Analysis and Prevention of Microplastics Pollution in Water: Current Perspectives and Future Directions

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ABSTRACT: The analysis, prevention, and removal of microplastics (MPs) pollution in water is identified as one major problem the world is currently facing. MPs can be directly released to water or formed by the degradation of bigger plastics. Nowadays, it is estimated that annually between 4 and 12 million tonnes of plastic go into the seas and oceans—with a forecast for them to outweigh the amount of fish in 2050. Based on the existing studies, the characterization of MPs in waters is still one of the remaining challenges because they can be easily confused with organic or other types of matter. Consequently, there is an urgent necessity to establish pathways for the chemical identification of the MP nature. In this perspective, the recent techniques and instrumentation for MP characterization (Raman and Fourier-transform infrared spectroscopies and microscopies, pyrolysis and thermal desorption gas chromatography, imaging techniques, etc.) are discussed including considerations to the multidimensionality of the problem. This perspective also summarizes and provides updated data on the sources and occurrence, transport and fate of MPs in aquatic ecosystems, as well as influencing conditions and factors affecting dispersal. Additionally, how engineering and biotechnological tools, such as advanced water treatments, would help to control, reduce, or even eliminate MP pollution in the near future is outlined.

1. INTRODUCTION

The term "microplastic" (MP) was formally introduced in 2004 by Thompson et al., who alerted to the growing problem of the plastic release to the seas. Since then, its presence in the environment has gained an increasing attention among the scientists, authorities, general population, and in the media. Although neither official definition or full agreement within the authors exists, MPs are generally defined as plastic fragments smaller than 5 mm in any dimension with an indeterminate lower limit. The recent introduction of the term "nanoplastics" (commonly <100 nm in any of their dimensions) is establishing a lower limit to these particles. However, studies showed certain discrepancies on the range of MP sizes as well as an evolution of the terminology according to their impact (Figure 1).

MPs are often classified into two categories: primary and secondary. Primary MPs are those already manufactured with a microsize, including the microspheres (<500 μm) contained in some cosmetic products, mixtures used for sandblasting/shotblasting, and MPs employed as pharmaceuticals vectors and to form 3D printing. Secondary MPs are the products of degradation of larger plastic materials, from mechanical or photo-oxidative pathways. To give an idea of the magnitude of this contamination in water, it is estimated that 1.5 million tonnes of primary MPs are released into water yearly. Plastics mismanaged waste entering into the aquatic environment, which could form secondary MPs, is higher in almost all countries with the exception of EEUU (Figure 2). MPs can be also categorized by their form, commonly in fibers, fragments, and spherical beads, as well as by their chemical composition, for example, polyethylene (PE), low-density PE (LDPE), PE terephthalate (PET), polycrylates (PA), and so on. MPs can be divided into many groups depending on the characteristics considered, describing a diversified class of materials that includes a wide range of polymer types, particle sizes (ranging over 6 orders of magnitude), shapes (from spheres to fibers), and chemical formulations (thousands of different types), which are likely to be found in water.

Nowadays, MPs have already been ubiquitous reported in almost all aquatic habitats of the planet, from the open seas to deep oceans, river, lakes, the water column, and sediments. The most pessimistic predictions on the impact of MPs establish that their amount will overpass that of fish by 2050. It has been demonstrated both in the laboratory and in nature
that animals can take up MPs. Effects are still largely unknown but are increasingly the subject of scientific scrutiny, as MP pollution is suspected to rapidly increase in water in the future. However, one of the gaps reported almost everywhere is the difficulty to establish the distribution and to quantify the amount of MPs in waters. This is attributed to the lack of proper and harmonized sampling and analysis methods. This growing concern is parallel to the increase of the production linked to the steady demand growth, which reached 49 million tonnes in Europe and 322 in the world in 2015. Plastics and, consequently, MPs are very stable and therefore stay in the environment a long time after they are discarded (Table 1).

Table 1. Several Characteristics of the Most Common Plastics Found in the MPs

| name                        | acronym | products                           | density (g/mL) | life span (years) |
|-----------------------------|---------|------------------------------------|----------------|-------------------|
| polyethylene terephthalate  | PET     | water bottles                      | 1.37−1.45      | 20                |
| polyester                   | PES     | polyester clothes                  | 1.39           | >20               |
| low density polyethylene    | LDPE    | plastic bags, squeeze bottles      | 0.917−0.930    |                    |
| high density polyethylene   | HDPE    | detergent bottles                  | 0.93−0.97      | >28               |
| polyvinylchloride           | PVC     | pipes, electric cables, clothing   | 1.20−1.45      | 140               |
| polypropylene               | PP      | clothing, stoppers                | 0.89−0.94      | >100              |
| polyamide                   | PA      | textile (Nylon), tooth brush       | 1.13−1.35/1.41 | >20               |
| polystyrene                 | PS      | ready-to-eat food                 | 1.04−1.11      | 50                |
| acrylonitrile-butadiene-styrene | ABS   | pipe systems, musical instruments | 1.04−1.06      |                    |
| polytetrafluoroethylene     | PTFE    | plain bearings, gears, slide plates, seals, gaskets, bushings | 2.10−2.30 | >140               |
been adopted to remove MPs from water sources, including biotechnology and engineering tools.22 However, removal techniques are still in its infancy with a number of issues not addressed yet.20

This perspective summarizes the advances in the analysis and prevention of MP’s pollution in water in order to perform an overall assessment of the situation in the aquatic environments. Through this analysis, several knowledge gaps and research biases in MP pollution and remediation in water are identified. Finally, a number of explicit proposals to fill these knowledge gaps are outlined.

2. METHODS OF SAMPLING AND ANALYSIS

A large number of analytical methods for determining MPs in water have already been published and several literature reviews compiled these methods.12,23–25 The determination of MPs in water samples involves 5 steps: sampling, separation, clean up, identification, and confirmation (Figure 3).

2.1. Sampling, Separation, and Clean-Up. The main difficulties in sampling are representativeness and integrity. First, MPs are not homogeneously distributed in the water column but depending on MPs characteristics (density, shape, size) and environmental variables (type of water, streams, waves).12,16 Thus, one identified gap is that MPs profiling will be highly conditioned by the sampling method and there is no consensus on it. Three approaches—nets, sieves, or pumps—are commonly used.12 The sample methods to determine MPs in seas and surface water are almost the same. The most common is the surface sampling with Neuston nets because they sampled large water volumes quickly. However, a study comparing different net-based sampling devices with different mesh sizes including bongo nets (>500 μm), manta nets (>300 μm), and plankton nets (<80 μm) showed that the use of lower mesh-size nets multiplied by 10 000 the number of MPs but decrease the resistance to clogging by organic and mineral suspended matter; so, the volume of water that passes through them must be reduced with lose reproducibility.26 Multiplying the number of samples could be a solution to increase sample representativeness.27 Alternatively, the use of filter cascades can reduce the matrix burden of the small mesh sizes and also result in a size fractionation during the sampling.27

Sampling in the water column is carried out by direct filtration of the water with submersible Teflon pumps, acquisition of batch samples, or plankton or bongo nets30 but has only been reported occasionally. Sampling at the wastewater treatment plants (WWTPs) is carried with pump filtration devices,31–35 batch samples,36 or 24 h composite samples.37 A high-volume homemade sampling device that fractionated MPs in situ using different mesh sizes has been able to process large volumes of several types of water (reversed osmosis samples up to 200 L, primary effluent between 16 and 100 L).38 Up to the moment, drinking water is grab-sampled and filtered at the laboratory or directly filtered through 3 μm stainless steel cartridge filters placed in filter housings. These samples were always passed through small pore size filters (0.2–3 μm) than those used in other types of samples involving several-step filtration through descending mesh size to pass the entire sample volume through the filter without clogging.39,40

Although some sampling methods are already well-established and their advantages and disadvantages have been discussed,41 there is an absolute lack of standardized method or guidelines to sampling water for MPs. Particularly, the use of different mesh sizes makes it difficult to compare the available monitoring data. Another problem of the MPs analysis, which begins with sampling but creeps through all remaining processes, is contamination due to MPs deposition from the atmosphere and through sampling or laboratory materials or operator clothes. Many studies tackled the problem and gave recommendations to avoid contamination that cover four aspects: (i) operators cloth protection, (ii) appropriate cleaning of the material, (iii) protect samples for the air, and (iv) perform sampling and laboratory blanks. Although it has been a widely treated topic, there is not a consensus among the different studies collaborating to make difficult the comparability.24

![Figure 3. Scheme of the different steps involved in sampling and analysis of MPs in water.](image-url)
The MPs isolated in the nets and sieves are commonly transferred to glass bottles using water (the so-called reduced sample). The reduced samples or the grab samples need further treatment to isolate the MPs.24,42 First, samples are filtered again using stain steel sieves or glass fiber filters. In the case of grab samples, the pore size of the filter is very important because this size determines the lower limit of the MPs isolated, whereas in the case of reduced samples, the MP lower limit isolated is already established by the size of the net.26 The next step is to distinguish MPs from other potential interferences, such as organic matter that could be easily confused with MPs. Thus, the separation of MPs from natural organic matter (O.M.) minimizes misidentification or underestimation of MPs. This separation can be carried out by oxidation of the organic matter and/or by density separation. The detected gap within these studies is the lack of systematic studies comparing the efficiency of the different methods and offering guidelines and established protocols.3 Many of the studies does not include information on the validation parameters, such as recovery, linearity, accuracy or sensitivity, or comparison with other methods. Neither development of reference materials or consensus on materials used as analytical standards has been achieved. Only one study, up to our knowledge, compared density separation methods (using sugar, olive oil, and ZnCl₂), and organic matter degradation methods (wet hydrogen peroxide oxidation) and BEPP to assess effectiveness, economical cost, time spent, simplicity, quality, and the total mass of recovered polymer. The ZnCl₂ density separation, wet peroxide oxidation, BEPP + wet peroxide oxidation, and BEPP are the more efficient methods (>90%). Among the methods that involved the degradation of organic matter, wet peroxide oxidation, and its combination with a BEPP were more efficient than the BEPP alone.20 As can be observed to monitor MPs in water, a broad array of analytical methods can be used. Many more studies comparing the extraction methods proposed up to the moment are needed to establish unique protocols and to know their advantages and pitfalls.

2.2. Identification, Quantification, and Confirmation. Interestingly, Renner et al.43 worked through more than 170 peer reviewed research papers published between 2015 and 2017 and dealt with MPs analysis to figure out how identification of MPs is currently performed. The detection, identification, sizing, and quantification of MPs is in 79% of the studied carried out by visualization (naked-eye or using a microscope). MPs are identified by their unnatural coloration (e.g., bright blue and multicolored) and/or unnatural shape (e.g., fragments with sharp edges, perfectly spherical).44 (Figure 4). However, even though clean-up to eliminate organic matter has been performed, MPs can easily be mistaken for other spherical anthropogenic particles (fly-ash, particles in road paint, metal fume, fish scales, ceramic flakes, etc.). Several physicochemical tests can help in the visual inspection (i.e., staining of natural and nonplastics particles),38 heating MPs at >100 °C,45 hot needle point for fibers,46 There has also been an evolution of the MPs visualization techniques to see lower size MPs parallel to the use of smaller net sizes. Visual counting with a stereomicroscope or an optical microscope is time-consuming and prone to human error but is the most well-established technique for quantifying MP.

Visual inspection alone is not adequate to characterize MPs, physical analysis is generally a more reliable way.32,47 Vibrational techniques—Fourier-transform infrared spectroscopy (FT-IR) and Raman spectroscopy, their microscopy versions (µFT-IR or µRaman) and their recently developed imaging version—have been the most widely applied techniques (28 and 14% of the studies, respectively, according to Renner et al.43). These techniques offer available libraries that help in the identification. The attenuated total reflection technique is preferred in FT-IR because its more efficient for thick samples as MPs but its inconveniences are the lack of sensitivity and that is not so efficient to detect low-size MPs.24

Apart from different IR absorption or Raman scattering properties,48 pyrolysis-gas chromatography/mass spectrometry (Pyr-GC-MS)59,60 or thermogravimetry coupled to differential scanning calorimetry51 is increasingly used to characterize MPs; we have still little examples of their applications (<10% of the studies according to Renner et al.43). Both techniques are based on the preliminary thermal decomposition of MPs in their monomers and additives. Although there is no enough

Figure 4. Typical appearance of different polymers detected in different stages of the WWTP and recipient lake and identified by micro-FTIR and/or micro-Raman. (A–E) Polyester, (F–I) PE, (J–K) polyamide and (L) polypropylene. Reprinted from ref27 Copyright (2018) with permission from Elsevier.
information yet to establish their advantages and disadvantages to chemically identify MPs, it is exciting to speculate on the prospects that these new techniques could open within the field.

3. TRANSPORT, DISTRIBUTION, AND FATE

Runoff from urban, agricultural, and recreational activities, indiscriminate disposal (plastic bottles, packaging, and shipping), industrial release (including fisheries and cosmetics), atmospheric fallout, and WWTP effluents are among the multiple plastic and MPs sources to the environment. Limited data exist that describe the processes and mechanisms removing plastic debris from the surface water. These processes include sedimentation, shore deposition, fragmentation, and ingestion (Figure 5). Combined with physical abrasion and/or microbial populations, exposure of plastic to solar UV radiation would result in photodegradation, break, and fragmentation. Aquatic organisms ingest MPs that accumulate through the food chain more readily than larger plastics. Their bioaccumulation potential increases with decreasing size. These studies have raised concern about detrimental effects of MPs in marine and freshwater ecosystems. Although the currently available information is somehow contradictory, plastics can absorb surrounding organic contaminants and serve as attachment media for pathogens acting as vectors to organisms for these chemical and microbial contaminants. More relevant is that once the MPs have been degraded enough, they release not only monomers but also toxic additives contained in almost all plastic materials since levels are much higher. It is demonstrated that ingestion of MPs by aquatic biota increases the bioaccumulation of plastic additives. In the environment, MPs and NPs may undergo various transformations commonly associated with natural or anthropogenic colloids, namely, homo- and heteroaggregation, interactions with microorganisms and macromolecules (e.g., adsorption of proteins, natural organic matter), and biodegradation. Few studies have examined the transformations and transport of natural colloids and how these environmental processes and conditions affect different types of MPs. This missing information together with the need to enlarge knowledge on MPs effects are important gaps to fill within the field.
Up to now, the majority of research conducted on plastic pollution (all size fractions) has focused on marine ecosystems. The frequency of occurrence of plastic debris in the surface samples of the open ocean was considerably high (88%; Figure 6). Plastic debris has accumulated in the ocean surface because its density is generally less than that of seawater. Oceanic circulation models predict possible regions of accumulation in the five subtropical oceanic gyres associated with the confluence of surface currents. In addition, the high concentrations of floating plastic debris that have accumulated in the North Atlantic may be due to the higher presence of densely populated coastal areas. Results of these models were further confirmed by the distribution pattern of plastic debris in the ocean surface that agreed with those predicted.

MP concentrations have been also reported in rivers, lakes, wetlands estuaries, and even on WWTPs. However, the comprehensive examination of this freshwater plastics literature shows that it is still scarce and fragmented, owing to the numerous differences between freshwater studies (including studied species and habitats, geographical locations, social and economic contexts, the type of data obtained, and also the broad range of purposes). This highlights the lack of a holistic view and indicates several information gaps and inconsistencies of MP pollution research within freshwater ecosystems.

One of the topics still little exploited is the presence of MPs in drinking water, even though it is of growing concern as one of the potential routes of exposure to humans. The presence of anthropogenic particles were reported in the 81% of 159 samples of globally sourced tap water. The majority of these particles were fibers (98.3%) between 0.1 and 5 mm in length. The range was 0–61 MPs L\(^{-1}\), with important differences according to the country (Figure 7). Pivokonsky et al. investigated MPs (size up to <1 μm) in raw and treated water of three water treatment plants supplied by reservoirs or river waters. The average abundance ranged from 1473 to 3605 particles L\(^{-1}\) in raw water and from 338 to 628 particles L\(^{-1}\) in treated water mostly with size <10 μm. Contrarily, Mintenig et al. analyzed ground water and drinking water for the presence of MPs (>20 μm). Concentrations ranged from 0 to 7 × 10\(^{-3}\) MPs L\(^{-1}\) raw water or drinking water with an overall mean of 0.7 × 10\(^{-3}\) MPs L\(^{-1}\). The difference could be explaining taking into account the different water supplies, surface waters in the former and groundwater in the latter, as well as the different MPs size covered. More global toxicological study is needed, together with further epidemiological evidence, for a comprehensive assessment of the possible risks resulting from the ubiquitous exposure to MPs.

### 4. REMEDIATION STRATEGIES

Strategies to solve the problem of MPs pollution should focus on (i) source control commonly achieved by legislation and awareness programs and (ii) remediation and clean up (to eliminate the MPs already present in water).

There are some legislative measures already in force in order to decrease MP release. Since 2017, US already banned the used MP beads in the cosmetics products. Many other countries including Australia, Canada, or European Union (EU) are also thinking in implementing effective measures in the same sense. The MPs used in cosmetics is the most important source of primary MPs to the environment. Regarding plastic (potential source of secondary MPs), there are also important effort to restrict the sale and consumption of single-use plastics, with a focus on plastic straws and plastic bags. Many countries have established restrictions to the use of single-use plastic bags. As an example, the EU in a recent press release has proposed a Europe-wide strategy on plastics, as a part of the transition toward a more circular economy. Under the new plans, all plastic packaging on the EU market will be recyclable by 2030, the consumption of single use plastics will be reduced, and the intentional use of MPs will be restricted. These legislative measures needs of the public enrolment to be effective. The combined approach of the levy and a restriction on plastic bag use applied in the program is an attempt to educate the public and increase their awareness on the environmental hazards of using plastic bags.

This restriction in the production and use of MPs is going in parallel to large-scale clean-up of plastics in the oceans and the increase application remediation technologies to reduce plastic pollution of water ecosystems. The former is based on floating systems that intercept and capture plastics. It is expected that this can remove half of the plastic in the Great Pacific Garbage Patch within five years’ time. Remediation technologies can be divided in (i) engineering tools, (ii) use of biobased or biodegradable polymers, and (iii) biotechnological tools. The first comprises advanced wastewater and drinking water treatment technology. The latter involves the application
of bacteria to biodegrade the plastics already present in the environment. The EU press release also highlights the need to drive investment and innovation in these fields in order to ensure a reduction of MP contamination.75

4.1. Engineering Tools. WWTPs are a source input of microliter and MPs to the environment. Then, these plants provide an opportunity to develop and implement novel technologies to manage MP pollution. Several studies evaluated the capacity of conventional and innovative WWTP technologies to remove plastics.27,80,81 These studies show that conventional WWTP treatments eliminate a high percentage of the MPs present in the influents (between 90 and 98%).27,82 Despite this, effluents are a source of microliter and MPs into the aquatic environment due to the large volume of effluent discharged constantly.80 The advanced wastewater technologies more frequently used are membranes, electro-deposition, and coagulation. The membrane bioreactor (MBR) — the combination of a membrane process like microfiltration or ultrafiltration with a biological wastewater treatment — is one of the most promising. This technique showed better removal efficiency of MPs (99.4%) compared to the overall conventional activated sludge-based process (98.3%).81 The efficiency of an MBR system that finishes treatment with microfiltration in removing MP s was also compared to that of WWTPs employing either secondary treatment (activated sludge) or tertiary treatment (granular sand filtration) as a final step.71 The MBR system provides the highest removal rate (99.4%) discharging 0.5 MP s L\(^{-1}\) (Figure 8).

MBRs have also been compared to other innovative tertiary treatments, such as rapid gravity sand filters and dissolved air flotation that provide removal rates of MP s >95% from primary and secondary effluents. The biologically active filter (BAF) process (filter that allow the growth of contaminant degrading microorganism in it) showed also high efficiency to remove MP s.81 The removal of microliter from wastewater during different treatment steps of mechanical, chemical, and biological treatments (activated sludge) followed by BAF in a large (population equivalent 800 000) advanced WWTP showed an overall retention capacity over 99%.80 MBR and MAF are already implemented in many WWTP showing their industrial viability, even though they are more expensive than other tertiary conventional treatment.

Furthermore, the efficacy of electrocoagulation (EC), a well-known and established process for MP removal from wastewater streams, has also been studied using artificial wastewater containing PE microbeads at different concentrations. Microbead removal efficiencies >90% were observed in different conditions (initial pH, NaCl concentration, and current density), thus suggesting that EC is an effective method of removing MP s from wastewater streams. The optimum removal efficiency of 99.24% was found at a pH of 7.5.44 This technique has been tested in a bench-scale stirred-tank batch reactor (1 L) and could be viable at the large scale using an industrial EC cell with a two-stage, continuous EC reactor/settler unit.

Some of the technologies applied to wastewater have possibilities to be extended to other freshwater systems, such as the pH-induced aggregation and subsequent removal of particles from water.83 This two-step-based process includes first a localization and second an aggregation of MP particles (250–350 μM) in a physicochemical process. This process is based on the strong increase in the particle size independent of pH of the aquatic milieu induced by the addition of trichlorosilane-substituted Si derivatives. The resulting Si-based MP aggregates (particle size after aggregation is 2–3 cm) could be easily removed by the use of, for example, sand traps. This process proved to be transferable and reproducible from the laboratory scale to the industrial scale.

Effluents of washing machine are one of the major sources of MP s and fibers in municipal and surface water. The impact of these effluents could be alleviated treating them before their discharge into the sewer system84 by electro-oxidation (EO) in an electrochemical flow reactor using active (Ti/Pt) or non-active (boron doped diamond (BDD)) anodes and Ti cathode. The BDD anode showed a well-defined trend as well as higher removal efficiency at all current densities studied when compared to Ti/Pt. Besides, faster and higher COD decay was attained by adding Na\(_2\)SO\(_4\) to the effluent compared to as-received effluent regardless of the anode material used. Active chlorine species were also electrochemically produced at both anodes from the Cl\(^-\) ions in the real effluent, contributing to the elimination of the fibers and MP s. Based on the reported results, EO could become an efficient and effective treatment approach for the remediation of MP s and other pollutants in washing machine effluents especially with the BDD anode.
These results up to the moment only establish the applicability of prepiilot electrochemical plants.

As MPs have been gradually detected in freshwaters, understanding how MPs, with their small particle size and low density, will behave during current drinking water treatment processes is urgently needed. However, up to the moment, only the PE removal behavior with commonly used coagulants and ultrafiltration membranes was systematically investigated.41 Results showed that Al-based salts performed better in PE removal efficiency than Fe-based salts. The smaller the PE particle size, the higher the removal efficiency. Polyacrylamide (PAM) addition played an important role in removing PE, especially anionic PAM addition, because of the positively charged Al-based flocks it generates under neutral conditions. For ultrafiltration, although PE particles can be completely rejected, slight membrane fouling was induced after coagulation with conventional Al-based salts. Based on this study, coagulation and ultrafiltration processes have potential application in drinking water treatment to eliminate MPs. However, the study was performed only at the laboratory scale but both techniques are viable at the large scale.

This information altogether pinpointed how advanced final-stage water treatment technologies can substantially reduce the MP pollution discharged from WWTPs into the aquatic environments as well as help to remove these contaminants from freshwater ecosystems and drinking water.

4.2. Use of Biobased and/or Biodegradable Polymers.

Other strategy to solve the problem of the presence of plastics, MPs, and NPs is to use more biodegradable materials.22 Bioplastics are made of renewable starting materials, such as starch, cellulose, lignin, and bioethanol. Currently, bioplastics represent about 0.5% of the about 335 million tonnes of plastic produced annually, which is expected to increase to approximately 2.62 million tonnes in 2023.63 Bioplastics can be classified in three groups:

- Biobased or partially biobased non-biodegradable such as, biobased PE, PP, or PET (so-called drop-ins) and biobased technical performance polymers, such as polytrimethylene terephthalate or thermoplastic polyester elastomers. These polymers are made of biological sources but as persistent as petroleum-based one.

- Simultaneously biobased and biodegradable, such as polyactic acid and polyhydroxyalkanoates or polybutylene succinate. These help to solve the urgent problem of pollution.

- Based on fossil resources and biodegradable, such as polybutylene adipate terephthalate or polycaprolactone diol. These also help to solve the problem of pollution but not the dependence of fossil resources.

Biodegradable plastics are capable of undergoing biological anaerobic or aerobic degradation. A major problem with these plastics is that they have the potential to be biodegraded, but this process requires suitable conditions and microorganisms that are not always reliable in environmental conditions. However, one study on the chemical modifications in the surface of commercial PCLD (average molecular weight of 1250 Da) incubated under aerobic and denitrifying conditions showed chemical modifications in the sample surface after 7 days allowing to be optimistic on this MP elimination in the WWTPs.80 This also pointed out the importance to specify the environment where biodegradation is intended to take place.

Some biodegradable bioplastics are also compostable that can be broken down by microorganisms into nutrient-rich biomass in as little as 3 months and leave behind no toxins or residue. Compost has many beneficial uses including improving and fertilizing soil. The European Standard EN 13432 lays down criteria for what can or cannot be described as compostable and what can be called biodegradable. The US Standard ASTM D6400-99, Canadian BNQ 9011-911/2007, and Japanese JBPA/2011, set out similar standards. The term compostable is nowadays preferred to that of biodegradable because it can be defined based on evidence.85

4.3. Bioengineering-Based Solutions.

The other bioengineering-based solution is to search new biodegradation routes for classical plastics, like different types of bacteria and fungi or isolate the involved enzymes to ensure the enzymatic hydrolysis of plastics. Biodegradable polyesters can be hydrolyzed by extracellular carboxylesterases.76 Plastics can be degraded by specialized bacteria, for example PET can be breakdown by Ideonella sakainensis77 and PE by the marine fungus Zalerion maritimum.87 Despite the alternatives that seem promising, the remediation of macro and MPs is in its infancy at the laboratory scale. It is crucial to develop strategies for in situ biodegradation of MPs by addition of microorganisms or by enhanced natural attenuation using native microflora. However, the present and future importance of the bioengineering-based solutions needs considerable further research and development to make it suitable for large scale application. It is clearly needed to move toward a more sustainable and circular plastic economy, and biotechnology-based strategies are the interesting approaches to apply in order to palliate what may be the most worrying environmental issue of our time.

5. CONCLUSIONS

In this perspective paper, the main analytical advances to identify, characterize, and quantify MPs have been summarized. With the latest advances in analytical technologies, most MPs can now be sampled, isolated, and extensively characterized. However, several needs, such as standardization/homogenization of the methods to facilitate comparison of the results obtained in different studies, establishment of guidelines to validate analytical methods, development of reference materials, and interlaboratory exercises, are identified. We believe that further exploration and gap analysis are of great importance for determining priorities in implementing solutions and developing new approaches important in the future.

Much progress has been made in the past few years in understanding the sources, transport, fate, and biological effects of MPs in aquatic ecosystems. The first important pillar is the evidence of the occurrence and accumulation of MPs in any aquatic environment. However, there is still little knowledge on the effect in different species as well as the effects of several types of plastics with different chemical compositions and different forms. Recent findings of MPs in drinking water have raised concern on human exposure to these particles (with food and air as additional sources of exposure). At present, although there is no reason to be an alarmist about the health effects, more research is needed to establish the hazard of these particles to humans. Nevertheless, since MPs have proven to be an environmental threat, measures addressed to reduce the release of plastics and
primary MPs and to eliminate the already existing MPs have become crucial.

Governments are dealing with the problem of MPs and we will see in the next coming years more measures in the direction of pollution prevention, like restricted use of plastic bags, plastic bottles, other plastic materials, and so on. In this respect, the European Union indicated in a recent press release that in the year 2030, all plastic packaging on the EU market would be recyclable. These legislative decisions must be supported by the development of smarter and more recyclable plastics materials, making recycling processes more efficient by the study and isolation of degrading microorganisms, and tracing and removing MPs through advanced wastewater treatments. Suitable combinations of these processes may modulate and reduce MP pollution in water. Furthermore, continuous press releases and information to the public in general from governments, nongovernmental organizations, and scientists are needed in order to reduce the use of plastic. These measures together with additional recycling/remediation/removal technologies will help to reduce plastic and litter pollution in our planet.

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