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Microplastics – Part 2: Evaluation of the microplastic pollution and treatment strategies in the wastewater treatment

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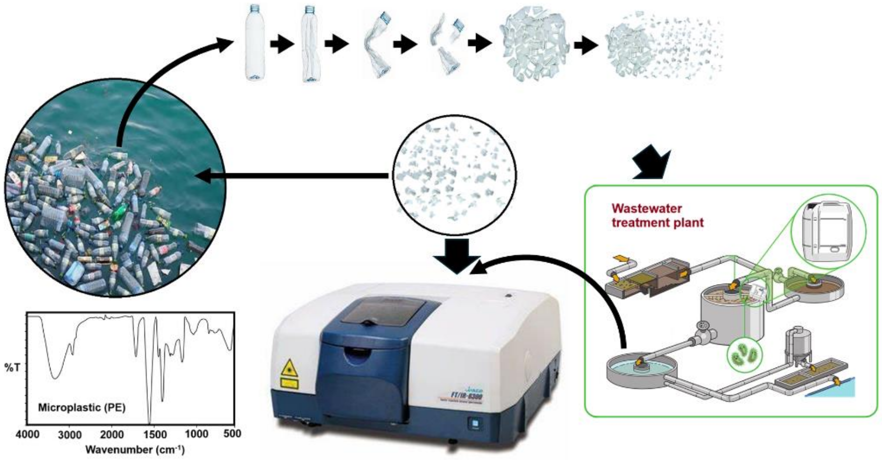
Graphical Abstract



Abstract. The main problem behind plastics lies in the difficulty of their biodegradation as well as in their uncontrolled use and the poor management of waste after the useful life cycle is completed. The objective of this article is to give an overview of the different approaches to the study of microplastics and elimination strategies in water treatment systems. As a result, large quantities of plastic materials are exposed to conditions that promote the physical degradation of these materials, reducing their size until they become a microscopic problem: Microplastics (MPs). Pollution by MPs represents a current challenge, and although elimination strategies in wastewater treatment plants are somewhat effective, more holistic approaches are required that include, among other things, public awareness campaigns on the environmental impacts of contamination by plastic materials, adopting responsible consumption habits, and proper disposal of plastics. From this approach, it is evident that preventive efforts, in order to avoid increasing the problem, involve collaboration between government agencies, the industrial sector, academia, and civil society.

Keywords: Microplastics, wastewater treatment, analysis of microplastics, plastic-by water pollution.

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Content

1. Introduction: An overview of microplastic pollution

Plastic materials with structural polymers of synthetic origin are widely used in the industry to manufacture many objects with the most varied applications. These materials are one of the main materials manufactured by humans throughout their evolution, which can be defined in terms of materials from the Stone Age to the Anthropocene. Under this approach, it is interesting to highlight that the advances of civilization begin with stone (materials of difficult malleability and molding, high density and hardness), continue with materials such as metals and their alloys (malleable, moldable, hard materials, and with relatively low density compared to stone), until reaching plastic materials (malleable, moldable, chemically resistant materials, with variable physical properties and low density) (Luna, 2020; Porta, 2021; Thompson et al., 2009). However, the term Anthropocene refers to the period in human history where its ecosystems are strongly influenced by human activities, including, for example, the chemical content of the atmosphere, soils, bodies of water and forests, sea level, climate, living organisms that inhabit the planet, etc. Consequently, the presence of plastics can be considered a decisive factor in defining the Anthropocene (Liu et al., 2021; Porta, 2021; Thomas, 2022). The massive and excessive use of plastics brings with it the dumping of these materials into the environment and at accumulation and treatment points. In addition, the difficulty of their biodegradation and the poor management of waste make plastics and their derivatives in size, microplastics (MPs), a new type of emerging pollutants. MPs are also industrially manufactured for different applications and are characterized by being non-biodegradable, water-insoluble, and of non-biological origin (Chellasamy et al., 2023; Hajji et al., 2024; Komorowska-Kaufman and Marciniak, 2024). In terms of their size, MPs are particles with a size less than 5 mm, which is clearly a reference definition rather than the result of their physicochemical properties or behavior (Chellasamy et al., 2023). Among the MPs identified in environmental samples and water treatment plants are Bakelite, rayon, nylon, polystyrene (PS), polyvinyl chloride (PVC), polypropylene (PP), polyethylene terephthalate (PET), polyurethanes (PUs) and polyethylene (PE) (Bodus et al., 2024; Chellasamy et al., 2023; Liu et al., 2021; Porta, 2021; Sudarsan et al., 2024; Thomas, 2022). When plastic materials reach the end of their life cycle, they are discarded and accumulated in landfills and recycling points, and some of them are reused. Due to the evil of waste, many plastics are dumped directly into the environment, so this waste has become a new environmental, technological, and logistical problem (Bodus et al., 2024; Liu et al., 2021; Um et al., 2023). Among the most common plastic waste are PP, PE, and PS, followed by PVC, PU, and PET (Iheanacho et al., 2023; Um et al., 2023), but also, poly(methylmethacrylate) (PMMA), polycarbonates (PC), and others (Ahmed et al., 2024; Franco et al., 2020; Liu et al., 2021).

MPs can be understood as emerging contaminants resulting from poorly managed plastic waste's physical and chemical degradation. When plastic waste is released into the environment, these macroplastics progressively reduce in size through physical and chemical weathering processes (humidity, thermal degradation, photolysis, mechanical breakdown, and hydrolysis, among others). As their size decreases, MPs have greater mobility; consequently, contamination by this type of microparticles is expected to show a greater extension in terms of surface area, as well as an accumulation in natural water reservoirs such as rivers, swamps, lakes, reservoirs, and seas, etc., or waste, for example, treatment plants, landfills, and valleys. Their small size, composition, accumulation, and mobility make MPs difficult to detect, distinguish, manipulate, have a high adsorption capacity, ingestion by animals and bioaccumulation (Ajithkumar et al., 2023; Franco et al., 2020; Komorowska-Kaufman and Marciniak, 2024; Liu et al., 2021; Luna, 2020; Monira et al., 2023; Palencia et al., 2021; Porta, 2021; Thomas, 2022; Sudarsan et al., 2024; Talukdar et al., 2024; Thompson et al., 2009; Um et al., 2023). It is estimated that approximately 13 million tons of plastic waste are released into the aquatic environment, and 5.25 trillion MPs are discharged into the oceans (Komorowska-Kaufman and Marciniak, 2024; Monira et al., 2023; Sudarsan et al., 2024; Talukdar et al., 2024).

Different levels must be taken to reduce MPs pollution. The first of these is to identify the magnitude of the impact on the environment and human health, including the risks and effects, extent and characteristics, as well as their dynamics in each of the phases that contain them. In addition, at a second level, appropriate study methods must be available, both at the level of identification, characterization, and quantification. This stage implicitly involves isolating the natural media that contain them, which, according to the available studies, are varied in nature, characteristics, and complexity. A third level is treatment, which involves separation and elimination operations through chemical transformation to safer products. A fourth level is related to education and social transformation strategies (awareness of the problem, government policies, educational and education strategies) (see **Figure 1**) (Sudarsan et al., 2024; Talukdar et al., 2024).

The objective of this article is to give an overview of the different approaches to the study of microplastics and elimination strategies in water treatment systems. For a description of the problems surrounding microplastics and their dynamics from a fundamental perspective, it is suggested to see part 1: Microplastics – Part 1: Dynamics of pollution by microplastics in the Journal of Science with Technological Applications (Palencia et al., 2024)

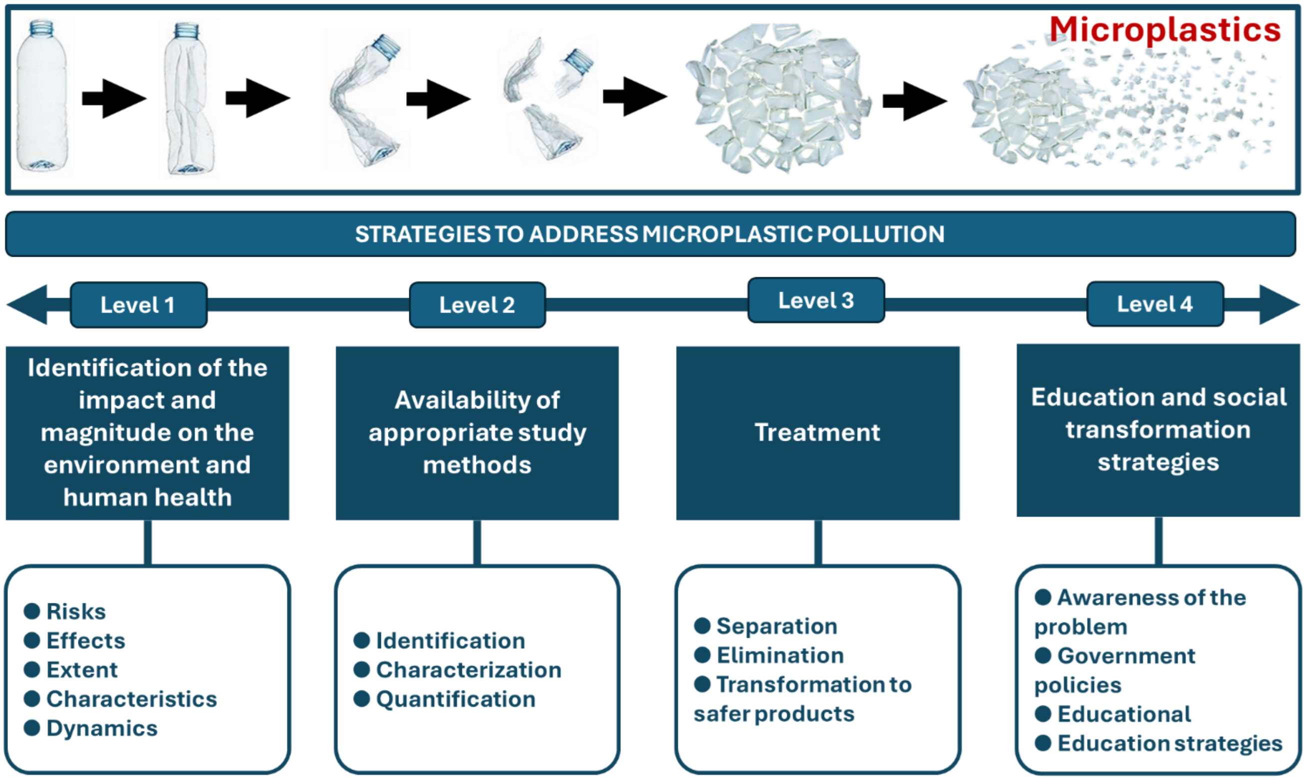

Figure 1. Strategies to address microplastic pollution (note that the levels are arranged horizontally since they must occur simultaneously).

2. Methods for detection and analysis of microplastics

2.1. Size-based characterization of MPs

Currently, there is no standard method for determining MPs; however, from its definition, it is clear that the magnitude and impact of the problem will depend on the size used as a reference to define whether or not there is evidence of MPs in a given sample. Plastics released into the environment can be found in various size fractions, for which categories such as megaplastics (> 100 mm), macroplastics (20 - 100 mm), mesoplastics (5 - 20 mm), microplastics (< 5 mm) and nanoplastics (1 - 100 nm) have been suggested (Sheriff et al., 2023; Upadhyay et al., 2024). However, the size of a three-dimensional object involves obtaining information about the length, width, height, diameter, perimeter, area, volume, or mass. When the object is macroscopic and of regular geometry, the determination of size can be simple, acquiring greater complexity if the object's morphology is irregular and reaching significant levels of complexity if it is micrometric in size and has an irregular morphology. The most used descriptor is based on assuming a spherical morphology when the particles are irregular and have a width-to-height ratio close to or equal to unity. A first approximation in the analysis of size consists of assuming that small variations in shape do not significantly affect the dynamics of the particles. Thus, using shape descriptors involves an unnecessary effort that does not provide relevant information. However, a general description can be based on three categories of shape: particles (pseudo-spherical materials), sheets (materials with a small thickness relative to their height and width), and fibers (materials whose shape is like that of short threads). Usually, size descriptors depend on the technique used; however, due to the relatively large number of particles, it is common to describe objects using ranges. Among the most used descriptors are the diameter of a sphere of equivalent volume (used in granulometry) and the diameter of a sphere of equivalent projected surface (used in microscopy and image analysis). In the first, the object is circumscribed in a circle that defines a sphere with a volume equal to that defined by the circle's diameter used to circumscribe the particle. The reliability of this measure will depend on how much the morphology can be like that of a sphere. A simple way to verify this is by visually inspecting the particles and, quantitatively, establishing how different the quotient between the perimeter and the diameter is from the value of pi. Another method can be through the relative comparison of the surface of the circle with respect to the surface delimited between the circle and the perimeter of the particle. In the second case, the area is established from the 2D projection, and the sphere's diameter with the same surface area is calculated from the area. Note that the interpretation of the effect of size on the behavior of particles in the

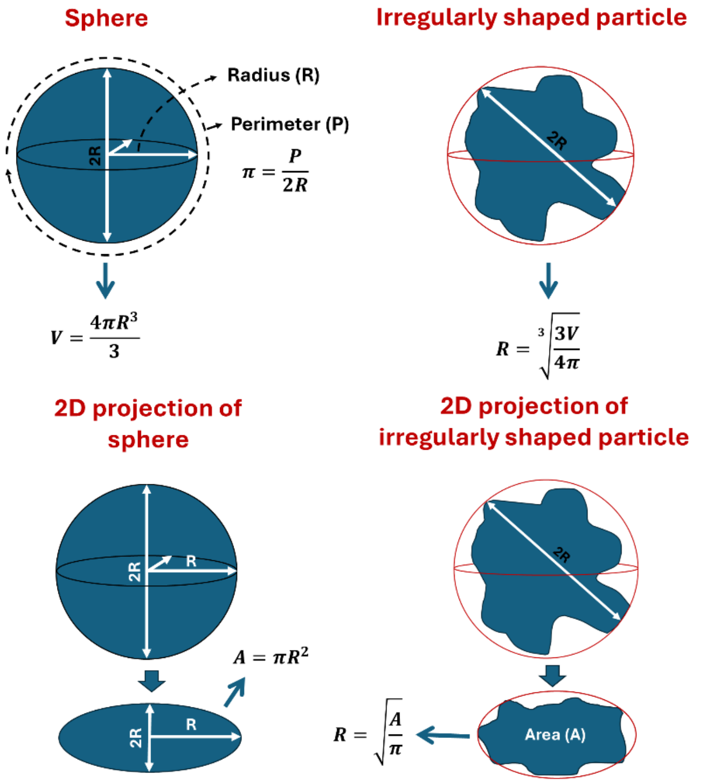

Figure 2. Usual size descriptor for irregularly shaped particles compared with spherical morphology.

strict sense is linked to morphology (see **Figure 2**) (Palencia, 2024). According to IUPAC, the concept is not geometric in nature but is associated with the property of interest being analyzed. Thus, the equivalent diameter is not equal to the diameter of a spherical particle but to the diameter obtained when an equivalent value is obtained in the property of interest (e.g., the hydrodynamic radius is the radius of a particle that has the same diffusion coefficient as a particle with the same size, under the same temperature conditions and in a specific medium, commonly water) (IUPAC, 2019; Palencia, 2024).

However, appropriate techniques are required for the proper application of shape descriptors, which in practice can be a limitation. Microscopic techniques currently offer an adequate alternative; however, they have the limitation that they are 2D projections of a 3D object. In any case, the tolerance for errors in the quantification of size and its variability is high since, in practice, there is no argument to justify the need to differentiate with a high degree of precision particles of 5 millimeters from those of 3, 4, 6, or 7 mm. Therefore, what should be sought is to establish a size distribution or size range. One of the simplest strategies consists of sample screening, which can be carried out in relatively large ranges but in a wide spectrum of sizes ranging from a few millimeters to micrometers and even nanometers (screening by filtration operations in the case of nanoparticles) (Palencia, 2024). In general, current analytical techniques allow for the definition of strategies for sampling, separation, and characterization of MPs. The difficulty in sampling will be linked to the ability to identify them. Strictly speaking, the analytical problem is simpler than other analogous problems since the particles under study are relatively large compared to nanoparticles, molecules, and atoms (Kong et al., 2023). Due to the particles' size, granulometry can carry out separation. Granulometry can be understood as the study of the statistical distribution of the sizes of a set of solid particles or liquid drops. Using this approach, a granulometric curve is sought from the combination of sieves. Depending on the characteristics of the sample, the distribution obtained may be non-Gaussian due to the relatively small number of data. Consequently, the best descriptors for these distributions are the mode, median, or interquartile ranges; however, if the number of data available is adequate, more common parameters such as mean, standard deviation, and coefficient of variation, among others, can be used. In addition, the distribution can be made by mass, volume, number of particles, or size.

Given the subjectivity of the particle size used in the study of PMs, a size scale with a more direct interpretation can be thought of in terms of reference particulate systems. One of these systems is soil. Thus, analogous to the textural classification of soils, the particle size of soils can be used to define a size scale to classify MPs. One point that supports the above approach is that soils are made up of particles with a wide range of sizes, from large particles (e.g., stones, sand) to small particles (e.g., clays). Soil texture is classified into three size ranges: sand (50 - 100 µm), silt (2 - 50 µm), and clay (< 2 µm); in addition, other higher order size categories such as alterite or small rocks (100 - 5000 µm) and gravel or large rocks (> 5000 µm) can be easily defined (here the size of small rocks was defined between 100 - 5000 µm to enable an equivalence with the definitions currently used in the study of MPs). Silt and alterite can be divided into intermediate ranges if greater size sensitivity is desired. Based on the above, a size scale for the characterization of MPs is type-C (< 2 µm, where C refers to "clay"), type-S (2 - 50 µm, where S refers to "silt"), type-A (50 - 100 µm, where A refers to "sand"), type-SR (100 - 1000 µm, where SR refers to "small rock"), and type-LR (1000 - 5000 µm, where LR refers to "large rock"). Additionally, size subranges of type-S may be defined as S1 (2 - 10 µm), S2 (10 - 25 µm), and S3 (25 - 50 µm), although more mnemonic notations may be S0210, S1025, and S2550. On the other hand, for type-SR sizes, the subranges can be SR1 type (100 - 500 µm), SR2 type (500 - 1000 µm), and SR3 type (1000 - 5000 µm), or if preferred, SR0105, SR051 and SR15 (in mm), respectively (see **Table 1**). An illustration of the proposed geological scale and its comparison with the scale used for the size characterization of MPs is shown in **Figure 3**. This proposed scale allows the association with geological material existing in nature in terms of size. However, it is important to consider that plastics are lighter materials than geological materials. Consequently, MPs type A par-

Table 1. Description of MPs' size by geological scale based on soil texture.

Classification		Size (μm)	Geological equivalent	Method for analysis
Group	Subgroup (in μm)			
LR	LR5000 or LR	> 5000	Large rocks	(1) Fractionation by sieving (separation of particles of MPs). (2) Elimination of coatings by washing or use of oxidant agents (H_2O_2). (3) Optical and/or digital microscopy (direct visualization and capture of images of particles). (4) Image analysis (counting and morphological analysis). (5) Analysis by FTIR, Raman, or other techniques.
SR	SR3	1000-5000	Small rocks with large size	
	SR2	500-1000	Small rocks with intermediate size	
	SR1	100-500	Small rocks with small size	
A	A50100 or A	50-100	Sand	
S	S3	25-50	Silt with coarse texture	Due to the small size, microscopic techniques require higher power, e.g. SEM. For sizing, DLS is also applicable with appropriate sample dispersion.
	S2	10-25	Silt with intermediate texture	
	S1	2-10	Silt with fine texture	
C	C	0.1 - 2	Clay fraction of soils	
	Nano C	< 0.1	Exfoliated layer of nanoclays	

ticles are expected to show a size comparable to the size of sand particles but with a lower density and greater mobility.

2.2. Collecting of MPs' samples, pretreatment and analysis

The analysis of MPs as environmental contaminants consists of identifying and quantifying the quantity of particles characterized by having a wide distribution of shapes and sizes in different media, as well as by coming from a different origin with variable composition. Therefore, sampling will vary widely depending on the characteristics of the study. If the sample is water, the MPs are isolated using sieves of different sizes. Generally, the screening technique using meshes does not offer greater selectivity than the classification by size of the particles presents in the medium, regardless of whether or not they are MPs. For example, it will not be possible to differentiate MPs' particles from algae or non-plastic low-density particulate matter, such as wood. Therefore, it is subsequently necessary to separate the particles of MPs from the rest of the particles. The isolation of the particles can be done in such a way that they are classified by size depending on the size of the meshes used (Arregocés-Garcés et al., 2024; Fan et al., 2023). This type of mesh can come from different materials, e.g., high-strength nylon coupled with a stainless-steel ring and a PVC end. Some commercial brands offer pore sizes of 20, 50, 64, 80, 153, 250, and 363 microns, diameters of 30 cm, and a length of 90 cm (see **Figure 4A**). Other specifications may be available on the market (Corporation S3, 2024).

A typical study on MPs in natural waters, industrial wastewater and sludge commonly includes the following stages:

- *Sampling stage*. This stage includes the delimitation of the study area and the taking of samples. Sampling can be done discretely, i.e., by taking sample fractions at different points, which are then transferred to the laboratory for separation, but it can also be done passively (or continuously), which consists of placing a collection system through a flow for a given period. Thus, what is transferred to the laboratory is not a sample of the effluent but the fractions of particles collected by the mesh system (see **Figure 4**) (Monira et al., 2023). At this stage, the sample volume analyzed is of great importance. Keep in mind that if only a small number of small samples are analyzed with respect to the study area, there will be a significant bias concerning the real situation. It has been suggested that a representative sample can be obtained by collecting pooled samples at 24-hour time intervals. A typical sampling of MPs may require a frequency of 3-4 months and sample volumes between 10 and 80 L depending on the characteristics of the sampling points, for example, 10 L in raw wastewater and 80 L in final effluent (Fan et al., 2023), while in other cases, researchers have considered that between 5 and 10 liters are sufficient at the different sampling points (Ahmed et al., 2024; Franco et al., 2020; Kong et al., 2023), but volumes of 1 L/sample and three samples per sampling point have also been used (Akdemir and Gedik, 2023). Depending on the sampling location and volume, several sampling methods have been commonly used: collection in containers, collection by pumping systems, and direct filtering of the sample using nets (e.g., Neuston plankton net). However, due to morphological characteristics, microplastic abundance is statistically affected depending on the mesh size (Komorowska-Kaufman and Marciniak, 2024).
- *Separation, fractionation, and pretreatment stage*. Sample fractionation can be done during sample collection or in laboratory analysis. For this purpose, sieves or other types of filtering systems are used. Thus, separation by size is commonly carried out using filters or sieves. Membranes can be used for smaller fractions, while sieves are mainly used for larger fractions. At this stage, morphology influences the separation, with fibers being the most difficult due to the morphological characteristics that allow them to

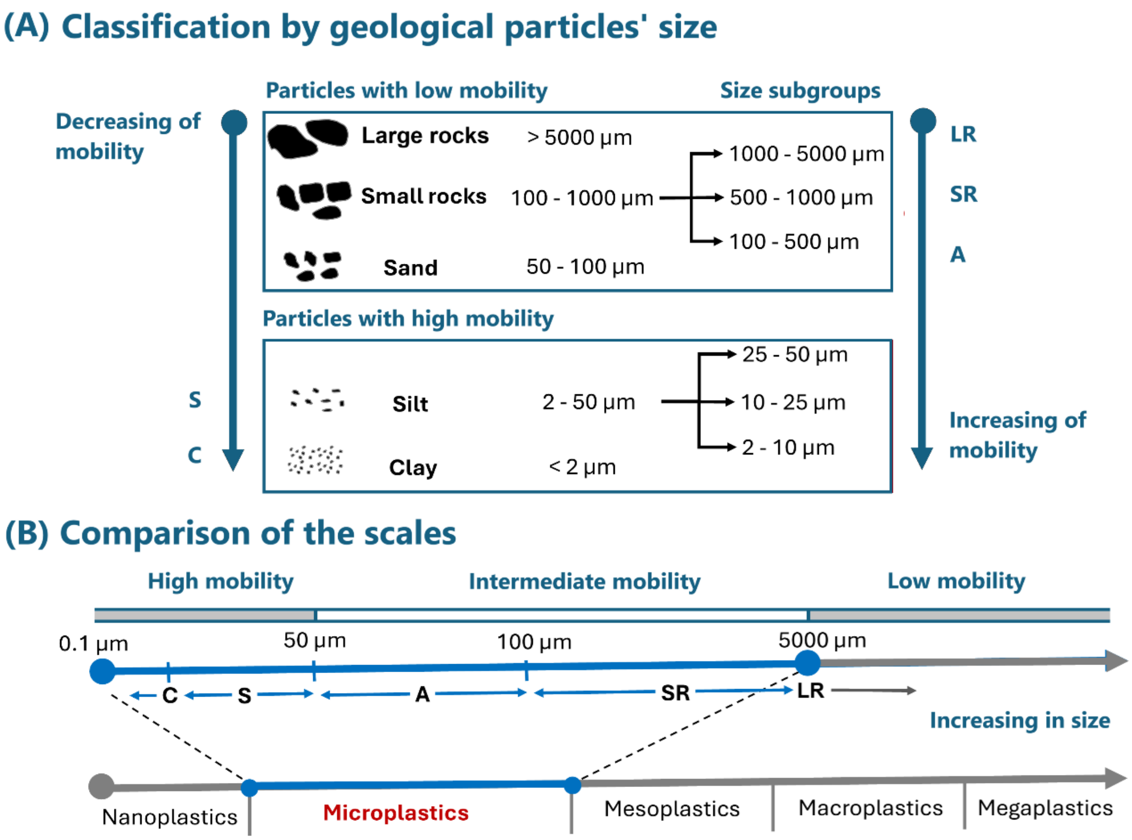

Figure 3. (A) Proposed geological scale for size classification of microplastics and (B) comparison with the size scale described commonly used for microplastics (Sheriff et al., 2023; Upadhyay et al., 2024).

pass longitudinally through filters with small pores. The above suggests that a microscopic analysis for morphological characterization must accompany the analysis of the fractions. In this way, the study of the microplastic shape is directed to the description of fibers, fragments, foams, granules, films, and others (Hajji et al., 2024).

The compositional complexity of wastewater is high compared to other matrices. Consequently, the great variability of organic contaminants can interfere during sampling, making it necessary to adequately differentiate the particles with respect to other components existing in the sample; thus, strategies to address these drawbacks are visual inspection by microscopy and the use of pretreatments (Monira et al., 2023). In the pretreatment, due to the presence of organic matter or other substances that may be adsorbed on the surface of the particles, they are treated with oxidizing agents, usually oxidizing hydrogen peroxide or Fenton's reagent, which combines ferrous iron with hydrogen peroxide. Failure to clean the surface could lead to erroneous results in terms of mass and overestimate the amount of plastic material present in the sample (see **Figure 4**). At this stage, different strategies are used to isolate the MPs particles. These include sedimentation of the water sample, separation of the precipitate, and, in some cases, chemical digestion with hydrogen peroxide at room temperature for several days and filtration. Due to the low density of some plastic materials, they can be separated by flotation (Ahmed et al., 2024; Akdemir and Gedik, 2023; Franco et al., 2020; Kong et al., 2023).

In addition, due to the fluidity characteristics of the sample, sampling can be done directly (high fluidity samples, such as entering or exiting bodies of water, canals, or pipelines), or pretreatment may be required. Thus, when sampling sludge, due to its low fluidity, it is necessary to disperse the sludge by adding water and removing organic matter and sediments. In the specific case of wastewater treatment plants, due to the high content of solid matter, microplastics cannot be separated by direct filtration. Among the pretreatment strategies is chemical oxidation using hydrogen peroxide and sodium hypochlorite, among others, but also enzymes (e.g., lipase, proteinase, chitinase, amylase, or cellulase) (Ahmed et al., 2024; Huang et al., 2023; Kong et al., 2023; Komorowska-Kaufman and Marciniak, 2024). These chemical oxidation strategies are viable due to the stability of the materials of interest.

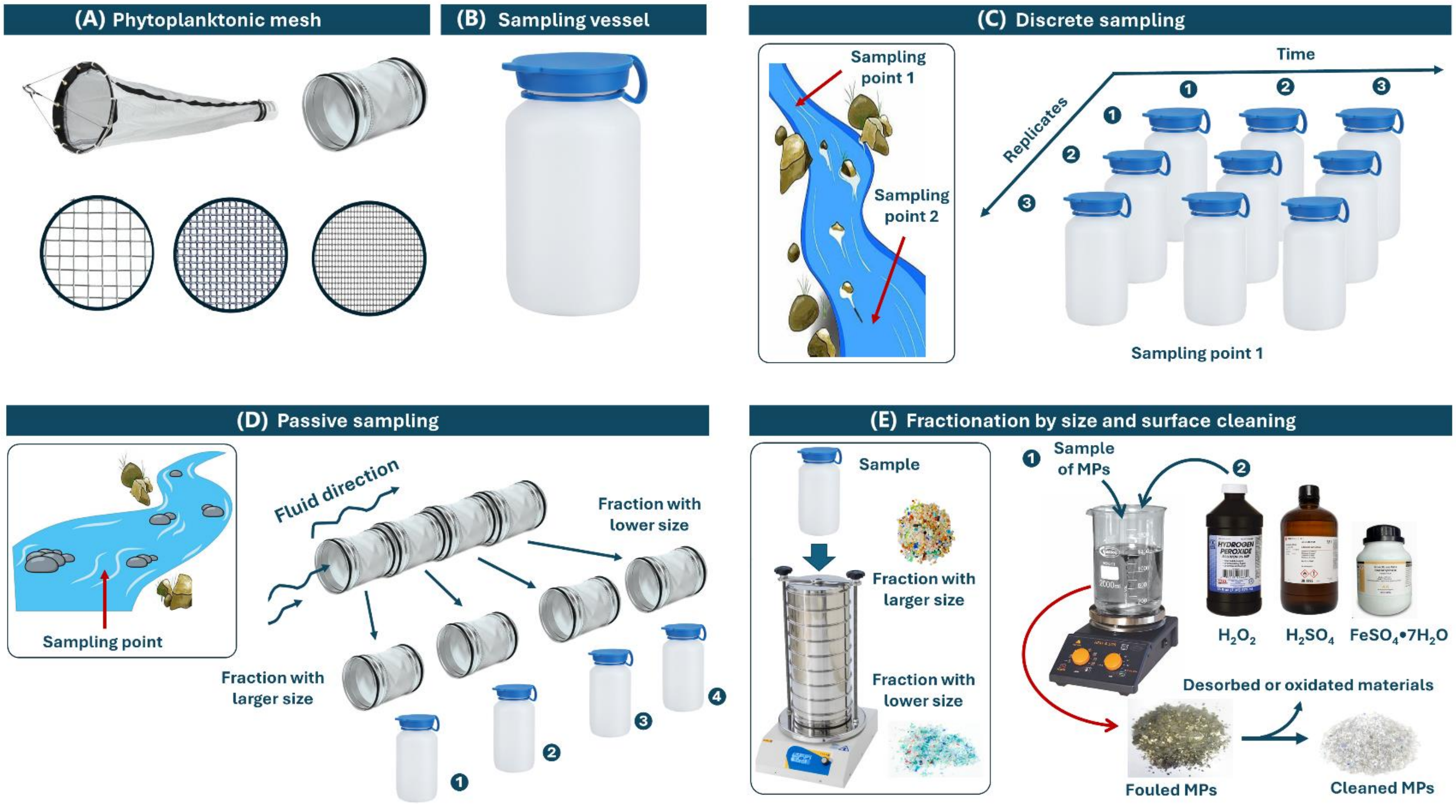

Figure 4. Illustration of analytical sequence for study of microplastics: (A) example of mesh for sampling of MPs, (B) illustration of recipient for sampling, (C) illustration of discrete sampling, (D) illustration of passive sampling, and (E) illustration of fractionation by size and pretreatment of sample for elimination of fouling and adsorbed substances.

However, these methods must be carried out so that the process is not excessively aggressive since some materials may change due to the influence of oxidizing agents (Huang et al., 2023). Some examples are PE and PP (Komorowska-Kaufman and Marciniak, 2024). In the same direction as the previous idea, treatment with acids and bases should be used with caution since, as they are highly aggressive treatments, they can cause the destruction of microplastics and the consequent alteration of the results (Kong et al., 2023). For example, when the sample is a sludge, the sample is usually dried at 105 °C, oxidized with H_2O_2 in the presence of a catalyst, $FeSO_4$•$7H_2O$ (2.5 g) + deionized water (165 ml) + H_2SO_4 (1 ml). As a result of this procedure, the plastic material remains while much of the easily oxidizable organic matter is removed (Haque et al., 2022).

- *Characterization.* MPs can be characterized using a wide range of techniques. These include infrared spectroscopy, Raman spectroscopy, scanning electron microscopy, and dynamic light scattering (for small fractions, in the nanometric range), among others (Ahmed et al., 2024; Akdemir and Gedik, 2023; Franco et al., 2020; Kong et al., 2023).

Clearly, one of the main techniques is gravimetry. This allows the establishment of the mass quantity of MPs in the sample to make projections in larger volumes, frequencies, and time series. Therefore, care must be taken with aspects that may change the mass ratio of the sample (i.e., the mass of MPs relative to the mass of the collected sample). For example, the removal of organic matter is important to establish precise quantitative parameters; for example, the mass of microplastic present in the sample can be affected by the adsorption of organic matter on the surface of the particles, including low-grade dissolved solutes but also biofilms due to the action of microbial colonization. It has been reported through infrared spectroscopy that up to 83 % of organic matter can be eliminated using hydrogen peroxide (concentration: 30 %, contact time: 7 days) (Komorowska-Kaufman and Marciniak, 2024).

Thus, correction factors established through control experiments may be necessary to quantify the mass of microplastics collected adequately. In addition, in empirical terms, eliminating adsorbed organic matter implies a significant time cost. Some treatments have required even more than 13 days, such as using enzymes in combination with hydrogen peroxide (Talukdar et al., 2024). However, the characterization stage can involve a significant challenge in terms of differentiation. Currently, determining the nature of MPs requires a lot of time and specialized equipment (e.g., dissection microscope, µFT-IR, µATR-FTIR, stereomicroscope,

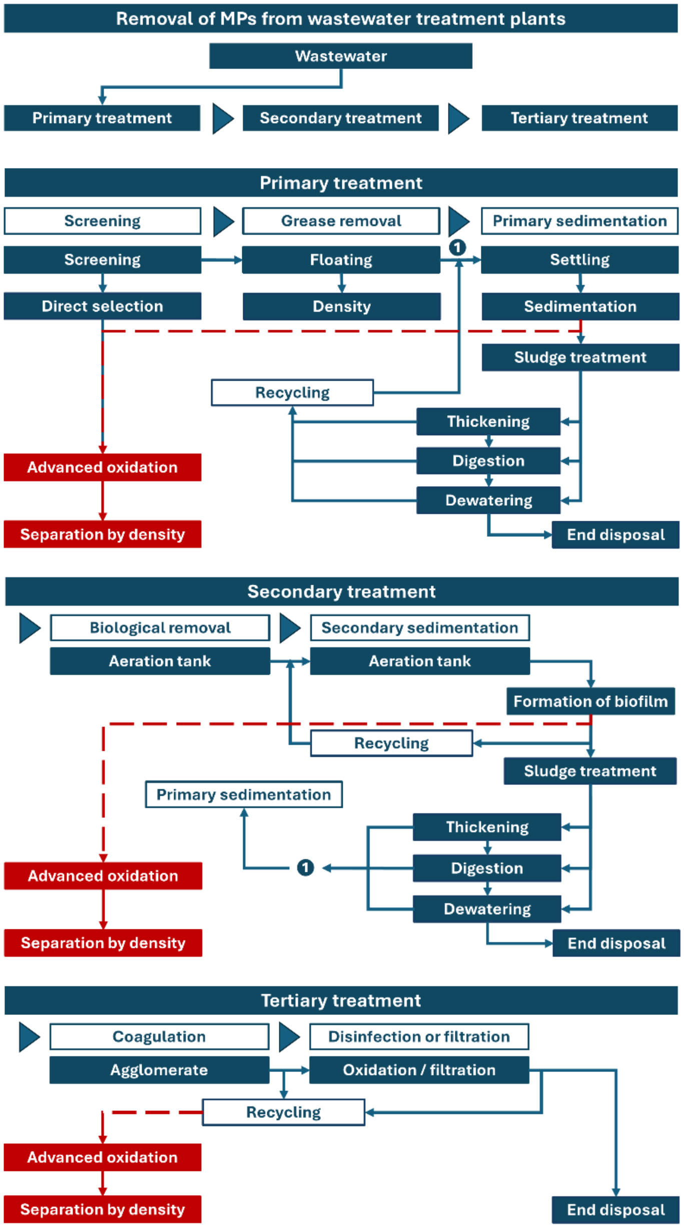

Figure 5. Generic processes for wastewater treatment.

confocal Raman spectrometer, 3D microscopy, Nile red fluorescence microscopy method, scanning electron microscopy, pyrolysis gas chromatography coupled to mass spectrometry, thermal-extraction-desorption gas chromatography coupled to mass spectrometry, among other) (Kong et al., 2023; Mesquita et al., 2023; Poursat et al., 2024). In addition, the similarity of some materials and the presence of additives can cause difficulties in some techniques, such as infrared spectroscopy and Raman spectroscopy (Kong et al., 2023; Komorowska-Kaufman and Marciniak, 2024; Talukdar et al., 2024).

3. Removal of MPs from wastewater treatment plants

Wastewater treatment plants receive microplastics through different routes, including discharge systems from domestic waste, discharges from municipal wastewater collection systems, stormwater runoff, and leachate from landfills (Kittipongvises et al., 2022; Kurt et al., 2022; Mesquita et al., 2023). Since the problem of MPs in drinking water and treated wastewater has been recognized, numerous studies have been conducted to assess the suitability of conventional treatment methods and techniques for removing MPs. Likewise, given the impossibility of eliminating them at the treatment plants, different research has focused on the development of new methods for their elimination (Sheriff et al., 2023; Keller et al., 2024; Lee et al., 2024; Talukdar et al., 2024). It should be noted that on a small scale, the elimination of MPs is easy; however, on a large scale, technical and economic factors restrict the alternatives. Among the different methods of removing microplastics are mechanical removal, sedimentation, filtration, coagulation, flocculation, electrocoagulation, magnetic extraction, biosorption, membranes separation, advanced oxidation, biodegradation, ceramic microfiltration, and biolectrochemical methods (Al-Amri et al., 2024; Qin et al., 2024; Takeuchi et al., 2023; Talukdar et al., 2024; Wang and Zhou, 2024). Details of these methods have been widely shown in different reviews (Bui et al., 2020; Das et al., 2024a, 2024b; Kurt et al., 2022; Lv et al., 2019; Reddy and Nair, 2022; Tadsuwan and Babel, 2022; Talukdar et al., 2024; Vo et al., 2024; Wang and Zhou, 2024).

In general terms, the wastewater treatment process is designed to remove relatively large material (primary treatment, which includes stages of sedimentation and/or coagulation) and reduce a load of organic contaminants of synthetic and biological origin before discharge into a receiving system (secondary treatment, which can include further coagulation, flocculation, and/or precipitation). It has been shown that typical wastewater treatment plants can remove significant amounts of microparticles; however, although the efficiency of microparticle removal reaches a removal of around 98–99 %, the remaining 1–2 % is still a significant amount of MPs, which can be around 1.5–1.9x109 particles/day (approximately 8.4 kg/day) (Jiang et al., 2022; Komorowska-Kaufman and Marciniak, 2024; Talukdar et al., 2024). Tertiary treatment is introduced when the effluent generated in the treatment plant is destined to be reused (e.g., biodegradation, filtration, adsorption) (Arregocés-Garcés et al., 2024; Komorowska-Kaufman and Marciniak, 2024). Different tertiary treatments have been successfully evaluated at the water purification plant level. They are rapid sand filtration, dissolved air flotation, and membrane bioreactors (Liu et al., 2021; Ahmed et al., 2024). It is important to note that removal efficiency refers to eliminating MPs when they reach the treatment plants; however, much of the discarded plastic does not enter this treatment system. A illustration of wastewater treatment is shown in **Figure 5**.

Studies on MPs focused on determining the existing quantities of these materials in wastewater treatment plants are very divergent (Huang et al., 2023). These differences can be the result of multiple combined factors, among which are the origin of the wastewater under treatment, the size of the population generating the effluents, seasonal variability, the characteristics of the sewage systems, the characteristics of the population in terms of consumption and recycling habits, sampling techniques, approaches used in the pretreatment stages and microplastic characterization methods (Huang et al., 2023; Komorowska-Kaufman and Marciniak, 2024; Talukdar et al., 2024).

In terms of the stages of treatment, it has been estimated that most MPs are removed in primary treatment (50–85 %). In contrast, in secondary treatment, between 8 and 35 % are removed (Komorowska-Kaufman and Marciniak, 2024). Thus, in tertiary treatment, between 2 and 8 % is expected to be eliminated. The above suggests that the efficiency in removing microplastics is related to their size among the different treatment stages. In the reactors, MPs are mainly removed by adsorption, entrapment in sludge flocs, and sedimentation in secondary clarifiers, but also, in wastewater treatment plants, mechanical wear, chemical oxidation, and biodegradation in the different stages of the process cause the aging of microplastics (Al-Amri et al., 2024; Qaiser et al., 2023).

One of the most promising techniques in wastewater treatment systems is bioremediation. This technology is considered safe and sustainable and is based on microbial metabolism to eliminate contaminants. However, it is relatively more expensive than other waste disposal processes, mainly in its development and implementation stage (Krishnan et al., 2023; Ahmed et al., 2024). Bioremediation is based on the capacity of microorganisms for the metabolic transformation of harmful substances into harmless metabolites (i.e., chemical modification promoted by microorganisms) or through indirect reduction of contaminants by their absorption and/or immobilization. Among the characteristics that the different biological entities must meet to be used in this technique are: (i) the microorganisms must correspond to native species, (ii) the species should be correctly confined in such a way that risks are minimized, and the process is controlled, (iii) the retention of microplastics must be efficient and harmless for the microorganism, (v) the speed of ingestion/filtration must be rapid, and (vi) the microorganisms must tolerate the different conditions of pH, temperature, and composition of the wastewater (Ahmed et al., 2024; Kong et al., 2023). In addition, the microorganisms should not damage the existing microbial populations, so they must be able to thrive and function in complex microbial consortia. More concisely, the ideal microorganism for bioremediation processes of MPs must adapt to the treatment conditions, degrade MPs efficiently, be economically viable, and be ecologically safe (Ahmed et al., 2024).

Several bacteria such as *Rhodococcus sp.*, *Ideonella sakaienes*, *Pseudomonas putida*, *Pseudomonas syringae*, *Pseudomonas aeruginosa*, *Bacillus cereus*, *Brevibacillus borstelensis*, *Acinetobacter sp.*, and *Bacillus gottheilii*are capable of degrading MPs (Ahmed et al., 2024; Komorowska-Kaufman and Marciniak, 2024); but also, photosynthetic microalgae have been evaluated with promissory results, being some examples *Scenedesmus sp.*, *Spirulina sp.*, *Chlorella sp.*, *Phaeodactylum tricornutum* and *Cyanothece sp*., and some fungi such as *Penicillium verticillium*, *Aspergillus*and *Fusarium* (Ahmed et al., 2024; Ajithkumar et al., 2023; Wang et al., 2023). Furthermore, the incubation times evaluated are varied, commonly between 40 to 120 days, and can be under aerobic or anaerobic conditions according to the requirements of the organisms (Ajithkumar et al., 2023).

On the other hand, MPs affect dissolution, hydrolysis, acidification, and methanogenesis in anaerobic digestion, depending on the types of MPs and substrates (e.g., waste-activated sludge, food waste, kitchen waste). For example, while PS microparticles (1, 100, and 1000 µm in size) during anaerobic digestion affect the processes of dissolution (by inhibition), hydrolysis (by inhibition), and methanogenesis (by inhibition), in acid-acetogenesis, it promotes the accumulation of acetate and butyrate. However, PS microparticles (1 and 10 µm) in waste-activated sludges do not affect dissolution during anaerobic digestion. At the same time, hydrolysis, acid-acetogenesis, and methanogenesis are affected in a positive, inhibitory, and negative, respectively (Kong et al., 2023). The different modes of action include high toxicity of bisphenol A leached from PVC microparticles, acidification processes by regulating the enzymatic activity, a significant increase in ROS levels, and enrichment of hydrolytic and acid-producing bacteria, among others (Kong et al., 2023). In the same context, membrane bioreactors (MBRs) emerge as a technological alternative for eliminating microplastics. MBRs are based on the combination of microbiological activity and ultrafiltration membranes (Palencia et al., 2017; Krishnan et al., 2023; Ahmed et al., 2024). Several studies show the effectiveness of MBRs in removing MPs. The main results show that they apply to various industrial effluents of complex composition, with a removal efficiency of 99.9 %. Furthermore, microplastics' nature and composition do not significantly impact elimination (Ahmed et al., 2024).

The interaction between microorganisms and MPs during treatment strongly influences the elimination of MPs. For example, extracellular polymers produced by biofilms of microbial colonies are capable of trapping microparticles through different adhesion phenomena. Furthermore, the interaction between microorganisms and microplastics is also directed towards the activity of microorganisms. For example, it has been reported that microplastics can promote the production of extracellular polymers in aerobic sludge (Jachimowicz et al., 2024; Talukdar et al., 2024). From a broad perspective, the longer the contact time between the surface biofilm and the plastic waste it coats, the greater the interaction and action that modifies the plastic material at the surface level regarding its effective size and the relative densities of the contaminants. Due to the above, MBRs have emerged as an effective technology for removing microplastics. In reactors of this type, ultrafiltration membranes act as a physical barrier that allows the removal of MPs larger than the membrane's pores. Therefore, a combined strategy results from the effect of microorganisms plus retention by part of the membranes. In contrast, the effectiveness in removing MPs by other processes shows varied results, for example, rapid sand filtration (50–98%), disc filter (80-98 %), granular filter (80-98 %), and dissolved air flotation (60-85 %) (Komorowska-Kaufman and Marciniak, 2024). The efficiency of MP removal can be increased by including flocculation stages in conjunction with membranes; however, this implies an increase in the overall costs of the process due to the need to include additional stages, such as cleaning membranes and sludge removal (Büngener et al., 2023). On the other hand, the elimination of MPs in the form of fibers is insignificant during secondary sedimentation, with the results obtained during primary sedimentation being different (Talukdar et al., 2024).

In tertiary treatments, which correspond to the final stage of the water purification process, pressure-operated membrane separation systems are applicable to efficiently eliminate microplastics through a size exclusion mechanism. In previous stages, primary and secondary treatments, this technology is not recommended due to the different types of fouling that can take place and affect the effectiveness and integrity of the membranes. Usually, these fouling mechanisms are mediated by pore blocking and biofilm formation (Palencia et al., 2017; Espinosa et al., 2020). Although in this technology, polymeric membranes are the most used in water and wastewater treatment, they are susceptible to damage or experience short periods of useful life when subjected to extreme operating conditions or frequent washing operations (Mora et al., 2021). Due to the above, ceramic membranes emerge as a more suitable alternative due to their chemical, mechanical, and thermal resistance. However, one of the limitations is that their average pore size, of lower value, is of the order of 5 µm.

Consequently, the efficiency in removing microplastics will be conditioned to the exclusion size of the membrane (removal efficiency of about 72 %) (Takeuchi et al., 2023). Therefore, the combined use of filtration systems results in greater efficiency. Thus, in-line systems composed of microfiltration modules followed by ultrafiltration modules improve the separation and elimination of MPs in terms of size and number (Ramos et al., 2024). However, this gain in efficiency inevitably implies an increase in costs and complexity of the operation (Mora et al., 2021; Ramos et al., 2024; Takeuchi et al., 2023). Similarly, the coupling of smaller membrane modules, such as nanofiltration and reverse osmosis, leads to an improvement in terms of efficiency but a significant increase in costs and operational complexity; thus, in general, terms, the smaller the pore size, the greater the energy necessary for the operation of the system and the greater the costs (Palencia et al., 2017; Ramos et al., 2024).

On the other hand, electrocoagulation is a novel and effective technique for removing microplastics. Electrocoagulation uses a low-voltage electric current to destabilize suspended, emulsified, or dissolved particles. During this procedure, oxidative processes take place aimed at the degradation of contaminants (Ahmed et al., 2024; Elkhatib et al., 2021). The removal of PMMA and cellulose acetate microparticles has been studied using electrocoagulation. Differences in effectiveness were obtained depending on the morphology, which is greater for fibers than for granular ones. Furthermore, the influence of the composition of the medium on effectiveness has been described. For example, in the removal of PE, aluminum salts show greater effectiveness than iron salts. Other relevant factors are the electrolyte concentration and the voltage density (Ahmed et al., 2024; Elkhatib et al., 2021). In contrast, it has been reported that other factors, such as ionic strength and turbidity, do not have a significant effect on the removal rate (Ahmed et al., 2024; Elkhatib et al., 2021; Wang and Zhou, 2024).

Among the experimental technologies are bioelectrochemical methods and the use of ferrofluids. In the first case, bioelectrochemical methods combine electrochemical catalysis with microbial metabolism to promote the oxidation of contaminants and subsequent anaerobic digestion (Wang and Zhou, 2024). This technology is also conceptualized as microbial fuel cells and has been successfully tested for eliminating volatile organic compounds, polycyclic aromatic hydrocarbons, and azo dyes. Some examples of the application of this technology are the degradation of PET by *Ideonella sakaiensis* through secretion of two enzymes, PETase and MHETase, which hydrolyze PET (Wang and Zhou, 2024). In bioelectrochemical processes, the hydrophobic nature of microplastics can be disturbed, promoting the formation of hydrophilic functional groups, e.g., -OH, –COOH, and consequently, the water solubility of plastic microparticles is improved; thus, the interaction between microorganisms and microplastic particles is improved, favoring the kinetics of the degradation process of MPs (Wang and Zhou, 2024). On the other hand, another novel technology for the removal of microplastics is based on the use of ferrofluids without the addition of stabilizing agents or surfactants. Because the composition of the ferrofluid is based on mixing oil with magnetic particles (Fe_3O_4), this technology has been described as low-cost, simple, and sustainable. However, it is still a technology in the research stage, and multiple aspects must be analyzed. The wastewater on which it has been evaluated is relatively simple compared to the input to wastewater treatment plants, and yet the efficiency achieved is relatively low (64 %) (Hamzah et al., 2021).

Another technique, surfactant-assisted air flotation, has been evaluated to remove MPs. This method is based on selective flotation technology in conjunction with surfactants. It depends on the wettability of the plastics, which is improved with the addition of surfactants and the density of the particles. However, although it has been successfully evaluated for the removal of MPs from aquatic environments, aspects such as cross-contamination due to the addition of surfactants and the reuse of the flotation solution must be considered (Selim et al., 2024; Shafiuddin et al., 2023).

In the final stage of the treatment process, disinfection, different strategies are normally used, among which UV radiation, ozonation, or chlorination stand out. If MPs manage to reach this stage, they may experience changes due to the action of this type of agent. MPs such as PE, PP, PS, PET, and PVC are susceptible to oxidative degradation promoted by UV radiation. This type of degradation acts superficially, causing cracks on the surface of the MPs and promoting their size reduction to levels even in the nanometer order. On the other hand, ozone and chlorine are directed at the chemical modification of MPs, including depolymerization with the subsequent formation of smaller particles and the insertion of groups such as aldehydes and ketones. Other changes are increased surface tension, hydrophilicity, and adhesion properties (Bitter et al., 2022; Kabir et al., 2023; Krishnan et al., 2023; Selim et al., 2024; Talukdar et al., 2024).

4. Conclusions

Pollution by MPs is an emerging problem resulting from the poor management of plastic materials. In developed countries, wastewater treatment plants can be considered the principal source of MPs; however, in many poor and developing countries, this type of system is limited, characteristic of large cities; therefore, rural areas and small cities can be considered significant sources of solid plastic waste that can be converted into microplastics by different physical, chemical, and biological factors. On the other hand, pollution by MPs represents a current challenge, and although elimination strategies in wastewater treatment plants are somewhat effective, more holistic approaches are required that include public awareness campaigns on the environmental impacts of contamination by plastic materials, adopting responsible consumption habits, and proper disposal of plastics. From this approach, it is evident that preventive efforts involve collaboration between government, industrial sector, academia, and civil society.

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