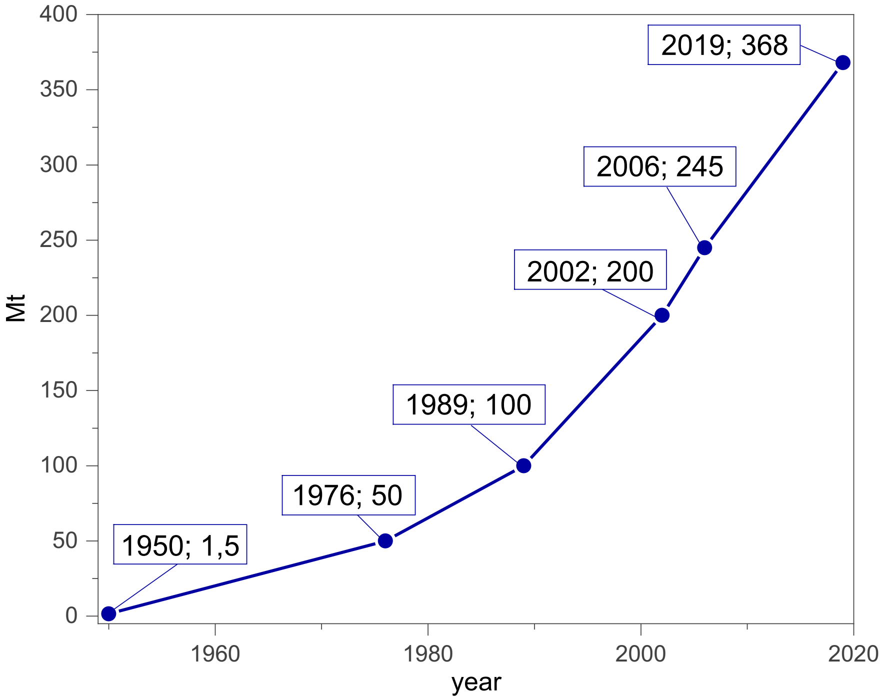
Plastics are a wide family of petrochemical materials broadly used for many applications thanks to their favourable properties, i.e., lightness, flexibility, resistance, stability, and durability. These properties have made plastic materials an incomparable success. Industrial plastic production has therefore increased exponentially, from 1.5 million tonnes (Mt) in 1950 to nearly 370 Mt in 2019 (Plastics Europe, 2008, 2019, 2020), as shown in Fig. 1. Unfortunately, with the growth of production of these materials, plastic pollution is also increasing because of mismanagement of its end of life. Eight megatonnes of plastic was released into the environment in 2010 and 90 Mt are estimated to be released every year by 2030, in a business-as-usual scenario (Lebreton et al., 2019). Thanks to its longevity and resistance to decomposition, plastic is destined to last for decades in the environment, where an estimated 60% of all plastics ever made are found (Geyer et al., 2017). Unsurprisingly, by 2050, plastics are predicted to outweigh the fish in the ocean, which is the aquatic environment most affected by plastic pollution (World Economic Forum, 2016).

Even though plastic pollution has existed for decades, it has aroused world attention only in the last few years. This is clear from the exponentially growing number of scientific publications, which have increased from just a few between 1991 and 2008 to over 1700 between 2015 and 2019 (Freeman et al., 2020).

Plastics pollute the aquatic environment in many forms: from plastic debris along riverside and coastlines, to limitless accumulations in the open oceans, called garbage patches. And besides the most evident big plastic debris, there are also microscopic plastic fragments everywhere; these are known as microplastics. These particles significantly contribute to plastic pollution; although almost invisible, they are very abundant.

In fact, microplastics represent over 90% of the total number of particles identified in the oceans, even though they account only for 13% of the total weight of ocean plastic litter (Eriksen et al., 2014). Moreover, according to a recent study, only 1% of plastics float on the ocean surface and 94% reach the deep sea, where it is estimated that there are over 14 Mt of microplastics (Lebreton et al., 2019). In fact, many microplastics disappear from the ocean surface layer because of various phenomena,

Fig. 1 Trend of plastic production since 1950 (Plastics Europe, 2008, 2019, 2020)



like settling, ingestion, aggregation, stranding, or even further degradation (Lebreton et al., 2019). This means that the problem of microplastic pollution is much more serious than meets the eye, and it is urgent to find a solution.

The gravity of microplastic pollution is exacerbated by the health hazard posed by microplastics. In fact, they seem to be a threat to every ecosystem and every living being, from smallest organisms to human beings. However, the assessment of the toxicological impacts of microplastics is challenging, because of their heterogeneity and great complexity. Once ingested, microplastics can cause both physical and chemical toxic effects (Wu et al., 2019; Landrigan et al., 2020; Wang et al., 2021). They are able to damage cells, injure tissues, and cause inflammation. Moreover, the smallest ones—known as nanoplastics—can easily pass through cell membranes, accumulating in tissues. Regarding their chemical toxicity, both the direct and indirect effects should be considered. In fact, microplastics usually contain countless chemical additives introduced during the manufacturing process. In addition, due to their high surface area, once in the environment, microplastics can adsorb many organic and inorganic chemical contaminants from the surroundings and can offer a favourable substrate for the growth of unique communities of microorganisms, including potentially pathogenic species (van Cauwenberghe & Janssen, 2014; Wu et al., 2019; Landrigan et al., 2020; Wang et al., 2021; Prata et al., 2021). All these substances may be released in the digestive systems of ingesting organisms with potentially deleterious effects.

However, the reported data are only rough estimations and a proper evaluation is quite difficult for many reasons: firstly because of the lack of knowledge about the topic, secondly because of the lack of standardized procedures of sampling and analysing, and thirdly due to the intrinsic complexity of detecting and counting such small particles.

Environmental plastic pollution is a complex problem because of the multiplicity of its forms and sources and therefore a multifaceted approach is necessary to properly tackle it. To date, much effort has been made with this purpose, aiming to identify the main causes, pathways, and effects of plastic pollution and the best technologies to prevent and solve it. Recently, microplastics pollution in particular has drawn much attention because of the difficulty of both studying and solving it.

The objective of this paper is to analyse the existing technologies and devices for the reduction of microplastics pollution. The first part provides general information about microplastics, their sources, and their effects. In the second part, an inventory of the main microplastic-collecting technologies and devices is presented, according to the interception point—in the open sea, at source, or halfway.

2 Microplastics

2.1 Definitions and Sources

Usually, microplastics (MPs) are defined as plastic fragments between 1 µm and 5 mm in size, even though there is still not a univocal definition provided by the world scientific committee (Boucher & Friot, 2017; GESAMP, 2015; Sundt et al., 2014). This definition has been accepted by the National Oceanic and Atmospheric Administration and it is the most frequent in the scientific papers on this topic. A more rigorous classification of all the size ranges of plastic debris is given by the joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), according to which microplastics are plastic fragments between 1 µm and 1 mm in size (GESAMP, 2015). In this paper, plastic fragments smaller than 5 mm are considered microplastics and fragments bigger than 5 mm are considered macroplastics.

Depending on their source, microplastics can be defined as primary or secondary and again there is not still a univocal definition. According to GESAMP (GESAMP, 2015), primary MPs are intentionally produced as microscopic particles for direct use, e.g., in cosmetics and abrasives, or as raw materials for the production of larger plastic items. Secondary MPs are originated from the degradation of larger plastic items by use, by waste management, or in the environment. Instead, according to Sundt et al. (2014), primary MPs are those directly released into the environment as small plastic particles, while secondary MPs originate from the fragmentation of large plastic waste into smaller plastic fragments once exposed to the marine environment, because of photodegradation and weathering processes.

The second definition is adopted in this work because it seems preferable to the authors. In fact, it is reasonable to consider primary microplastics those emitted into the environment as microscopic particles, consistent with Sundt et al. (2014), since they are added at the "well" and their emissions are an inherent consequence of human activities. Furthermore, according to this interpretation, primary microplastics can be released during various stages of the plastic lifecycle, i.e., production, transport, use, maintenance, or recycling, while secondary microplastics mostly originate from mismanaged waste. Primary microplastics have many different sources and they are mostly generated from land-based activities. As previously said, based on the definition by Sundt et al. (2014), primary MPs either can be an intentional addition to products or can originate from the abrasion of large plastic objects during their manufacturing, use, or maintenance. According to a recent study conducted by the International Union for Conservation of Nature, the main sources of these particles are constituted by the laundering of synthetic textiles and the abrasion of tyres. City dust, road markings, marine coating, plastic pellets, and personal care products also contribute to the release of microplastics (Boucher & Friot, 2017). The contribution of each source is displayed in Fig. 2.

The estimated global release of primary microplastics into the environment is about 3.2 Mt per year, 1.5 Mt of which are directly released into oceans. Considering their microscopic dimensions, this means an immeasurable number of particles (Boucher & Friot, 2017).

The estimation of the release of secondary microplastics is more complicated. To obtain a real quantification of this kind of pollutants, too many factors have to be considered simultaneously such as the amount of mismanaged plastic waste, the degradation rate, and the factors conditioning the degradation. To date, to the best of the authors' knowledge, there is no exact estimate of the amount of released secondary microplastics.

Because of their small size and their lightness, microplastic particles can be easily transported for long distances and they end up in the soil or the ocean through road runoff, wind transfer, and wastewater treatment plants (WWTPs). Unsurprisingly, microplastics have been found throughout every ecosystem, from the deep ocean (Barrett et al., 2020; Kane et al., 2020; Pohl et al., 2020), to the beaches of remote islands (Young & Elliott, 2016), from the snow of the Alps to the Arctic waters and ices, along all the water column (Bergmann et al., 2019; Lusher et al., 2015; Peeken et al., 2018). The main potential releases, transfer pathways, destinations, and general environmental impacts are summarized in Fig. 3.

2.2 Impacts of Microplastics Pollution

Dispersed in the environment, microplastics threaten the equilibrium of many ecosystems and affect nearly all living beings. As previously discussed, they have various effects depending on the exposure, partly still unknown but certainly severe in many cases. Animals of lower trophic levels ingest microplastics mistaking them for food, and animals of upper trophic levels assume microplastics too, indirectly through

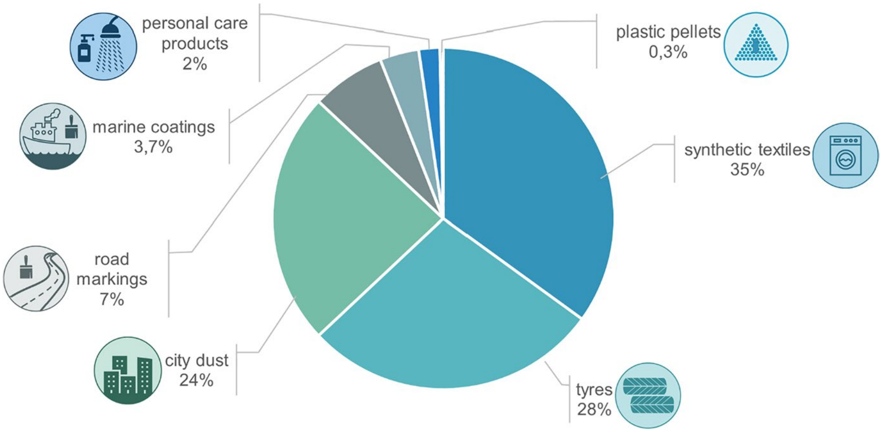


Fig. 2 Main sources of release of primary microplastics (Boucher & Friot, 2017)

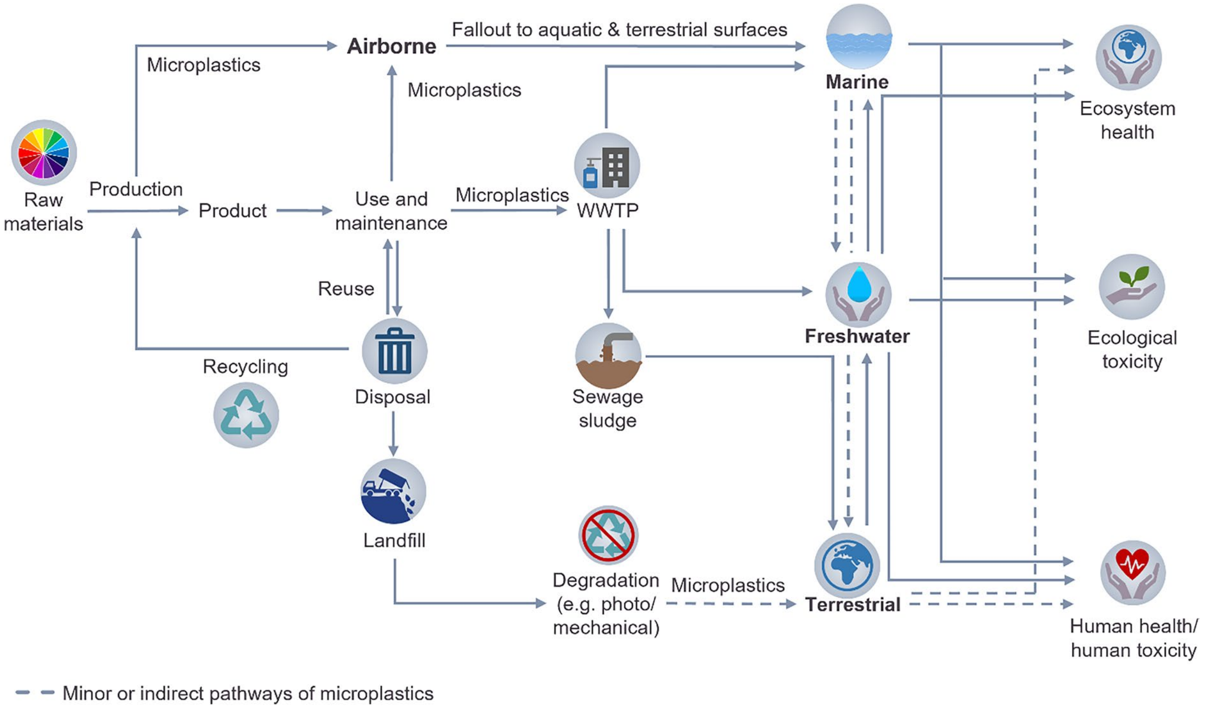


Fig. 3 Main potential releases, transfer pathways, destinations, and general environmental impacts adapted from (Henry et al., 2019)

"polluted" prey or directly through water ingestion (van Cauwenberghe & Janssen, 2014). Thus, far very little is known about the non-lethal consequences of the ingestion of microplastics, but it seems that they have the potential to be taken up by epithelial cells of the intestinal tract and to migrate through the intestine wall to the circulatory system. Moreover, microplastics can also act as vectors of additives from the manufacturing process and of organic pollutants adsorbed from the surrounding environment (van Cauwenberghe & Janssen, 2014; Wu et al., 2019; Landrigan et al., 2020; Wang et al., 2021). The assessment of the impacts of microplastics is very challenging, as evidenced by the divergent results of the various studies conducted (Landrigan et al., 2020).

Transported by deep-sea currents, which determine the location of important biodiversity hotspots since they are efficient conveyors of nutrients and oxygen, microplastics also reach seafloor microorganisms (Kane et al., 2020).

Ingested by the smallest organisms, microplastics enter the food chain from the bottom and climb up to the top, also threatening human beings. According to a recent study, an average person may ingest approximately 5 g of plastic every week (Wit & Bigaud, 2019). The intake of microplastics seems to be unavoidable since they are present in many common foods and beverages. The most dangerous food is obviously fish, both wild and cultured, in particular shellfish and crustaceans, because they are often consumed intact with their digestive apparatus, where microplastics are concentrated (Ghosh et al., 2021; Jaafar et al., 2021; Marques et al., 2021; Piyawardhana et al., 2022; Rochman et al., 2015; van Cauwenberghe & Janssen, 2014; Vital et al., 2021; Wit & Bigaud, 2019). Moreover, bivalves are particularly exposed to microplastics pollution because of their filter-feeding mechanism that allows them to feed by straining suspended matter and food particles from water ("Filter Feeding"). Unfortunately, the assumption of microplastics cannot be avoided because they drastically pollute an essential food, i.e., water, which is actually the main source of human exposure to microplastics through ingestion. Microplastics have been detected in many samples of bottled, drinkable, and tap water (Kosuth et al., 2018; Mason et al., 2018; Schymanski et al., 2018; Zuccarello et al., 2019). This means that nearly all the water on the planet is polluted, affecting many water-related products and activities. Thus, it is not surprising to know that microplastics have also been spotted in table salt samples and in many fruits and vegetables (Fadare et al., 2021; Karami et al., 2017; Kosuth et al., 2018; Oliveri Conti et al., 2020; Yang et al., 2015).

Moreover, ingestion is not the only means of exposure to microplastics for humans. They can also be affected by airborne microplastics through inhalation (Dris et al., 2017; Roblin et al., 2020), to the point that microplastics have been found in human lung tissue (Amato-Lourenço et al., 2021; Jenner et al., 2022). Even though the intensity of the exposure to microplastics is not well known and the risks that microplastics pose to human health are not yet well understood, it has been ascertained that the presence of microplastics in the human body increases the incidence of severe diseases (Prata, 2018; Wright & Kelly, 2017). It is therefore urgent to take action and find solutions to microplastics pollution, not only for the environment and animal well-being but also for human health.

Given the multiplicity of sources and pathways of microplastic pollution, various sets of solutions are necessary to ensure the removal of the microplastics already dispersed in the environment and a proper reduction of microplastics emissions.

3 Removal

Once they are formed, primary and secondary microplastics become undistinguishable and their distinction is actually irrelevant to their removal. As discussed in Sect. 2, microplastics already pollute all the ecosystems, both aquatic and terrestrial. Their removal from the environment is certainly challenging because of the small size of the particles; however, some technologies have already been developed for this purpose. A brief description of the main existing solutions is presented in the following.

3.1 Removal from Open Water

3.1.1 Seabin Project

The Seabin unit (“Seabin V5”) is a trash bin designed to be installed in water bodies with a calm environment and suitable services available, like docks. The unit moves up and down with the range of tide and skims the surface of the water by sucking water into the device, intercepting floating debris in this way. It can clean the water from contaminated organic material, macro- and microplastics and even microfibres, and can absorb petroleum-based surface oils and detergents thanks to oil absorbent pads. It must be connected to the electrical grid for running the pump, which has a capacity of 25.000 l/h. The Seabin requires dedicated stuff for maintenance and emptying. It has a holding capacity of 20 kg; it can catch nearly 4 kg of debris per day and remove an estimated 1.5 tons per year. So far, over 800 Seabins have helped to collect nearly 3000 tonnes of waste all over the world.

3.1.2 Cloud of Sea

Cloud of Sea (“Cloud of Sea”) is a device intended to remove microplastics from water and designed to be hooked on any type of boat through ropes. It does not need external sources of energy, as it takes advantage of its shape to create a friction with the water allowing water to flow into the filter. It consists of two external parts that make up the water passage channel and hold the rope, a removable central ring, and an internal helical-shaped rotating filter. The internal filter is made of a semi-rigid membrane with holes that taper inwards, allowing for the entry of plastic particles but not their leaving in this way. The project, honoured by the James Dyson Award 2020, must be further developed and tested before being released on the market.

3.1.3 MP Collection on Vessels

Mitsui O.S.K. Lines developed a microplastics collection device for mercantile vessels MOL Mitsui (OSK Lines, 2020). The microplastics collection device is activated during the operation of the ballast water treatment system, with the assumption that the collection takes place during cargo handling operations. Using a filter with a backwashing function, the device collects microplastics trapped in the filter right before the treated water is discharged overboard (MOL Mitsui OSK Lines, 2020). Microplastics and microalgae collected by the device have been successfully converted into carbon products; these products represent a valuable alternative to conventional energy carriers since their calorific value is comparable to that of wood pellets (MOL Mitsui OSK Lines, 2021).

Joint with the Finnish technology group Wärtsilä, the Italian shipowner Grimaldi Group has developed and patented a system capable of filtering the wash water from shipboard exhaust gas cleaning systems, known as scrubbers (Grimaldi Group, 2022; Dunn, 2022). Open-loop scrubbers suck huge quantities of water from the sea every day and then return them to the sea. The new system filters the water before its release and captures the microplastics. Pilot tests have already been completed with promising results, collecting over 60.000 microplastic particles, even smaller than 10 µm, on a single voyage from Civitavecchia to Barcelona.

These systems are very interesting because they allow the collection of microplastics from open seas during usual sailing, not requiring dedicated vessels in this way.

3.2 Removal from Water Treatment Plants

Since the collection of microplastics from broad expanses of water is quite difficult, it is convenient to intercept them before they reach open water. In fact, water is involved in a wide cycle that allows its use for human activities. Before being released again into the environment, discharge water is treated in designated plants, named WWTPs. They represent the final stage of the anthropogenic water cycle and they purify water from undesired substances through a series of standardized steps. The interception of microplastics in WWTPs would therefore be convenient and would contribute to the reduction of further release of MPs in the environment, but it is still challenging.

In a typical WWTP, processes are classified into four main groups: preliminary, primary, secondary, and tertiary treatments. Preliminary and primary treatments consist of coarse screens, grit chambers and sedimentation tanks for removing coarse particles. Secondary treatments allow the removal of suspended organic matter. Finally, tertiary treatments are optionally performed for disinfection purposes, to remove pathogenic contaminants (Enfrin et al., 2019). In the end, water is purified from pollutants and contaminants and can be released back into the environment. A general scheme of a typical WWTP is provided in Fig. 4.

Similar processes are used in water treatment plants to produce drinkable water.

MPs in wastewater are very different in type, shape, size, composition, and concentration depending upon the sources of wastewater itself. WWTPs treat domestic discharge water, industrial discharge water, wet sedimentation process water, or landfill leachates separately in the case of distinct discharge systems, or together in the case of combined discharge systems (Ngo et al., 2019). Consequently, sources of MPs, and therefore MP type, vary with wastewater source. In domestic wastewater, MPs from textiles and personal care products prevail; in industrial wastewater, MPs derive from surface blasting and moulding; in wet sedimentation, there are airborne MPs dragged by stormwater runoff, and in landfill leachates MPs come from the fragmentation of landfilled plastics (Ngo et al., 2019).

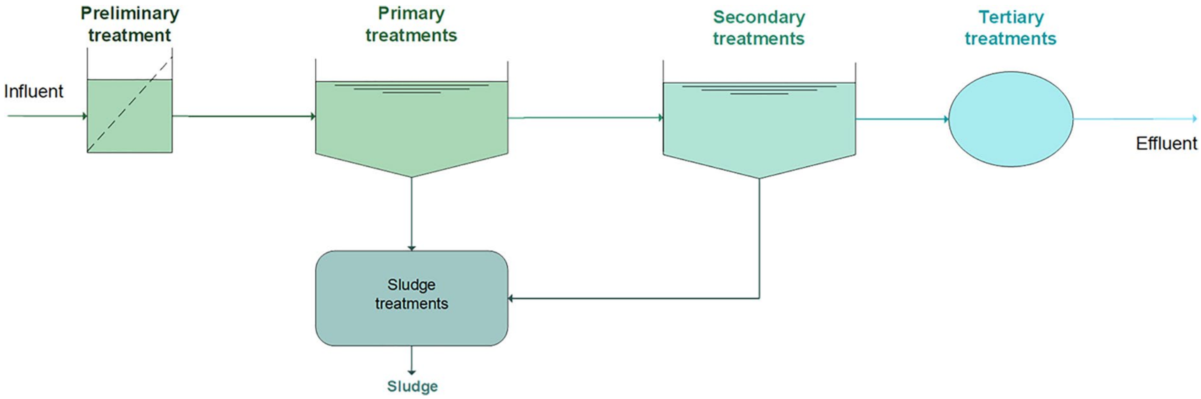


Fig. 4 Scheme of a conventional WWTP

While current treatments are effective in MP interception, they are not specifically intended for this purpose. Every treatment step is able to remove MPs from wastewater with a total efficiency that can reach 90% and even 99.9% (Cheng et al., 2021; Edo et al., 2020; Ngo et al., 2019; Poerio et al., 2019; Sun et al., 2019), as outlined in Table 1.

However, because of the enormous flowrates treated—up to millions of litres per day—even if MP concentration in the effluent is very low, the total discharge of MPs in water bodies is still considerably high. WWTPs thus remain the main culprit for MP emissions releasing 10^5–10^{10} particles every day (Edo et al., 2020; Liu et al., 2021; Magni et al., 2019; Sun et al., 2019).

Much effort has already been made for the optimization of current treatment technologies and their potential replacement with advanced technologies, which are more efficient in MP removal than conventional ones even though they are not still specifically intended for it. Some of the most interesting innovations are described in the following, considering both the effectiveness of current and advanced technologies, and the development of MP-targeted treatments.

The optimization of current treatments focuses especially on coagulation and settling performances and aims to determine the best flocculant substances able to aggregate MPs. Conventional coagulants are shown to provide poor removal of pristine MPs, while higher efficiency is reached with weathered-surface MPs and with cationic polyacrylamide (Lapointe et al., 2020). Some alternatives to conventional coagulants have been investigated so far. An interesting solution is constituted by biopolymers, such as extracellular polymeric substances (EPS) produced by microalga. EPS have shown high flocculant activity even in low concentrations and hence represent a potential replacement for hazardous synthetic flocculants, already banned in several countries (Cunha et al., 2020).

Flocculants can also be used to enhance the performance of dissolved air filtration, an advanced technology able to remove up to 95% of suspended MPs (Talvitie et al., 2017). It consists in saturating water with high-pressure air and pumping it into a flotation tank at atmospheric pressure. Dispersed water is formed in this way, and the released air bubbles adhere to the suspended solids causing them to float to the surface, allowing their removal by skimming (Talvitie et al., 2017).

Among the advanced technologies, Membrane BioReactor (MBR) seems to be the most efficient one. It combines membrane filtration and biological processes to treat the primary effluent, which contains both suspended solids and dissolved organic matter. Hence, MBR is suitable to replace secondary clarifiers in conventional activated sludge systems (Talvitie et al., 2017). It shows high MP-removal efficiency, between 79 and 99.9% (Bayo et al., 2020; Lares et al., 2018; Talvitie et al., 2017), but it suffers from rapid clogging and significant technical barrier in size-based treatment plants (Hou et al., 2021).

However, with the usual treatment steps, MPs removed from wastewater are gathered in sewage sludge, like other intercepted solids. The sewage sludge is commonly used as a soil conditioner in

Table 1 Removal efficiency of each treatment step and final content of MPs in outlet effluent and sewage sludge

Removal efficiency				MP content		References
Preliminary	Primary	Secondary	Tertiary	In effluent	In sludge	
n.a	25%	75%	98%	n.a	n.a	Poerio et al. (2019)
35–59%	50–98%	86–99.8%	98–99.9%	0.1–2%	69–80%*	Sun et al. (2019)
6–58.6%	19.1–99%	66.7–92.6%	72.7–99.9%	n.a	n.a	Cheng et al. (2021)
n.a	25–45.31%	51–72.82%	90–99%	15–35%	n.a	Xu, Zhang, et al. (2021)
35–59%	15–40%	3–37%	0–24%	1–35%	80–99.9%*	Hou et al. (2021)
35.1–58.6%	56.8–98.3%	84.3–99.7%	92.2–99.9%	0.1–7.8%	n.a	Xu, Bai, et al. (2021)

*Of retained MPs; *n.a.* not available

landfills and cultures (Ngo et al., 2019; Sun et al., 2019); this means that MPs removed from wastewater are not completely eliminated. Sooner or later, they return to WWTP through leachate, or they enter the natural water environment by stormwater runoff or they even end up in cultured products for human consumption. Hence, if wastewater treatments are optimized or improved with advanced technologies to ensure the complete removal of MPs from wastewater, the polluted sewage sludge would then have to be properly disposed of, e.g., through burning, to avoid further soil and water contamination (Sun et al., 2019). Otherwise, it would be necessary to develop MP-targeted treatment technologies for WWTPs aimed at their separation from both wastewater and sewage sludge, ensuring water safety and sludge usability. Furthermore, according to recent studies, the presence of MPs in wastewater affects the efficiency of treatments themselves, inhibiting the microbiological activity involved in the nitrogen cycle and responsible for the removal of nutrients in activated sludge systems (He et al., 2021; Rong et al., 2021; Seeley et al., 2020). Hence, the removal of MPs during wastewater treatments is clearly compelling, even though the implementation of new MP-targeted technologies in WWTPs is certainly more problematic than the optimization of current ones because it implies the addition of further treatment steps and consequently a new design of the overall process.

Rhein et al. investigated the viability of magnetic seeded filtration (MSF) for the separation of MPs from dilute suspensions, that are similar to wastewaters, reaching a separation efficiency of 95% (Rhein et al., 2019). In MSF, magnetic seed particles are dispersed into the suspension and agglomerate with the target particles, i.e., microplastics. The newly formed hetero agglomerates can be removed by magnetic separation due to the magnetic properties of the seed particles. By choosing the right seed particles and using permanent magnets, MSF can be an efficient separation process, also considering that it is designed with lower flow resistance and pressure drop than those of classical filtration technologies. Moreover, the size dependency of MSF can be manipulated by the choice of magnetic seed particles, thus not limiting the process to a certain minimum particle size. To date, MSF for the removal of MPs has not yet been implemented in treatment plants but it has only been tested on a pilot scale; therefore, concerns remain about separation efficiencies, process costs, and scale-up potential.

In any case, the interaction between these MP-targeted technologies and other eventually suspended solid particles should be considered. In fact, in most cases, the studies used ad hoc prepared solutions, in which only MPs were dispersed. However, the optimal MP removal in WWTPs should be located as soon as possible during the treatment steps, where organic matter and suspended solids are still abundant, to avoid sludge contamination and allow its valorization.

MSF is also the principle behind the MP-removal method presented by Fion Ferrreira (Ferreira), who proposed the use of ferrofluids to remove MPs from water in WWTPs. The method consists in the addition of oil in a suspension of microplastics in water. MPs migrate into the oil phase and the subsequent addition of Fe_3O_4 powder into the oil phase allows the separation of the MP-containing ferrofluid from the water using proper magnets. This extraction method has shown a preference towards microfibres and an overall MP removal efficiency of about 87%, with homemade experiments. The effectiveness of Fe_3O_4 in the removal of MPs from water has been recently proved by other studies, even without the addition of the oil phase (Shi et al., 2022).

Another promising solution is represented by organosilanes, the use of which has been studied in the last few years for the specific removal of MPs from water (Herbort et al., 2018; Schuhen et al., 2019; Sturm et al., 2020, 2021). Organosilanes consist of one organic group and three reactive groups. The organic group is able to attach to the surface of the microplastic and collect it in agglomerates, while the reactive groups form a solid hybrid silica gel thanks to a water-induced sol–gel process that entraps the microplastic (Sturm et al., 2021). The organic group can be adapted to different polymer types, making organosilanes effective in the removal of different plastics. The method seems to have a great possibility of being applied on a technical scale, but further investigation is needed to ensure its applicability in WWTPs, where organosilanes could be used in place of standard flocculants.

The SimConDrill project ("SimConDrill") aims to develop innovative filter modules to remove MPs from wastewater, enabling the filtration of particles down to 0.01 mm thanks to a patented cyclone filter, which is clogging- and maintenance-free and not disposable. The prototype is still under development and, once ready, it will be tested in a real wastewater treatment plant.

Kiendrebeogo et al. (2021) recently proposed the application of the electrooxidation process, originally developed for the degradation of persistent pollutants, to degrade polystyrene microparticles suspended in water. Differently from other treatments, electrooxidation does not break MPs into smaller particles but degrade them directly into gaseous non-toxic molecules, i.e., water and carbon dioxide, ensuring the removal of MPs from both water and sewage sludge and avoiding the need for their disposal. The process is based on the in situ generation of oxidizing radicals by direct and indirect electrochemical processes. The standard reduction potential of the radicals allows them to break the polymeric bonds of MPs and degrade them. In their work, Kiendrebeogo et al. studied the effect of various anode materials, supporting electrolyte type, and electrolyte concentration on MP-removal efficiency reaching promising results. However, the process has been studied only on a laboratory scale and the interactions with wastewater samples should be further investigated before its application on real-scale plants.

3.3 Removal from Land

Some devices have been developed for the removal of microplastics from land too, even though microplastics collection can occur also with sifting devices for general cleaning purposes. The latter have been omitted in the present work since they are not specifically intended for the collection of microplastics.

3.3.1 Nurdle technologies

To remove microplastics from sand, Nurdle has developed two different devices. The first one is the Nurdle Machine, which is like a big vacuum cleaner. Towed by a car along the beach, it sucks up the litter, dividing the plastic material from the natural debris in its inside (“Nurdle Machine”). The natural debris is returned to the environment, while plastic litter is retained and upcycled. The machine has a capacity of 75 kg, divided into three bags of 25 kg each to allow healthy and safe lifting by a single person. It has interchangeable size diameters for a range of sizes and grain size (“Microplastic Machine”). The second one is the Nurdle Trommel, a drum filter that allows the separation and collection of small plastic fragments from the beach sand. It requires handwork since it must be spun manually (“Nurdle Trommel”). It is lightweight and modular, and easily transportable in a standard car (“Microplastic Trommels”).

3.3.2 Hoola One

Hoola One (“Hoola One solutions”) is an innovative customizable set of solutions for ridding beaches of micro and macro plastics. Hoola One technologies allow the natural matter to be put back on the beach thanks to an innovative separation method. In this way, the total amount of collected waste is significantly reduced, the environmental impact is minimized, and collected plastic can be upcycled. Hoola One includes three different devices, allowing users to access even hard-to-reach areas. The so-called HO micro is made of four modules; it works on any type of soil and can also collect plastic in deep soil. It can recover plastic particles as small as 10 µm using a buoyancy separation method. The HO Wrack is a single-module innovative sieving technology that allows the collection of plastics within the desired size range. The HO Backpack is a hand-held vacuum device, optimal for the removal of surface plastic. The versatility of solutions enables to adjust the processing capacity of the machine and to adapt to different conditions, from rugged terrains to flat beaches.

The existing devices for the collection of microplastics from land are mainly devised to treat sand and sandy terrains, allowing the separation of microplastics through sieving. They are little apparatuses, they require operators to work, and they are difficult to be employed on large-scale clean-ups without great effort and huge time consumption.

4 Interception at Source

To properly evaluate the various existing solutions for the interception of microplastics at their source, it is necessary to distinguish primary and secondary microplastics since they have quite different sources, as previously discussed.

4.1 Primary Microplastics

Primary microplastics are emitted by various sources, as outlined in Sect. 2.1 and Fig. 2. Therefore, to analyse primary microplastics interception technologies, it is necessary to consider each source separately, to accurately identify every source and understand the mechanism of release from it.

Besides the interception after the release, important actions to prevent the release of primary MPs are clearly the withdrawal of microplastic additives from products and their replacement with environmentally friendly alternatives. For this purpose, natural and biodegradable microbeads made of cellulose, called naturbeads ("NaturBeads"), have been invented to replace plastic microbeads in many applications, e.g., cosmetic and personal care products, paints and coating, adhesive, and packaging. Thus, it is not necessary to renounce the benefits of microbeads for reducing environmental microplastics pollution. However, their broad application in place of common plastic microbeads is still a long way off; moreover, they are not the only type of primary MPs, so it is important to also find interception technologies where microplastics are unavoidable.

4.1.1 Pellets

Pellets are the primary form of many plastics that facilitate the transport to plastic transformers, where plastic products are generated. Given their small dimensions—they are typically 2–5 mm in diameter—pellets can be accidentally spilt into the environment during manufacturing, processing, transport, and recycling, along the whole plastic value chain.

Operation Clean Sweep ("Operation Clean Sweep") is an international program voluntarily conducted in thousands of plants around the world and designed to prevent plastic granules losses along the plastics value chain and their release into the environment. It is aimed at improving awareness, promoting best practices, and providing guidance and supportive tools to companies. It supplies information about how to set up, review, and improve existing environmental protection and safety measures. In Europe, associations have committed to developing an OCS (Operation Clean Sweep) certification scheme by the end of 2022 to ensure compliance with settled common requirements for the minimization of pellet loss across the entire plastic supply chain ("OCS Certification Scheme").

4.1.2 Personal Care Products

The release of microplastics from personal care products is the only one that can be considered intentional: in this case, a product containing specifically added microplastics is intentionally poured into water (Boucher & Friot, 2017).

In 2012, Plastic Soup Foundation started the "Beat the Micro Bead" campaign against microbeads, raising awareness of microbeads and microplastics in companies, governments, and people ("Global Impact"). At first, this led many multinational companies to promise to withdraw microbeads from cosmetic products and then led many governments to ban microbeads from products. In 2014, microplastics and microbeads were banned from rinse-off cosmetic products certified by the EU Ecolabel, and even though there is still not a European-wide ban, various European countries have declared national legislations since then (Anagnosti et al., 2021; Eu Ecolabel rinse-off cosmetic products, 2014). Withal, cosmetics containing microbeads are still in the European market, in a significantly higher number than that supposed (Anagnosti et al., 2021). In 2015, Obama signed a bill against microbeads in the USA, the so-called Microbead-Free Waters Act ("Microbead-Free, 2015," 2015). Since then, 15 states and 448 brands from 119 different manufacturers have taken action to ban and remove microplastics from personal care products ("Global Impact"). However, in some cases, legislation is limited to specific products, e.g., rinse-off cosmetics for exfoliating and cleansing purposes, leading to a limited reduction of emissions in this way (Anagnosti et al., 2021). Moreover, the reformulation of some products, e.g., leave-on cosmetics, is not easy, immediate, and cost-effective, meaning that traditional products will remain on the market still for a long time to come, keeping on polluting.

4.1.3 Marine Coatings

Marine coatings are applied to all parts of vessels and marine infrastructures for protection and include solid coatings, anticorrosive paint, or antifouling paint. They are usually made of several types of plastics and, consequently, primary microplastics are released during building, maintenance, repair, or use of boats. The key activities that seem to lead to the release of microplastics are surface pre-treatment, coating application, and equipment cleaning (Boucher & Friot, 2017).

Pinovo supplies various tools engineered with innovative and patented technology for dust-free abrasive vacuum blasting of surfaces, preventing the release of microplastics in the environment and allowing their collecting and recycling in this way, being in addition safer for operators ("Pinovo").

4.1.4 Road Markings

Road markings are applied during the manufacturing of road infrastructure and its maintenance. They include different types of markings, mainly paints, thermoplastics, preformed polymer tape, and epoxy resins that is all fossil-derived materials. Loss of microplastics results from weathering or abrasion by vehicles (Boucher & Friot, 2017).

4.1.5 City Dust

The term city dust refers to nine different sources occurring in urban environments that are grouped together because their individual contribution is small. It includes losses from the abrasion of common objects and infrastructure as well as from blasting of abrasives and intentional pouring (Boucher & Friot, 2017).

4.1.6 Tyres

During use, the outer parts of the tyres become eroded. The formed particles consist of a matrix of synthetic polymers in a mix with natural rubber and additives (Boucher & Friot, 2017). Tyre dust is then spread by the wind in the atmosphere, accounting for up to 50% of air particulate emissions ("The Tyre Collective"), or washed off the road by the rain. In any case, after a certain time, they can reach aquatic systems.

Clearly, prevention can be performed by rethinking the design of the products. However, the wear of tyres is probably unavoidable; hence, the improvement of interception technologies also plays a significant role in tackling microplastics pollution.

The Tyre Collective ("The Tyre Collective") aims to mitigate the emissions of microplastics from tyres by capturing them at the source. It consists of a device combined with the tyre and located close to where the tyre meets the road. When rubber particles are released from the tyre, they are electrically charged, and the device takes advantage of this charge to capture them. The particles can be easily collected and reused for other applications. The device is still under development and, according to the most recent tests, it is able to capture 60% of all airborne particles.

4.1.7 Synthetic Textiles

Primary microplastics originate from the wearing and washing of synthetic textiles, through abrasion and shedding of fibres. During wearing, microplastics are released mostly into the atmosphere but they can be washed out by rain, or reach rivers or sewage water with road runoff, ending up in the ocean in this way. During washing, they are discharged directly into sewage water and potentially end up in the ocean again. The release of microfibres can be reduced by modifying the productive process and developing novel finishing treatments for fabrics but most likely it cannot be totally avoided (de Falco et al., 2019).

For this reason, many devices are being developed to intercept released microfibres at the outlet of washing machines, preventing them from reaching sewage and hence WWTPs. To date, most devices are meant to be placed outside of the household appliance, on the water discharge pipe, and they take advantage of a filtering medium to catch microfibres. Various systems differ from each other in the filtering medium material and its mesh size, which determine different efficiencies, as well as in the cleaning mode, as outlined in Table 2. Other developing devices, instead, are designed to be integrated in the washing machine, which will then be sold equipped with this innovative feature. Finally, some washing accessories are available to reduce

Table 2 Main washing machine microfibres filters, their efficiency, cleaning frequency, and main features, divided into (a) external filters on the washing machine's discharge hose, (b) internal filters, (c) in-drum filtering devices

Name	Efficiency	Cleaning frequency	Description	References
a)External filters on washing machine's discharge hose				
Filtrol	89%	8–10 loads	It has a reusable mesh fabric filter	("Filtrol")
Lint LUV-R Microplastics	87–100%	2–3 loads	It has a steel grid, with a mesh size of 150 μm. It is based on a dynamic filtering mechanism It does not need replacement parts	("Microplastics LUV-R"; McIlwraith et al., 2019; Napper et al., 2020)
The Microfiber Filter by Girlfriend Collective	Percentage in process	3 loads	It has a steel grid, with a mesh size of 200 μm	("The Microfiber Filter")
PlanetCare	29–90%	15–20 loads	Full cartridges are sent back to the seller, allowing no direct contact with filtered fibres	("PlanetCare"; Napper et al., 2020)
Microplastics Filter by MarcelvangalenDesign	n.a	n.a	IoT device: check the state of the filter and make data available Under development	("MarcelvangalenDesign Microplastics Filter")
Eddy	n.a	n.a	It has a steel grid, with a mesh size of 5 μm. It is cleanable with the vacuum hose Not developed	("Eddy")
Fibio	97%	12–17 loads	It is an external filter with a drawer-like configuration	("Fibio")
Mimbox by Mimbly	n.a	n.a	Designed for shared laundry rooms Allows water and energy saving and microplastic filtration	("Mimbox")
b)Internal filters				
XFiltra	78–90%	n.a	Integrated in the washing machine It has a mesh size of 60 μm Under development	("XFiltra"; Napper et al., 2020)
FiberCatcher	90%	n.a	Integrated in the washing machine (Arcelik) Available starting from 2021	("FiberCatcher")
c)In-drum filtering devices				
Guppyfriend	54–86%	n.a	It is a PET washing bag with a mesh size of 50 μm It prevents fibres from shedding (− 86%) and collects released fibres	("Guppyfriend washing bag"; Napper et al., 2020)
Cora Ball	26–31%	n.a	It prevents fibres from shedding and collects released microfibres as fuzz	("Cora Ball"; McIlwraith et al., 2019; Napper et al., 2020)

n.a. not available

the production of microfibres and intercept those released. These systems are easily inserted into the drum during the washing; they are cheaper than the previous filters, but they are also less efficient.

4.2 Secondary Microplastics

Secondary microplastics derive from the degradation of bigger plastic debris that ends up in the ocean mostly because of mismanaged plastic waste. Thus, implementing better waste management is one of the main actions that could help reduce microplastics pollution. However, tonnes of plastic debris already pollute many aquatic environments, from the open oceans to the rivers and beaches, so their removal is also important. Without the removal of macroplastic debris, the level of microplastics in the ocean could double by 2050 as a consequence of the degradation of the already-accumulated plastic waste, as outlined by the recent research of Lebreton et al. (2019).

Much effort has already been made to collect macroplastic litter from the aquatic environment; in general, it can be distinguished between removal from the open sea and interception in rivers and coastlines. In fact, according to a recent study (Lebreton et al., 2019), nearly 67% of all the buoyant macroplastic released into the marine environment since the 1950s is still stored by the world's shoreline, as the debris is stranded, settled, and buried, or captured and resurfaced.

4.2.1 Ocean Clean-Up Technologies

The removal of macroscopic plastic waste is easier than that of microscopic waste because of its bigger size and also because it is concentrated in specific ocean areas, known as Ocean Gyres, where it is pushed by ocean currents forming the so-called Garbage Patches. Apart from focused expeditions, there are only a few solutions dedicated to a systematic clean-up of garbage patches.

The Ocean Cleanup The Ocean Cleanup is a non-profit organization that aims to remove plastic debris from the Garbage Patches, and it is actually the only one of this kind to date. It has developed a system that concentrates the plastic taking advantage of the natural oceanic forces, wind, waves, and currents ("Cleaning up the Ocean Garbage Patches"). The device consists of a long floater that provides buoyancy to the entire system and a skirt that hangs beneath it and prevents debris from escaping underneath. A speed difference between the system and the plastics is ensured through active propulsion to allow their catch and retainment. Thanks to the U shape of the floater, plastic debris is collected into a retention zone at its far end, from which it can be taken once the system is full. Collected plastic is then sorted and recycled. Since it is meant to stay deployed for long periods, the system is designed to withstand the forces of the ocean. Extensive measures are implemented to ensure the safety of the system and of vessels eventually passing through, even though no heavily trafficked shipping routes traverse the garbage patch, so the chances of a crossing vessel are minimal. The first trial campaign has been carried out in the Great Pacific Garbage Patch in 2019 and the collected trash has been processed and successfully recycled ("Cleaning up the Ocean Garbage Patches"). In 2021, the organization reached the proof of technology. Now, an upscaled, scalable, and fully operational version is under development.

Project Kaisei—Ocean Voyages Institute Ocean Voyages Institute is a non-profit organization founded in 1979 with the mission of teaching maritime arts and science and preserving the world's oceans. In 2009, it launched Project Kaisei, which focuses on major ocean clean-up in particular in the North Pacific Garbage Patch, promoting clean-ups through periodic vessel expeditions. Three expeditions have been organized so far, in 2009, 2010, and 2012 ("Project Kaisei").

4.2.2 Plastics Interception Technologies

Concerning the interception of plastic litter in rivers and coastlines, many different devices have been developed to date, for local customized applications or with scalability and adaptability purposes, but, in general, they can all refer to three main technologies and their combination: boats, barriers, and receptacles. They are mainly intended to be deployed in rivers, which have been identified as the main source of ocean plastic pollution, as they carry waste from the hinterland to the open sea (Lebreton et al., 2017; Meijer et al., 2021; Schmidt et al., 2017).

Table 3 Main features of plastic interception devices, according to their type of technology and preferable placement

Name	Technology	Location	Description	References
AquaPod *Clean Sea Solutions*	Receptacle	Harbours and coastlines	It is a flexible modular floating jetty equipped with an industrial centrifugal pump that creates a waterfall inside the system attracting plastic waste from the surrounding water surfaces. It has an integrated system for collection and storage, with a closing mechanism to prevent leakage and a lifting mechanism to ease the emptying. It can collect particles larger than 2 mm; it has a filtration capacity of 100 m^3/h and a storage capacity of over 700 l. It has Internet connectivity for constant monitoring and notifications	("AquaPod")
Interceptor *The Ocean Cleanup*	Boat	Rivers	It is made of three main parts: a barrier, a conveyor belt, and a shuttle. The floating barrier guides river waste towards the opening; conveyor belts continuously extract debris from the water and deliver it to the shuttle, which automatically distributes debris across six dumpsters for a total capacity of 50 m^3. The catamaran design optimizes water flow path to pass through the system carrying the plastic onto the conveyor belt. It requires external ships and operators only to empty the dumpsters. It is completely solar-powered and designed for series production. At the time of writing, five Interceptors have already been deployed in some of the most polluted rivers of the world	("The Interceptor")
Manta Project *The Sea Cleaners*	Boat	Coastlines	It is a processing ship for the collection, treatment, and upcycling of micro- and macroplastic litter. It is equipped with floatable collection systems, waste-collecting conveyors, and cranes, and it is supported by smaller collection boats. Its launch is expected in 2025	("Manta Project")
Blue Barriers *Sea Defence Solutions*	Boom	Rivers	It takes advantage of water flow to push floating litter towards a collection basin on the side of the river. It is made of two or more modules to allow boat navigability and to guarantee no impact on river life. It also stops the waste under the water surface, and it works in both standard and flooding conditions	("Blue Barriers")
River Cleaning system	Boom	Rivers	It is flexible, modular, scalable, and adaptable to any watercourse. It is made up of a series of floating self-levelling devices located diagonally on the course of the river. Each device is a rotating plate activated by the river current and anchored as a common buoy, allowing boat passage. The chain of devices intercepts the sailing waste and diverts it by transferring it from one device to another, up to the storage area on the riverbank. It has a collecting efficiency of 85%	("River Cleaning system")

Table 3 (continued)

Name	Technology	Location	Description	References
The Great Bubble Barrier	Boom	Rivers	It is able to remove waste from the entire water column thanks to a perforated tube located on the bottom of the waterway. Air is pumped through the holes creating a bubble curtain that pushes plastic waste towards the surface. The diagonal placement of the bubble curtain in the waterway directs the floating waste towards the side catchment system. Bubble curtain also reduces noise pollution and increases the dissolved oxygen rate, with benefits for the aquatic ecosystem	("The Great Bubble Barrier")

Boats are usually employed to gather floating plastic waste from well-known hotspots along rivers and they are often equipped with booms for this purpose. Floating barriers are also frequently deployed in rivers to intercept floating litter and prevent it from reaching the open sea. They are usually low-tech and low-cost technologies that can be settled also in poor countries. Receptacles are instead mainly used in closer areas, such as marinas and harbours, which are other relevant pollutant areas due to the many occurring human activities. However, receptacles can also be installed in rivers to gather the plastic waste intercepted by the booms. The employment of boats for litter collection often implies a huge consumption of fuel to perform every mission, contributing to another form of environmental pollution; instead, most of the boom technologies obstruct the river flow, thus not fitting for navigable rivers.

The existent solutions for ridding rivers and oceans of plastic have been recently inventoried by other authors and are not analysed in this work (Helinski et al., 2021; Schmaltz et al., 2020). Table 3 only summarizes some of the most innovative devices that are engineered to overcome the main flaws of these technologies.

5 Conclusion

This paper provides an overview of the existing and developing solutions to tackle the problem of microplastics environmental pollution. Given the complexity of the problem, information is categorized by spot—removal after spread or interception at source—and by origin—primary or secondary microplastics. In fact, microplastics pollution has a multiplicity of implications and hence it must be faced from several sides. Certainly, dispersed microplastics must be urgently removed from the environment to limit their harmfulness. Then, as a long-term goal, their further production and emission must be prevented, intercepting them before their release and withdrawing potential sources. Finally, the removal of scattered plastic waste must be paired with the enhancement of its collection and disposal, to progressively reduce the mismanaged fraction. Thus, a single solution would be insufficient to solve microplastic pollution, but every solution contributes to tackling it and herein an overview of the main relevant ones has been presented.

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Declarations

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