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Review

Are you drowned in microplastic pollution? A brief insight on the current knowledge for early career researchers developing novel remediation strategies

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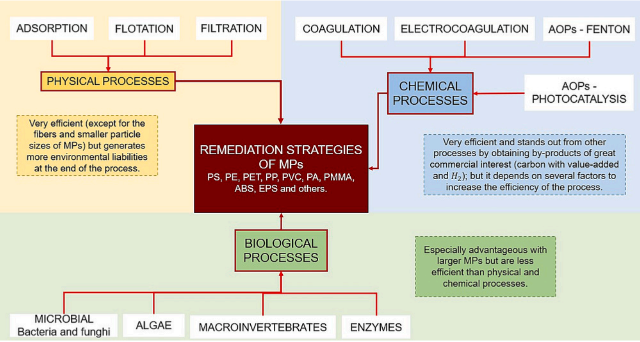
HIGHLIGHTS

- Microplastic pollution is a complex issue with environmental and social dimensions.
- Holistic technologies that acknowledge this complexity are urgently needed.
- ERCs with innovative perspectives can develop holistic remediation proposals.
- This ERC's-focused mini-review provides the insights of microplastic pollution.
- Recommendations for the development of remediation strategies are provided.

GRAPHICAL ABSTRACT



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ABSTRACT

Microplastics (MPs) composed of different polymers with various shapes, within a vast granulometric distribution (1 μm - 5 mm) and with a wide variety of physicochemical surface and bulk characteristics spiral around the globe, with different atmospheric, oceanic, cryospheric, and terrestrial residence times, while interacting with other pollutants and biota. The challenges of microplastic pollution are related to the complex relationships between the microplastic generation mechanisms (physical, chemical, and biological), their physicochemical properties, their interactions with other pollutants and microorganisms, the changes in their properties with aging, and their small sizes that facilitate their diffusion and transportation between the air, water, land, and biota, thereby promoting their ubiquity. Early career researchers (ERCs) constitute an essential part of the scientific community committed to overcoming the challenges of microplastic pollution with their new ideas and

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innovative scientific perspectives for the development of remediation technologies. However, because of the enormous amount of scientific information available, it may be difficult for ERCs to determine the complexity of this environmental issue. This mini-review aims to provide a quick and updated overview of the essential insights of microplastic pollution to ERCs to help them acquire the background needed to develop highly innovative physical, chemical, and biological remediation technologies, as well as valorization proposals and environmental education and awareness campaigns. Moreover, the recommendations for the development of holistic microplastic pollution remediation strategies presented here can help ERCs propose technologies considering the environmental, social, and practical dimensions of microplastic pollution while fulfilling the current government policies to manage this plastic waste.

1. Introduction

In modern life, plastics have huge technological and economic importance because of their lightness, durability, versatility, and low-cost production. The mass production of plastics began in 1950, and by 2015, 8300 million metric tons (Mt) of virgin plastics were produced (Geyer et al., 2017). However, when examining their entire life cycle, it should be recognised that plastics negatively impact the environment and society at every stage, from the extraction of raw materials and manufacturing of products to consumption and disposal. Consequently, pollution from plastics has become a social justice issue, as vulnerable communities often disproportionately bear the consequences of plastic production, usage, and disposal. Plastic materials are synthetic macromolecules consisting of monomers produced synthetically or by natural product conversion (Lechthaler et al., 2020), and their production contributes to climate change due to greenhouse gas emissions linked with oil extraction and refining. Moreover, the transport of raw materials and pellets for the fabrication of plastic products emits greenhouse gases (Calil et al., 2021). During the lifetime of plastic products, their excessive utilisation is of concern because some chemicals included in plastic formulations, such as bisphenol A (BPA) and phthalates (plasticisers), can leach from plastic items (Berger et al., 2015; Chen et al., 2019; Farooq et al., 2021). These substances are classified as endocrine disrupting chemicals (EDC) (Sharma et al., 2021), which can mimic hormones and take their place in the human system, triggering abnormal processes in the body. For instance, EDC can affect sperm quality and fertility, lead to early puberty, and cause cancer, heart disease, and obesity (Calil et al., 2021). Additionally, a recent report from the United Nations Environment Programme (UNEP) and Azul Organisation found that the excessive use of plastic products disproportionately impacts women worldwide (Calil et al., 2021). Plastics have become a prevalent product associated with many household responsibilities that tend to affect women, increasing their exposure to toxic substances from plastic formulations. For example, carcinogenic dioxins from burning plastic waste, a common fire-starting practice in many Global South countries, have a negative impact on women (Calil et al., 2021). Phthalate plasticisers, commonly found in some cosmetic and feminine care products, are found at higher levels in women than in men, increasing the risk of recurrent miscarriage. Such pregnancy losses or congenital disabilities in pregnancies carried to term can lead to social consequences for mothers, who may be blamed or abused for these adverse outcomes (Calil et al., 2021).

After its (usually short) product lifetime, the management of plastics that are transformed into waste can be accomplished through recycling, incineration, or disposal. According to the estimations reported by Geyer et al. (2017), of the 6300 Mt. of plastic waste generated since 1950, 79 % has been accumulated in landfills or the environment, 12 % has been incinerated, and 9 % has been recycled (Geyer et al., 2017). Even if at first sight it may seem reasonable to think that landfilling may be the worse scenario for proper plastic waste management because it represents an irreversible loss of valuable raw materials for recycling or energy recovery through incineration (Song and Hall, 2020), each one these plastic waste management practices have their own negative impacts on both environment and society.

Recycling has been proposed as a valid alternative for plastic waste management because of its benefits: the reduction of raw material consumption and pollution levels, the creation of jobs, the minimisation of global warming, and the reduction of landfill contamination (Mwanza, 2021). However, a major drawback of recycling is that the products manufactured from recycled plastics (thermoplastics) are of lower quality than the products obtained from virgin plastics because of the drop in mechanical properties (Mwanza, 2021). Additionally, recycling plastics has other disadvantages, such as a higher cost compared to landfilling, damage to recycling batches caused by contaminants, additional consumption of energy and resources associated with the transportation of plastic waste from collection points, sorting, and cleaning, and the fact that recycling only postpones the final disposal of plastics (Geyer et al., 2017; Mwanza, 2021). At the social level, the unhygienic and unsafe characteristics of some recycling sites and the lack of proper recycling infrastructure have led to waste pickers being exploited with low salaries and unsafe working conditions (Calil et al., 2021; Mwanza, 2021). Considering the heating values of some plastic wastes (i.e., 41.80 MJ/kg for polyethylene (PE) and 30.90 MJ/kg for polypropylene (PP)), the incineration of plastics is regarded as a promising way to partially replace the use of fossil fuels (Song and Hall, 2020) while recovering heat and reduce plastic volume by up to 90 % (Feng et al., 2022). Additionally, combusting plastic waste as a fuel can also achieve the fast degradation of conventional non-biodegradable plastics, rather than degradation in landfills or the environment with long-lasting pollution (Song and Hall, 2020). However, incineration for energy recovery not only releases chlorine, hydrogen chloride, dioxins, and furans which can be dispersed over large regions (Calil et al., 2021; Feng et al., 2022), but also impacts communities close to incineration facilities as this process is frequently carried out in settings where the produced toxic chemicals can rain back on the populations surrounding incineration plants (Calil et al., 2021). Plastic waste can also be disposed of in managed landfilling systems; however, this practice is associated with greenhouse gas emissions derived from the shipping of plastic waste across the planet on a massive and unprecedented scale (Calil et al., 2021). Moreover, plastic waste occupies space in landfills for a long time. Additionally, conventional plastics containing additives or plastics such as polyvinyl chloride (PVC) may release hazardous chemicals. Although recycling, incineration, and landfilling are waste management practices that currently present environmental and social limitations that are challenging to solve, they still allow the management of conventional plastic waste, that is, macroplastics. According to Lechthaler et al. (2020), macroplastics are plastics larger than 5 mm (Lechthaler et al., 2020). Unfortunately, owing to common human practices derived from a lack of environmental education and poor waste management systems, macroplastic waste is frequently left uncontained in open illegal dumps or in the environment, where it produces methane and ethylene greenhouse gases when exposed to solar radiation (Royer et al., 2018). Additionally, macroplastics are transported through aerial, terrestrial, and aquatic pathways within these environmental compartments or from one to another, whereas the flora, fauna, ecosystems, and economy function as receptors (Lechthaler et al., 2020).

Similar transport behaviour has been widely reported for a particular type of plastic waste, known as microplastics (MPs). Microplastics are defined by most scientific literature as plastic particles with sizes below 5 mm and, in recent years, have become the main characters of a pollution crisis that may be even more arduous to solve than that related to macroplastic waste. The challenges of microplastic pollution are related to the complex relationships between their generation mechanisms (physical, chemical, and biological), physicochemical properties, interactions with other pollutants and microorganisms, changes in their properties with aging, and small sizes that facilitate their diffusion and transportation between environmental compartments, thereby promoting their ubiquity. Indeed, it is currently known that microplastics composed of different polymers with various shapes, within a vast granulometric distribution, and with a wide variety of physicochemical bulk and surface characteristics spiral around the globe with different atmospheric, oceanic, cryospheric, and terrestrial residence times (Brahney et al., 2021), while interacting with organic, inorganic, and biological pollutants (Song et al., 2022). Similar to macroplastics, microplastics not only negatively influence the environment but also society. The presence of microplastics in aquatic environments affects coastal communities that depend on the fishing industry for food and income as microplastics pollute seafood. Another example is mothers, as microplastics have been detected in human placentas (Braun et al., 2021; Ragusa et al., 2021; Zhu et al., 2023) and breastmilk (Ragusa et al., 2022). The challenging nature of microplastic pollution is also related to the lack of globally implemented management practices or technologies specially designed for this tiny but highly dangerous type of plastic waste.

The previous arguments clarify why the current efforts to manage and reduce plastic pollution at all stages of the plastic life cycle are considered inadequate to address the social and environmental issues it entails (Calil et al., 2021); therefore, changes must be made. A UNEP report released ahead of the June 2023 second round of negotiations of the Intergovernmental Negotiating Committee to develop an international legally binding instrument on plastic pollution, including in the marine environment (INC-2), laid out a roadmap to end plastic pollution through a circular approach that keeps plastics out of the ecosystems, human bodies, and in the economy (Fig. 1) (United Nations Environment Assembly of the United Nations Environment Programme, 2023).

1. Reuse: Transform the throwaway economy into a reuse society by creating an enabling environment to ensure that the reuse market has a stronger business case than the single-use plastic market. This shift could reduce the plastic pollution by 30 % by 2040.
2. Recycling: Accelerating the market for plastic recycling by ensuring recycling becomes a more stable and profitable venture. This shift could reduce plastic pollution by 20 % by 2040.
3. Reorient and diversify: Shape the market for plastic alternatives to enable sustainable substitutions, thus avoiding replacing plastic products with alternatives that displace rather than reduce impacts. This shift could reduce the plastic pollution by 17 % by 2040.

However, even with this market transformation approach, plastic waste management will still be required to handle 100 Mt. of plastics from short-lived products not yet reduced, substituted, or brought into circularity by 2040, together with a significant legacy of existing plastic pollution (United Nations Environment Assembly of the United Nations Environment Programme, 2023), which makes the overall challenge of plastic waste a significant part of the global pollution crisis (Andersen, 2020). The global pollution crisis, along with biodiversity loss and climate change, represents the triple planetary emergency derived from the relentless and unlimited extraction of resources from the Earth (Andersen, 2020).

Although the challenge of plastic waste involves both macroplastics and microplastics, microplastics are more prevalent in terms of particle count (Calil et al., 2021), and scientific research for the development of remediation technologies is urgently needed. Early career researchers (ERCs), such as master's students, Ph.D. candidates, and even postdoctoral researchers, constitute an essential part of the scientific community committed to overcoming the challenges of plastic pollution (Mitrano et al., 2023). ERCs can provide new ideas and innovative scientific perspectives for the development of remediation strategies for microplastics. However, a survey conducted in December 2023 using the keyword "*microplastics*" in the Brazilian tool *Portal de Periódicos da CAPES* (comprising 395 journal databases including Scopus, Web of Science, PubMed, ERIC, IEEE Xplore, ScienceDirect, Directory of Open Access Journals (DOAJ), and SpringerLink) returned 17,934 peer-reviewed scientific articles (CAPES Brazilian tool, 2023). Owing to the enormous amount of available information, it may be difficult for ERCs to determine the complexity of this environmental issue and further design remediation proposals appropriately targeted for microplastic pollutants. Therefore, the objective of this mini-review is to provide ERCs with key concepts related to microplastic pollution: definition,

Fig. 1. The systems change towards a new circular plastic economy.
Taken from UNEP Report "Turning off the Tap. How the world can end plastic pollution and create a circular economy" (United Nations Environment Assembly of the United Nations Environment Programme, 2023).

characteristics, distribution and transfer within the environmental compartments, interaction with other pollutants, relationship with climate change, physical, chemical, and biological strategies for remediation and valorization, and current government policies. Additionally, this mini-review includes a bibliometric study of the current status of research in the field of microplastic pollution. The overall information presented here can help ERCs conceive highly innovative remediation technologies for microplastic pollution from a holistic perspective, considering its environmental, social, and practical dimensions while fulfilling the current government policies to manage plastic waste. In this way, novel research performed by ERCs can provide stakeholders with concrete technologies to restore the health and well-being of the environment and people that coexist with microplastic pollution.

2. Definition

Microplastics were first defined in the 2009 International Research Workshop on the Occurrence, Effects, and Fate of Microplastic Marine Debris as “plastic particles smaller than 5 mm” (Arthur et al., 2009). Although this definition is still widely used in most academic studies, Frias and Nash (2019) proposed that microplastics are synthetic solid polymeric matrix particles with regular or irregular shapes and sizes ranging from 1 μm to 5 mm of either primary or secondary origin, which are insoluble in water (Frias and Nash, 2019). Plastic is defined as a material which contains as an essential ingredient a high-molecular-weight polymer, which, at some stage in its processing into finished products, can be shaped by flow (International Organization for Standardization, ISO, 2013). Then, the definition provided by Frias and Nash excludes other materials that should also belong to microplastics, such as rubber derivatives or inorganic polymers, plastics with a high additive load (i.e. polyvinyl chloride (PVC) containing >50 % additives), and crystalline fibres, which are not moulded by flow, although they have the same composition as other microplastics (Hartmann et al., 2019).

3. Microplastic classification and characteristics

Microplastics can be classified according to their polymer composition, origin, particle size, or shape, and these characteristics are important factors to consider when developing physical, chemical, or biological remediation technologies for microplastic pollution.

3.1. Origin of microplastics

The origin of microplastics can be classified as primary or secondary. Primary sources include the production of plastic particles in the size range of microplastics for personal care and cosmetic applications, air blasting technology or drug delivery systems. Secondary sources correspond to fragmentation or decomposition of conventional macroplastic products (Arthur et al., 2009). Environmental factors that contribute to the fragmentation or decomposition of macroplastic products are light irradiation (Zha et al., 2023), mechanical abrasion (Zha et al., 2023), temperature, pH, salinity, biodegradation, oxidation, and association with other chemical elements (Ge et al., 2023; Miao et al., 2022). Photoaging of polymers in marine environments due to light irradiation is slower than that in other ecosystems because of lower oxygen availability and temperature (Andrady, 2011). Therefore, in these environments, the more significant presence of microplastics is due to fragmentation by mechanical action, especially of floating or submerged plastics (Andrady, 2008).

Several studies on macroplastics have found a correlation between the mechanical properties and crystalline structure of plastics, and their fragmentation into secondary microplastics and nanoplastics. For instance, Arhant et al. observed that degradation can cause a decrease in the molar weight of polyethylene terephthalate (PET) below the critical molar weight value (M'c), which in turn changes the mechanical behaviour of the plastic from ductile to brittle (Arhant et al., 2019). A more brittle mechanical behaviour is related to a higher hardness value, which translates into greater abrasion resistance (Callister and Rethwisch, 2019). Therefore, a reduction in molar weight caused by degradative processes such as hydrolysis or exposure to UV transforms semicrystalline macroplastics into brittle materials and influences the microplastic and/or nanoplastic generation rate. On the other hand, according to Sipe et al., the amount of mechanical fragmentation caused by abrasion tests on high-impact polystyrene (HIPS), nylon, polycarbonate (PC), polyethylene glycol terephthalate (PETG), polyactic acid (PLA), and thermoplastic polyurethane (TPU) polymers cannot be correlated with their mechanical properties (Sipe et al., 2022). However, based on their data, the authors hypothesised that lower values of maximum tensile strength would produce more microplastics in the abrasive process. Julienne et al. carried out experimental work to control the morphology of the crystalline structure of low density polyethylene (LDPE) films (Julienne et al., 2022). Their results indicated that films with large spherulite morphologies are more sensitive to surface erosion and crack initiation. Therefore, when subjected to environmental aging, these structures are more fragile during the fragmentation process.

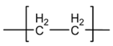
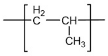
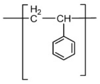
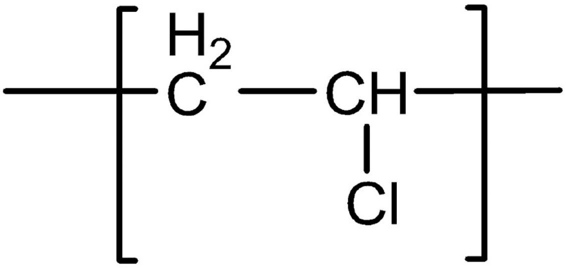
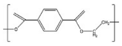
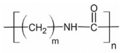
3.2. Composition

Composition is one of the most important factors to consider when classifying microplastics. In terms of synthetic polymers, microplastics found in all environmental compartments are mainly composed of PET, polystyrene (PS), polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyester (PES), polyamide (PA), and rubber. However, it is important to highlight that secondary microplastics may also contain antioxidants, flame retardants, plasticisers, pigments, and UV absorbers that originate from original plastic formulations (Nguyen et al., 2023). PE, PP, PS, PVC, and PET microplastics are abundant because these polymers together account for 90 % of the total global production (Koelmans et al., 2019; C. Wang et al., 2021). PA, popularly known as nylon, has also been identified as one of the most abundant microplastics in the form of fibres (called fibre microplastics or microfibres) and shed from synthetic textiles (Carney Almroth et al., 2018; Strady et al., 2020). Table 1 presents the most abundant microplastic monomers in the environment and their density values. This last parameter is extremely important to consider during the development of remediation strategies that involve microplastics in aquatic environments, as the density of microplastics dictates their distribution in the water column. Microplastics with a density lower than that of water tend to float (PE and PP), whereas denser microplastics (PVC, PS, PET, and PA) tend to settle. However, the density undergoes continuous changes during aging and biofouling (Guo et al., 2019), changing these trends.

3.3. Particle size

There is still no consensus on the classification of particle size. The first effort to bring limits for determining the size of microplastics was reported in the Proceedings of the International Research Workshop on the Occurrence, Effects and Fate of Microplastic Marine Debris in 2009 (Arthur et al., 2009), which considered a lower limit of 0.3 mm, referring to nets that capture plankton and floating debris; and an upper one of 5 mm, which despite being visible to the naked eye, generates impacts on the environment and intestinal obstruction of living beings. In 2014, Eriksen et al. suggested the classification of macroplastics to nanoplastics by size as follows: macroplastics (>200 mm), mesoplastics (4.76–200 mm), large microplastics (1–4.75 mm), small microplastics (0.00001–1 mm), and nanoplastics (<0.00001 mm or 0.1 μm) (Eriksen et al., 2014). The Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) used 5 mm as the upper limit and included a nano-sized range (1 nm) as the lower limit (GESAMP, 2015). Gigault et al. (2018) and Caputo et al. (2021) stated that nanoplastics exhibit colloidal behaviour within sizes ranging from

Table 1
Microplastic monomers and their density values.

Polymer	Monomer	Density, g/cm^3 (Blair Crawford and Quinn, 2016)
PE	 $-[\overset{H_2}{C}-\overset{H_2}{C}]-$	0.92-0.97
PP	 $-[\overset{H_2}{C}-\underset{CH_3}{CH}]-$	0.88-1.23
PS		1.04-1.50
PVC	 $-[\overset{H_2}{C}-\underset{Cl}{CH}]-$	1.15-1.70
PET		1.30-1.50
PA	 $-[(CH_2)_m-NH-\overset{O}{\overset{\Vert}{C}}]_n-$	1.01–1.60 (Omnexus, 2023)

1 nm to 1 μm, defining a lower size limit for microplastics (1 μm) (Caputo et al., 2021; Gigault et al., 2018). As most scientific literature defines microplastics as plastic particles with sizes below 5 mm and nanoplastics as particles with sizes ranging from 1 nm to 1 μm, these size-based definition will be used in this review (Caputo et al., 2021; Gigault et al., 2018).

3.4. *Shape*

In terms of shape, microplastics can be classified into beads, foams, fragments, sheets, fibres and films, as shown in Fig. 2.

Beads are primary microplastics smaller than 1 mm, which are usually derived from commercial cosmetic products. They are mainly

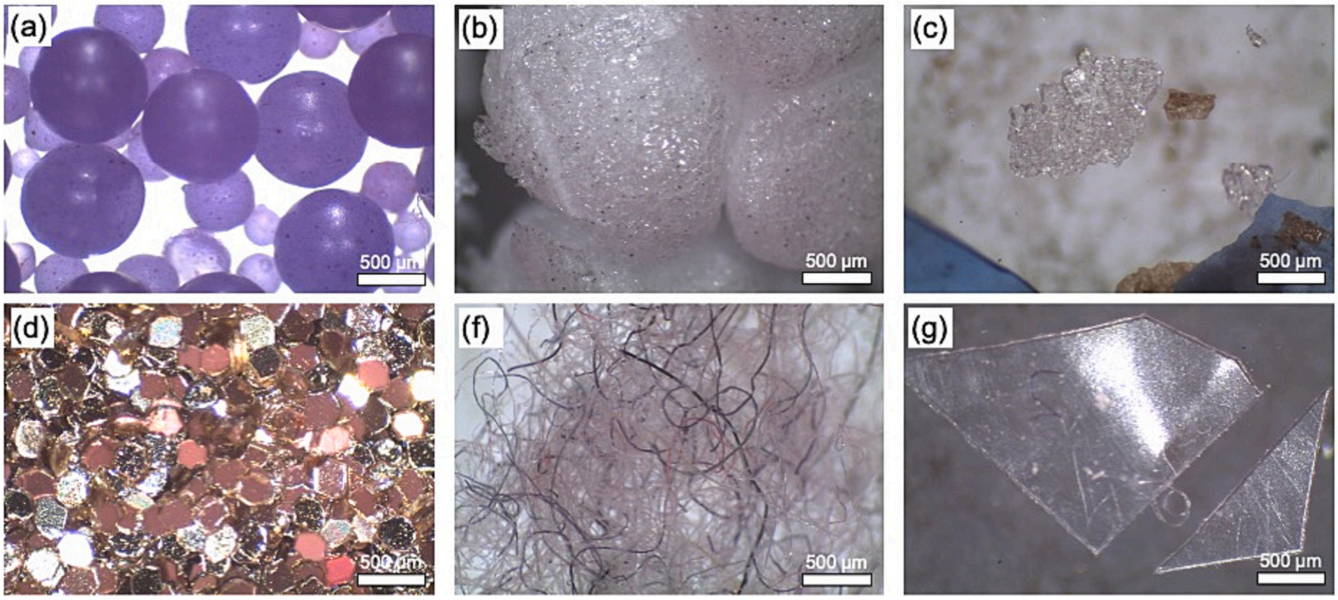


Fig. 2. Optical micrographs (35×) of the (a) beads, (b) foams, (c) fragments, (d) sheets, (e) fibres and (f) film microplastics.

composed of low-density polyethylene (LDPE) and, in some cases, PP and PS (Cheung and Fok, 2017; So et al., 2018). Foams are secondary microplastics that are frequently found in marine environments, and their main sources are foam floats, Styrofoam, and cushions (Free et al., 2014; Lee et al., 2015; Zhou et al., 2018). Fragmented secondary microplastics originate from the fragmentation of macroplastic products. Sheet-form microplastics come from glitter, a form of PET metallised with aluminum, titanium, iron, or bismuth (Yurtsever, 2019a, 2019b). Synthetic fibres account for approximately 60 % of the total global fibre production, with PP, PA, PET, and PES predominating (Carney Almroth et al., 2018; Strady et al., 2020). Therefore, laundry is an important source of microplastic fibres in the environment (Napper and Thompson, 2016; Periyasamy, 2021). Microplastic films have an irregular appearance, but are thinner and more flexible than other fragments (Edo et al., 2021) and are often found on agricultural land (Jia et al., 2022; Wang et al., 2020). These films are often derived from the fragmentation of PE films used in agricultural practices to increase moisture conservation and heat retention in the soil (Jia et al., 2022).

4. Microplastics across the environmental compartments

Microplastics are ubiquitous worldwide. The revelation of microplastics, even in remote and seemingly pristine areas, has sparked the development of the concept of a dynamic “microplastic cycle” (Bank and Hansson, 2019), elucidating the intricate pathways through which plastic particles migrate across diverse environmental compartments, including marine and freshwater ecosystems, soil systems, atmospheric transport, and even the internal tissues of organisms. The transportation of microplastics across different compartments involves a combination of physical, chemical, and biological processes (Andrady, 2011), and is heavily influenced by their physical properties, such as density, size, shape, and buoyancy (Li et al., 2020). In this regard, the abundance and fate of microplastics within each environment depends on their source and connectivity with neighbouring environments (Horton and Dixon, 2018).

4.1. Microplastics in soil

Plastics, manufactured and consumed primarily on land, naturally result in the retention of plastic waste in terrestrial environments (Su et al., 2022). The amount of plastic released annually into the terrestrial environment is estimated to be 4–23 times greater than that released into the marine environment (Horton et al., 2017). The entry of microplastics into soils stems from multiple sources, including agriculture-related practices such as plastic mulch films (Huang et al., 2020), sewage sludge (Rolsky et al., 2020), and plastic-coated fertilisers (Lian et al., 2021). Other sources of terrestrial environment include landfills (Y. Wan et al., 2022), tire particles (Leifheit et al., 2022), and atmospheric deposits (Zhu et al., 2019). Intriguingly, microplastics have been reported to exhibit vertical and horizontal migration within soils, primarily driven by root growth, plant uprooting, and inputs from various animal activities (Guo et al., 2020). UV exposure, erosion, thermal oxidation, and microbial activity are processes that can result in the degradation of microplastics, altering their physicochemical characteristics (Dissanayake et al., 2022). For instance, various chemical substances, such as phthalates, retardants, stabilisers, pigments, oligomers, and oxygenated products, may be released into the soil during this process (Dissanayake et al., 2022). Moreover, recent studies have demonstrated that microplastics can absorb soil pollutants, such as fungicides and pesticides (Ya et al., 2021), and serve as vectors for these pollutants in terrestrial environments (Wang et al., 2020).

4.2. Microplastics in aquatic environments

Aquatic systems play a dual role as both sources and sinks of microplastics, facilitating the degradation of macroplastics from inland sources while retaining microplastics within their environments (Horton and Dixon, 2018). The improper disposal of plastics, wastewater treatment plants (WWTPs), and agricultural activities collectively contribute to the significant influx of microplastics into aquatic environments. The indiscriminate disposal of plastic waste leads to its eventual transport through stormwater runoff and river systems, ultimately reaching lakes, rivers, and oceans (Grbić et al., 2020). Although WWTPs are designed to remove pollutants from domestic and industrial wastewater, they fail to remove all microplastics from their influent (Iyare et al., 2020). Moreover, plastic items can be broken down into microplastics during different treatment stages, thereby becoming an important source of microplastics in aquatic environments (Wu et al., 2022). Agricultural practices also contribute to this problem, as microplastics can migrate from soils to waterways through erosion and rainfall events (Rehm et al., 2021). Microplastics can migrate to remote marine environments through ocean gyres, which are large, rotating systems of currents that circulate water around the subtropical regions of the world's oceans, where microplastics tend to accumulate owing to the convergence of currents (Cole et al., 2011). Aquatic ecosystems can also act as a source of plastics to the atmosphere via sea spray formation and bubble burst ejection (Allen et al., 2020), eventually contributing to terrestrial microplastic transport (Bank and Hansson, 2022).

4.3. Microplastics in the atmosphere

The small size and lightweight nature of numerous microplastic particles enables them to be suspended and transported as urban dust in the atmosphere (Su et al., 2022). Atmospheric microplastics exhibit a predominance of fibres, accounting for over 90 % of all recovered items (Su et al., 2022). Studies on airborne microplastics have identified their chemical compositions, with PP, PE, PS, and PET being the dominant polymer components in atmospheric fallout (G. Chen et al., 2020). The principal sources of microplastics in the air are synthetic textiles (Dris et al., 2016); however, other potential sources include the degradation of macroplastic items, plastic waste from landfills or incineration, industrial emissions, and tire particles released from traffic (Ahmad et al., 2023). Atmospheric transport facilitated by wind is likely responsible for airborne microplastics in remote and sparsely inhabited areas (Zhang et al., 2019). Different urban centres exhibit different types of atmospheric microplastics, with fibres dominant in some locations and fragments prevalent in others (Y. Zhang et al., 2020). Wind-transported microplastics can also be deposited on glaciers, while microplastics in snowfall and rainfall can contribute to their occurrence in surface oceans and Arctic environments (Bergmann et al., 2019).

4.4. Microplastics in biota

The ubiquity of microplastics has promoted their ingestion by a diverse array of organisms across different trophic levels, leading to their widespread presence in the biota. Once ingested, microplastics cause a range of adverse effects such as depleted energy reserves arising from reduced feeding activity, longer gut residence times of ingested material, and inflammation (Wright et al., 2013). It has been established that microplastics enter the human body regularly through inhalation and ingestion; however, their effects on health are yet to be clarified (Vethaak and Legler, 2021). When ingested, larger microplastics can be excreted through gut faeces or mucociliary clearance when deposited in the respiratory tract (SAPEA, Science Advice for Policy by European Academies, 2019; Wright and Kelly, 2017). However, smaller microplastics may be able to cross the epithelial barriers of the airway, gastrointestinal tract, and skin (Vethaak and Legler, 2021), and some particles may even cross cell membranes (Wang et al., 2022), the placenta (Ragusa et al., 2021), and the brain (Prüst et al., 2020). When in contact with epithelial linings, microplastics can potentially cause several adverse effects, including physical toxicity, inflammatory and immune reactions, cellular and DNA damage, and neurotoxicity

(Vethaak and Legler, 2021; Yong et al., 2020).

While robust evidence points to the ingestion of microplastics via the food chain and inhalation from the atmosphere, resulting in the identification of potential health hazards, it is crucial to emphasise the existing uncertainty surrounding the quantification of microplastics within the human body and ingestion sources. This uncertainty stems from the absence of a standardised and universally acknowledged protocol for thorough microplastic analysis of biological samples and the atmosphere (G. Chen et al., 2020; Kutralam-Muniasamy et al., 2023). Additionally, it is essential to acknowledge the potential implications of cross-contamination on the conclusions drawn from recent studies when interpreting their findings (Kutralam-Muniasamy et al., 2023).

5. Interaction between microplastics with organic environmental pollutants

The sorption capacity of contaminants by microplastics is multifactorial, depending on the physicochemical properties of microplastics and pollutants and on the environmental conditions of the environment in which they are found (Alimi et al., 2018; Guo et al., 2019; Hartmann et al., 2019; L.-C. Wang et al., 2021). Persistent organic pollutants (POPs), such as polychlorinated dibenzo-p-dioxins (PCDDs), furans (PCDFs), polychlorinated biphenyls (PCBs), and polybrominated diphenyl ethers (PBDEs) are synthetic chemicals that are resistant to various degradation processes (L.-C. Wang et al., 2021). Owing to the hydrophobic surfaces of microplastics, POPs tend to concentrate on these surfaces at high concentrations, representing an emerging environmental problem (L.-C. Wang et al., 2021). In the research conducted by Alimi et al., the authors presented a relative classification of the sorption capacity according to the type of plastic between the years 2001 and 2017, in ascending order: PE > PS > PP > PVC > PET (Alimi et al., 2018). The justification found by the authors is the correlation of the sorption capacity with the glass transition temperature of plastics. Polymers with negative glass transition temperatures, such as PE and PP, exhibit ductile behaviour and high flexibility at room temperature and should allow greater diffusion of contaminants within their microstructures. On the other hand, polar microplastics (PET, PVC, and PA) show a much higher sorption capacity than traditional nonpolar microplastics (PE, PP, and PS) (Guo et al., 2019; Upadhyay et al., 2022; Wu et al., 2019).

Environmental characteristics can influence contaminant adsorption, as previously mentioned. For example, in environments with an alkaline medium ($pH > 8.0$) (Elizalde-Velázquez et al., 2020; Guo et al., 2019) and high salinity (Guo et al., 2019), the adsorption capacity of microplastics for pollutants is significantly diminished. On the other hand, increasing the temperature of the medium can reduce the glassy phase of the polymer, consequently increasing its affinity for contaminants. However, the same increase in temperature can lead to an increase in the solubility of pollutants. These contradictions make it challenging to predict the sorption capacity of microplastics for pollutants (Alimi et al., 2018).

Table 2 presents some peer-reviewed articles regarding the sorption of organic pollutants on microplastics (ranking them in descending order of sorption, from the most absorbent material to the least) published between 2019 and 2023. Table 2 shows that there is no clear trend that defines which microplastics have a greater tendency for sorption of organic pollutants. This occurs because in each analysed article, there are different experimental conditions (analysed contaminant, medium in which they are inserted, and other characteristics).

Although there is no linear trend in the behaviour of microplastics with respect to contaminants, we list some crucial observations from the articles presented in Table 2. Liu et al. (2019) studied the sorption of hydrophobic organic compounds (HOCs) (17β-Estradiol) by PA, PE, PP, PS, PVC, and other polymers, and particle size plays a fundamental role in the adsorption capacity of contaminants of the same polymeric species, that is, the smaller the particle, the greater the surface area available to promote these reactions (Liu et al., 2019). Puckowski et al. (2021) evaluated the sorption capacity of nine drugs (POPs) (enrofloxacin, ENR; ciprofloxacin, CIP; norfloxacin, NOR; 5-fluorouracil, 5-FU; methotrexate, MET; flubendazole, FLU; fenbendazole, PEN; propranolol, PRO; and nadolol, NAD) on the surface of PP, LDPE, high-density polyethylene (HDPE), and PVC microplastics (Puckowski et al., 2021). The results reported by the authors point to the complex nature of sorption, including hydrophobic, electrostatic, and ionic strength interactions. Cruz-Salas et al. determined the sorption capacity of hydrocarbons derived from petroleum by microplastics (LDPE > PS > PP > PVC > PET > HDPE) and correlated the results with the specific area and crystallinity of the particles (Cruz-Salas et al., 2023). Abihssira-García et al. evaluated the potential to disseminate POPs in microplastics in a salmon farming region. The authors also highlighted a much greater risk associated with PVC and PET because of their tendency to sediment and, therefore, become food for benthic communities and persist longer in the food chain (Abihssira-García et al., 2022). Other studies have shown the possibility that microplastics heteroaggregate in living organisms (such as algae and small organisms), which contributes to the vertical transport and sedimentation of these particles and increases their pollution potential (Cunha et al., 2019; Lagarde et al., 2016; Long et al., 2017).

Several recent literature reviews have highlighted the mechanisms of sorption of POPs and other contaminants on the surface of microplastics. In a review by Torres et al. (2021), the main factors that trigger these processes are presented: the properties of microplastics (type of polymer, crystallinity, polarity, functional groups, and particle size), environmental characteristics (pH, salinity, and ionic strength), and pollutant characteristics (Torres et al., 2021). The authors also presented six mechanisms that make this process possible: (I) hydrophobic interactions, (II) pore filling, (III) van der Waals interactions, (IV) hydrogen bonds, (V) π–π bonds, and (VI) electrostatic interactions. In addition to these mechanisms, Upadhyay et al. (2022) mentioned (VI) fragmentation and (VII) cationic bridges (Upadhyay et al., 2022).

6. Complex relationship between microplastic pollution and climate change

Microplastics affect climate change by contributing to pollution and altering species interactions. For example, in 2020, Evangeliou et al. presented global simulations of the atmospheric transport of two microplastic particles produced by road traffic (TWPs (tire wear particles) and BWPs (brake wear particles)) (Evangeliou et al., 2020). The authors found that atmospheric transport was a significant pathway for

Table 2
Papers related to the sorption of organic pollutants by microplastics and ranking (1: highest sorption; 5: lowest sorption).

Polymer	X. Liu et al. (2019)	Guo et al. (2019)	Elizalde-Velázquez et al. (2020)	Puckowski et al. (2021)	Song et al. (2021)	Abihssira-García et al. (2022)	Cruz-Salas et al. (2023) (Giraldo et al., 2019)
PE	1	5	1	2	2	4	
PP	2	2	3	1		3	2
PS	3	3	2		3		1
PET		4			4	1	4
PVC	4	6		3	5	2	3
PA		1			1		

road plastic pollution in remote regions. They suggested that the Arctic may be a susceptible receptor region because the light-absorbing properties of road traffic microplastics may cause accelerated warming and melting of the cryosphere. In their review of the contribution of plastics and microplastics to global climate change and their conjoining impacts on the environment, Sharma et al. established that the presence of microplastics at the ocean's depth can negatively affect the distribution of carbon organic matter at the depth of water bodies, ultimately affecting the ocean's carbon stock (Sharma et al., 2023). The impact of microplastics on climate change is complex because these plastic particles not only directly affect the climate, as in the previous two examples, but also alter interactions between species. For example, O'Brien et al. (2022) found that microplastics from tire wear particles can potentially disrupt duckweed plant-microbe mutualism, which is important for ecosystems and agricultural systems (O'Brien et al., 2022). Regarding the marine environment, Sharma et al. stated that the persistent occurrence of microplastics in aquatic bodies impacts the carbon dioxide (CO_2)-involved functions of phytoplanktons and zooplanktons, hampering the ocean carbon sequestration process as the carbon cycle pattern gets disturbed (Sharma et al., 2023).

7. Current strategies for microplastic pollution remediation

Microplastic remediation technologies can be classified into physical, chemical, and biological processes. Environmental education strategies and awareness campaigns have also been investigated. Physical mitigation technologies involve the mass transfer of microplastics. Chemical and biological technologies aim to degrade microplastics into simpler organic substances or mineralise them into CO_2 and water (H_2O) using either chemical processes or organisms, although these technologies also allow microplastics to be removed from aqueous environments through the aggregation of microplastics using chemical coagulants or extracellular substances secreted by algae. Finally, environmental education strategies and awareness campaigns distribute reliable information about microplastic pollution to sensitise people and minimise microplastic waste inputs into environmental compartments. In the following sections, a mini-review of recent advances (2019 – date) in these remediation approaches is presented. Most have been developed for the removal of microplastics present in water, while few biological approaches can be applied to terrestrial microplastics. To date, specific proposals for the removal of atmospheric microplastics are still lacking.

7.1. *Physical processes*

The most commonly used physical processes for remediating microplastic pollution are adsorption, filtration, and flotation.

7.1.1. *Adsorption*

Adsorbent materials have been successfully used to remove microplastics and nanoplastics from aqueous media (Y.-J. Chen et al., 2020; Huang et al., 2022; Oliveira et al., 2023; Peng et al., 2022; Sun et al., 2020; H. Wan et al., 2022; J. Wang et al., 2021; Zhao et al., 2022; Zheng et al., 2022). Adsorption is a process by which atoms and/or molecules (adsorbates) are retained on the surface of a material (adsorbent) through physical (physisorption) or chemical (chemisorption) interactions.

In chemisorption, a single layer of molecules, atoms, or ions is attached to the adsorbent surface through chemical bonds (Fig. 3a). In physisorption, one or more layers of atoms or molecules are adsorbed by electrostatic attractions or Van der Waals forces: dispersion forces, induced dipole-dipole forces, and dipole-dipole forces (Fig. 3b). Processes involving the adsorption of microplastics can occur in both ways, and one adsorption mechanism may stand out more than the other. This is directly related to several parameters, such as the chemical composition, porosity, particle size of the adsorbent and adsorbates, pH, temperature, and presence of ions in the solution.

The main advantages of the adsorption technology are its low cost, high efficiency in removing microplastics and nanoplastics, and the possibility of using renewable raw materials as adsorbents. The main challenges are the limited sorption capacity in an aqueous medium, difficulty of filtration at the end of the process, and interference of adsorbing ions (Huang et al., 2022; Zheng et al., 2022).

7.1.2. *Filtration*

Filtration is a process by which particles and microorganisms dispersed in an aqueous medium are retained through membranes or

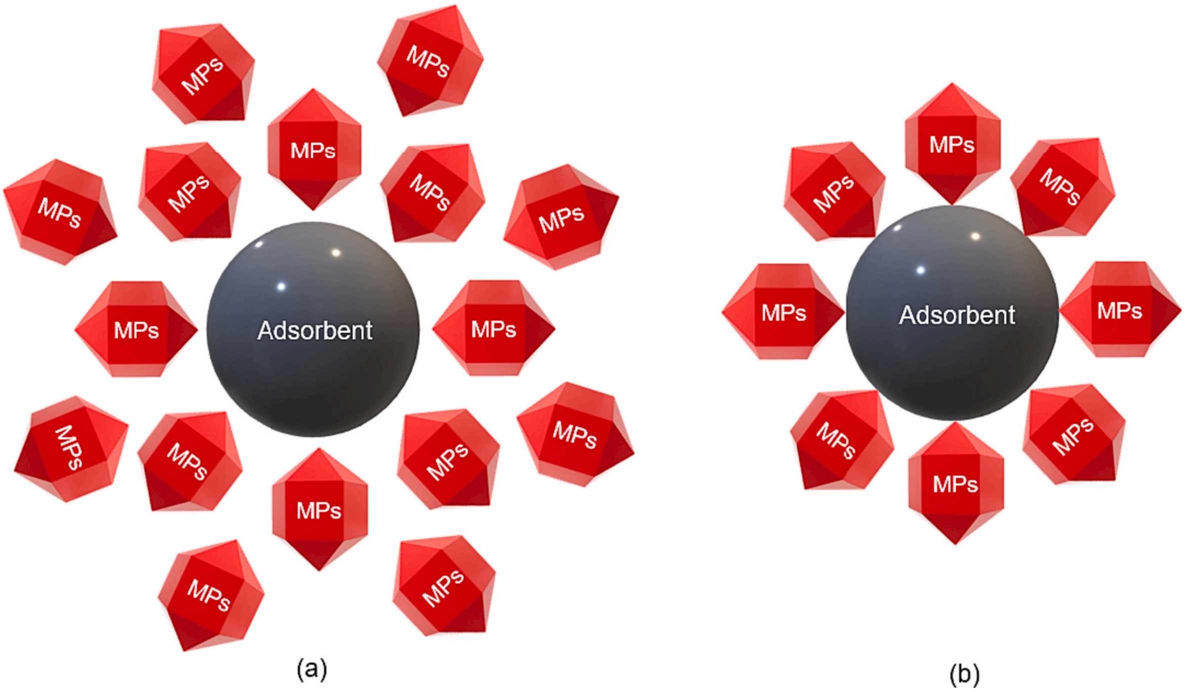


Fig. 3. (a) Physisorption and (b) chemisorption of microplastics (MPs) on adsorbents.

granular materials. This retention occurs owing to the transport mechanisms (diffusion, interception, and sedimentation) and adhesion (through physisorption or chemisorption), as shown in Fig. 4. Filtration transport mechanisms have been elucidated and correlated with the efficiency of filter materials (Chabi et al., 2024; X. Zhang et al., 2022). Regarding microplastic pollution, the efficiency of filtration depends on both the filter material (i.e. porosity and surface area) and the characteristics of microplastics and nanoplastics, which vary according to time and environmental exposure (particle size, shape, and concentration). Additionally, the direction of the liquid flow in relation to the filtering material (dead-end or cross-flow (Fig. 4a, b)) and the liquid flow rate also affect the efficiency of filtration. As demonstrated by Tanis-Kanbur et al. (2022), the dead-end direction tends to present greater microplastic incrustation in a shorter time than the cross-flow direction (Tanis-Kanbur et al., 2022). They found that microplastics with irregular shapes due to cross-flow tend to leave empty spaces in the filtering material, which reduces the incrustation of microplastics in the material and increases its lifetime.

Compared to other physical processes, it is observed that the control of process parameters for filtration is simpler; however, the cost associated with using pumps to direct the flow or pressure and the acquisition of other auxiliary equipment can make full-scale applications costly and difficult. Additionally, to promote a longer operating time during the filtration process, the use of multiple layers is recommended (Simon et al., 2019). A disadvantage of filtering is that it is not considered efficient for microfibres or microplastics with particle sizes smaller than 20 μm because they pass through filter materials and reduce their efficiency as shown in Fig. 4c (Hanif et al., 2022). Another disadvantage is that after recovery, there is the possibility of microplastic and nanoplastic detachment from the filters during cleaning, releasing them into the environment (Ding et al., 2021).

7.1.3. Flotation

Flotation is a process in which air bubbles are added to an aqueous medium so that pollutants are added to the floccules formed in the mixture, similar to what occurs in flocculation. This process has been successfully applied to remove microplastics from liquid media (Jiang et al., 2022; Pramanik et al., 2021; Swart et al., 2022; F. Yuan et al., 2022; Y. Zhang et al., 2022). A study that can be considered as a reference for microplastic flotation is that of Swart et al. (2022), in which the authors presented in detail the four mechanisms of interaction between bubbles and plastic particles and indicated the difficulty of removing particles smaller than 100 μm (Swart et al., 2022). According to the authors, the four mechanisms that influence bubble efficiency are: (I) the probability of microplastics being intercepted by ascending bubbles, which depends on both the size of the plastics and bubbles and on the number of bubbles present in the solution; (II) the effective measurement of microplastics that collided and did not necessarily adhere to rising bubbles, with the trajectory determined by hydrodynamic and interparticle forces, including Van der Waals forces and hydrophobic interactions; (III) the proportion of colliding microplastics that attach to the bubble after the collision occurs; and (IV) the proportion of microplastics detached after initial adhesion, being affected by gravity, inertia, turbulent conditions, and collisions with other bubbles (Fig. 5).

The efficiency of microplastic remediation through flotation also depends on the characteristics of both the flocculants and microplastics. Lehmann et al. (2023) reported that bubbles adhere much better to clean, hydrophobic particles, which are therefore transported significantly better than weathered hydrophilic particles dragged along the surface flow around a bubble (Lehmann et al., 2023). Chubarenko et al. (2023) reported that high densities of microplastics were correlated with a greater probability of adhesion to bubbles generated in flotation processes in polar regions, while the less dense microplastics remained suspended in surface waters until they biofouled and sedimented (Chubarenko et al., 2023).

Table 3 presents a selection of recent reports (2019 – date) regarding adsorption, filtration, and flotation technologies for microplastic pollution remediation. Selection was performed to illustrate the wide variety of materials used to adsorb, filtrate, and float microplastics achieving the highest removal efficiency. As shown in Table 3, microplastics can be adsorbed on a wide variety of engineered, natural, or waste-derived adsorbents. Engineered materials include metal-organic frameworks (MOFs), graphene-based sponges, magnetic biochars, 3D double oxides, and aerogels. Natural adsorbents include kaolin, bentonite, and diatomite, whereas waste-derived adsorbents are based on agricultural wastes (bagasse and fruit peel) and fly ash. Filtration can be performed using either filters or membranes, whereas flotation is

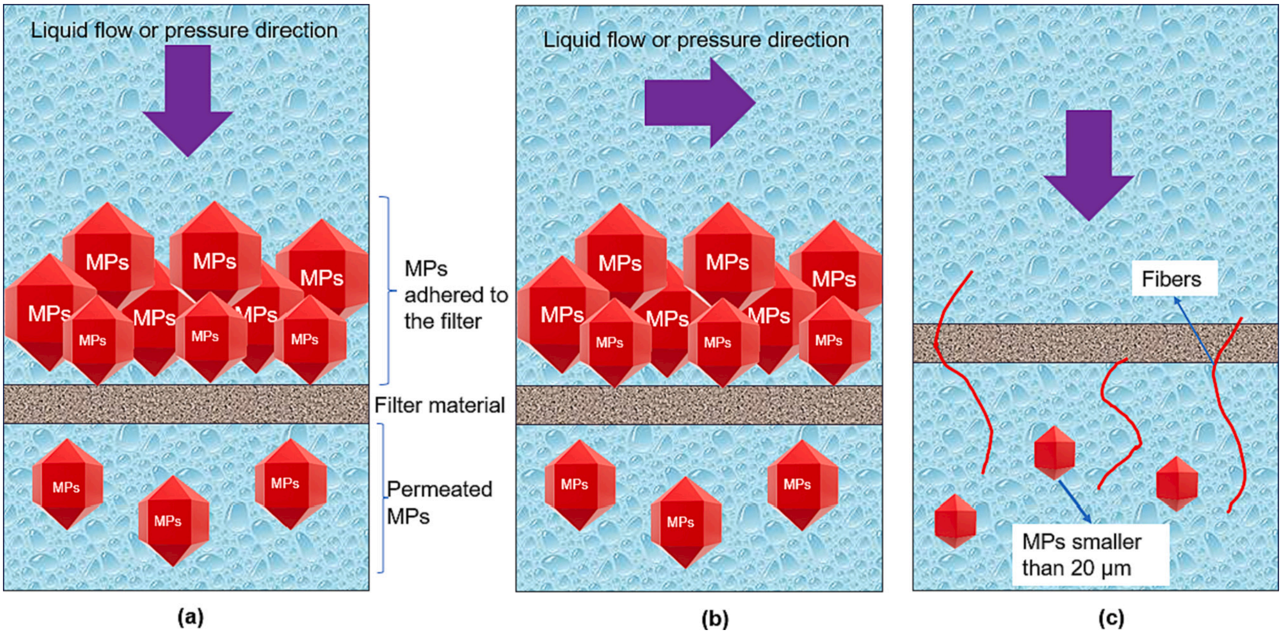


Fig. 4. Filtration of microplastics (MPs) with different liquid flow directions: (a) dead-end filtration and (b) cross-flow filtration. (c) Microplastics that cannot be filtered using currently available technology.

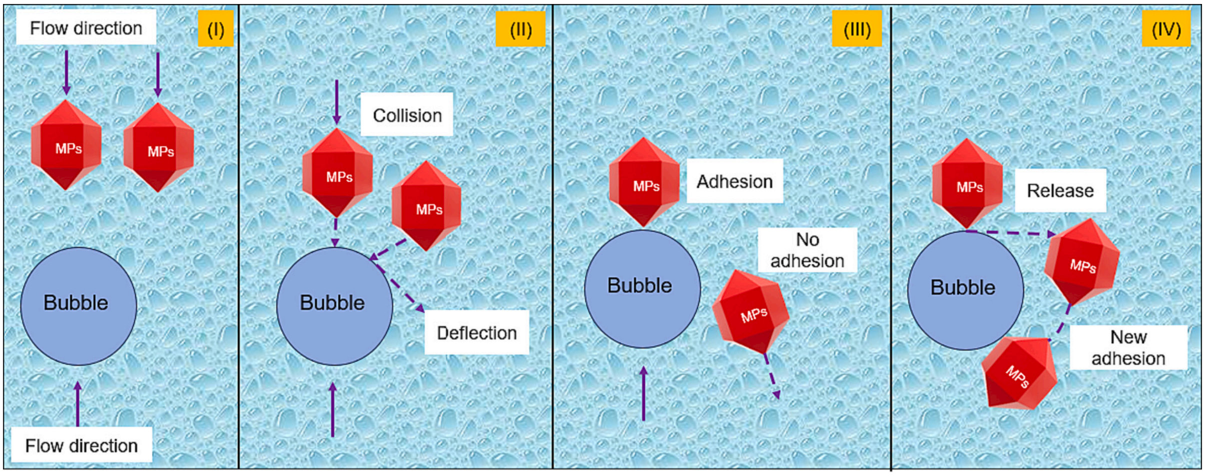


Fig. 5. The four mechanisms (I-IV) proposed by Swart et al. (2022) that influence the bubble efficiency for microplastic (MPs) removal through flotation (Swart et al., 2022).

performed using a variety of columns or bubbles. As presented in Table 3, the three approaches allow for the removal of microplastics with different polymer compositions and shapes. However, it seems that adsorption is adequate for relatively small microplastics (size <60 μm), while the removal of larger plastic particles can be achieved through filtration (from nanoplastics up to 500 μm microplastics) and flotation (from 10 μm – 5 mm).

Although the individual processes presented in Table 3 show optimum results, greater efficiency is still achieved when different processes or materials are combined (Cai et al., 2021; Hanif et al., 2022; Hsieh et al., 2022; Pramanik et al., 2021; Sembiring et al., 2021). Hanif et al. (2022) reviewed patents filed in the area of microplastic remediation and pointed out that there was a prevalence of studies that combined filtration processes with flotation. Less dense polymers found more frequently in the environment (PE, PP, and PS) are easily precipitated with the help of flocculants, which facilitates subsequent filtration processes.

A disadvantage of the physical technologies presented here is that there is no available information regarding the toxicity or environmental impact of adsorbents, filtration, and flotation devices throughout their life cycle (production, use, and disposal). Additionally, a complete solution that involves environmentally adequate disposal of recovered microplastics is still missing. The final fate and toxicity of the recovered microplastic waste should also be assessed, as microplastics and their retained additives can physically and chemically interact with the materials used for physical removal and release even more toxic compounds into the environment.

7.2. *Chemical processes*

The most commonly used physical processes for remediating microplastic pollution are coagulation-flocculation-sedimentation (*CFS*), electrocoagulation, heterogeneous photocatalysis, and the Fenton process, the last two of which correspond to Advanced Oxidative Processes (AOPs).

7.2.1. *Coagulation, flocculation and sedimentation (CFS)*

Coagulation is one of the most studied chemical remediation processes for microplastics (Xia et al., 2020; Yao et al., 2023) and is commonly associated with other processes such as flocculation and sedimentation. The overall process is known as coagulation-flocculation-sedimentation (CFS) (Esfandiari et al., 2022; Lapointe et al., 2020; Lee et al., 2023; Lu et al., 2021; Ma et al., 2019; Xue et al., 2021; Yingshuang Zhang et al., 2021; Zhang et al., 2021a, 2021b; G. Zhou et al., 2021) and is based on the addition of coagulants to an aqueous medium. The interaction of coagulants with pollutants induces their agglomeration and sedimentation, as illustrated in Fig. 6.

A large proportion of microplastics found in the environment has hydrophobic characteristics and a distribution of negative charges on the surface, increasing the probability of being suspended in aqueous solutions. However, if microplastics are in contact with coagulants with positive charges, these charges will be neutralised, inducing the agglomeration of microplastics and coagulants. This agglomeration tends to form a large flock, which settles because of the increase in density. Other physicochemical interactions may occur depending on the chemical composition of the targeted microplastics and coagulants employed. Furthermore, the concentration of both coagulants and microplastics, the pH of the medium, and the presence of ions can further affect the interactions between coagulants and microplastics and the efficiency of the process. The main disadvantage of CFS is the need for high coagulant concentrations to achieve a satisfactory efficiency rate. Coagulants that are not adequately removed after treatment with microplastics can bioaccumulate in living beings and the environment.

7.2.2. *Electrocoagulation*

Coagulation is commonly associated with electricity (a process called electrocoagulation) (Akarsu et al., 2021; Akarsu and Deniz, 2021; Elkhatib et al., 2021; Senathirajah et al., 2023; Shen et al., 2022). Electrocoagulation uses electrodes for the continuous generation of coagulants. The advantage of electrocoagulation is the overall increase in process efficiency, including a decrease in chemical oxygen demand and other pollutants in the case of wastewater (Elkhatib et al., 2021). However, there may be a higher cost associated with the operation, as it uses electrical current to generate coagulants, in addition to the need to change sacrificial agents with a certain frequency and the accumulation of coagulants in the environment after the microplastic treatment process.

Senathirajah et al. (2023) attempted to determine the correlation between the efficiency of electrocoagulation and the characteristics (density, crystallinity, and hydrophobicity) of micrometric-scale thermoplastics from the primary and secondary sources most commonly found in the environment: PET, LDPE, PP, and PA (Senathirajah et al., 2023). The authors highlighted that hydrophilic and amorphous microplastics such as PA, exhibited the lowest removal efficiency. However, the influence of other external parameters (such as coagulant properties) can modify this trend. For example, Hu et al. (2023) achieved a removal efficiency of 96.82 % for PA microplastics using Fe—Al electrodes for 120 min (Hu et al., 2023). Senathirajah et al. (2023) also explained that microplastics from secondary sources are more likely to be manipulated or adsorbed than those from primary sources because of

Table 3
Physical processes for microplastic pollution remediation.

Physical process	Material	Microplastic/nanoplastic characteristics			Nature of treated sample	Removal efficiency (%)	Reference
		Polymer	Size/concentration	Shape			
Adsorption	Zeolitic imidazolate MOF ZIF-68. Physisorption	PVDF, PS	60–110 nm (PVDF) and 90–140 nm (PS)	Irregular spherical	Water and seawater (Haikou City, Hainan Province, China, South China Sea)	91.4 % and 85.8 %	(Y.-J. Chen et al., 2020)
Adsorption	Sponge prepared from chitin and graphene oxide (ChGO). Physisorption	PS, carboxylate-modified PS, and amine-modified PS	1 μm, 1 mg/L	Spherical	Laboratory with distilled water	89.8 %, 72.4 %, and 88.9 % respectively	(Sun et al., 2020)
Adsorption	Magnetic biochar (MBC), Mg modified magnetic biochar (Mg-MBC) and Zn modified magnetic biochar (Zn-MBC). Physisorption	PS	1 μm	Spherical	Pinewood sawdust was from Zhejiang Province, China. The river water was sampled from a local river and the wastewater was printing and dyeing wastewater collected from a local wastewater treatment plant in Hangzhou, China.	94.8 %, 98.8 % and 99.5 %	(J. Wang et al., 2021)
Adsorption	Zeolitic imidazolate MOF ZIF-67. Physisorption	PS	5–50 mg/L	–	Laboratory with deionized water	92.1 %	(H. Wan et al., 2022)
Adsorption	3D graphene-like carbon assembled layered double oxide material (defined as G@LDO). Physisorption/ chemisorption	PS	80 nm	Spherical	Tap water, lake water from Jiangxi before lake and industrial wastewater from a factory in Nanchang, Jiangxi province	80.0 %	(Peng et al., 2022)
Adsorption	Fly ash modified with iron. Physisorption/ chemisorption	PS	1–20 mg/L	Spherical	Laboratory with distilled water	94.1 %	(Zhao et al., 2022)
Adsorption	Co/Mn–kaolin and Fe-kaolin. Physisorption	PVC, PS, PET and ABS mixture	0.25 g for each dilluted to a 100 mL mixture solution of H_2O and ethanol (volume ratio, 3:1). The final concentration of the mixture was 0.01 g/mL	Various shapes	Laboratory with distilled water	24.6 % and 14.5 %	(Huang et al., 2022)
Adsorption	Polydopamine enhanced magnetic chitosan (PDA-MCS) aerogels. Physisorption	PET, PE and PS	28.2 μm, 32.2 μm and 36.6 μm	Irregular fragments	External drainage from the sewage plant and river water from tributaries of the Pearl River	97.3 %, 94.6 % and 92.3 %	(Zheng et al., 2022)
Adsorption	Coconut bagasse, sugarcane bagasse, banana peel bagasse, bentonite and diatomite. Physisorption	PVC, PET, PS, PP and HDPE microemulsified	<60 μm	Irregular fragments	Laboratory with distilled water	51.2 %, 79.7 %, 68.1 %, 52.9 % and 66.5 %	(Oliveira et al., 2023)
Filtration	Disc filter	PE, PS and PVC	4.2–407.1 μm	Irregular fragments	Water from WWTP by Billund Vand and Energi A/S in Grindsted, Denmark	89.7 %	(Simon et al., 2019)
Filtration	PVDF from membrane bioreactor	PP, PE, PA, PET and PVC	0–450 μm	Fragments, fibres, films and pellets	Water from WWTP Yantai City, Shandong Province, China	98.0 %	(Cai et al., 2021)
Filtration	Biomimetic gill-inspired membranes	PS	500, 700 and 1000 nm	Spherical	Laboratory with deionized water	97.6 %	(X. Zhang et al., 2022)
Filtration	Rapid sand filter	PET and tyre flakes	10–500 μm	Flakes, fragments and fibres	Tap water	97.0 %	(Sembiring et al., 2021)
Filtration	Rapid sand filter	PP and PS	0–6 μm	Sheets	Tap water	98.0 %	(Chabi et al., 2024)
Flotation	Short column with a standard glass frit, pore size 16–40 μm	PE, PVC and PET	75–300 μm	Fragments	Laboratory with water	85.0 %, 82.0 % and 69.0 %	(Pramanik et al., 2021)
Flotation	Column made of PMMA	PET and PS	0.074–5 mm	Irregular fragments	Laboratory simulating seawater and industrial effluent	100.0 %	(Yingshuang Zhang et al., 2021)
Flotation	New-designed flotation column, spherical air stone, and air pumps (24 L/min)	PVC and ABS	0.074–5 mm	Sheets	Laboratory with water	84.3 % and 98.3 %	(Jiang et al., 2022)
Flotation	Column made of PMMA with an adjustable air pumps	PVC	2–4 mm	Irregular fragments	Laboratory with water	100.0 %	(Y. Zhang et al., 2022)
Flotation	Mini-hydrocyclone	PE	10–120 μm	Irregular fragments	Laboratory with water	96.0 %	(F. Yuan et al., 2022)
Flotation	Microbubbles	PE, PP, PVC and PMMA	10–600 μm	Spherical and irregular	Laboratory with deionized water	90.3 %	(Swart et al., 2022)

MOF = metal-organic framework; PVDF = poly(vinylidene fluoride); PMMA = poly(methyl methacrylate); ABS = acrylonitrile butadiene styrene.

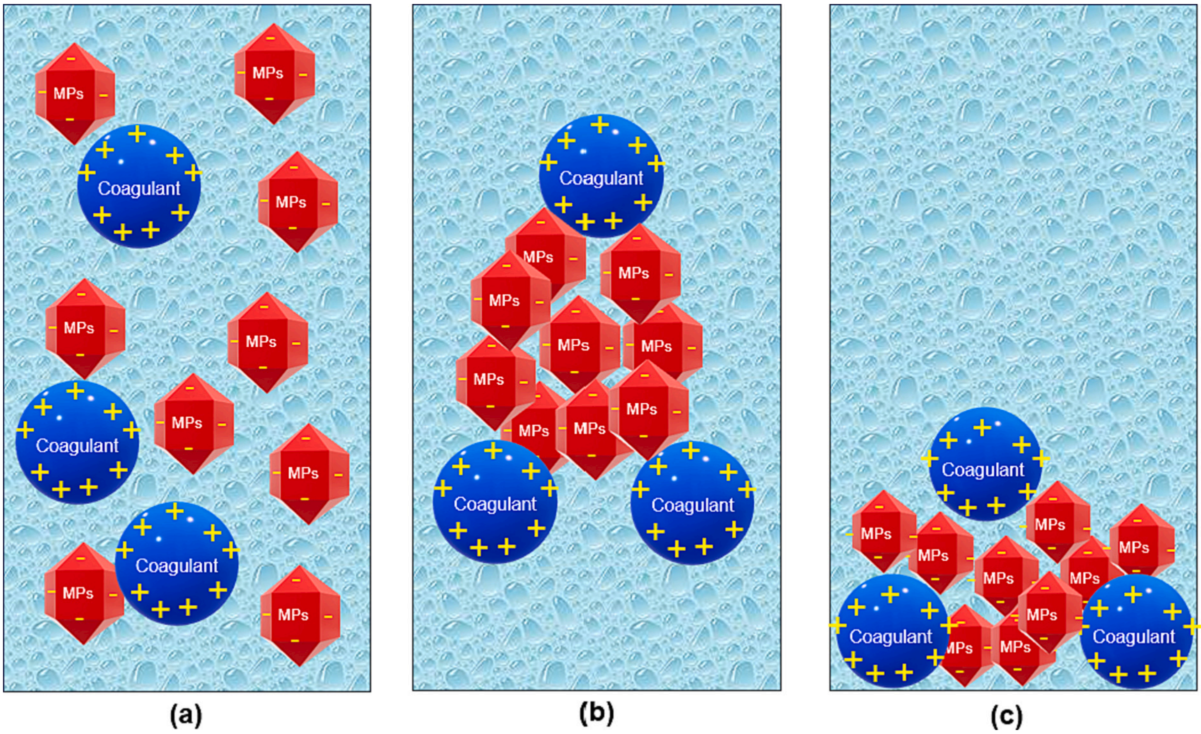


Fig. 6. (a) Coagulation, (b) flocculation, and (c) sedimentation of microplastics (MPs).

aging actions and changes in surface morphology. In relation to morphology, fragments are more easily removed than fibres (Hanif et al., 2022).

7.2.3. *Advanced oxidation processes (AOP)*

Advanced Oxidation Processes (AOPs) use highly oxidising compounds to generate hydroxyl radicals or superoxides that act in the degradation of recalcitrant compounds until complete mineralisation, that is, obtaining CO_2 and H_2O as products. These processes have been used to degrade recalcitrant pollutants from various sources (Nohara et al., 2023, 2022; Y.-L. Zhang et al., 2022), being recently applied to the degradation of microplastics (Cedillo-González and Siligardi, 2023; Hu et al., 2022; Ortiz et al., 2022). The best-known and currently used processes for the degradation of microplastics are Fenton and photocatalysis.

Fenton processes use hydrogen peroxide (H_2O_2) and Fe^{2+} in an acidic medium to generate hydroxyl radicals ($OH^\bullet$) and consequently degrade microplastics (Hu et al., 2022; Ortiz et al., 2022; Piazza et al., 2022). The Fenton reaction occurs in two steps: (i) Fe^{2+} and H_2O_2 (fast step, Eq. (1)), and (ii) regeneration of Fe^{2+} by H_2O_2 (slow step, Eq. (2)) (Haber et al., 1934; Ricardo et al., 2021).

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + OH^{\cdot} k = 76 \text{ L mol}^{-1} \text{ s}^{-1} \tag{1}$$

$$Fe(OH)^{2+} + h\nu \rightarrow Fe^{2+} + OH^{\cdot} \tag{2}$$

Fenton processes generate radical species in solution. One way to make this process even faster is to use UV–Vis irradiation, a process known as photo-Fenton. Other variations are also possible, such as modified Fenton, thermal Fenton, and electro-Fenton-like processes (Ricardo et al., 2021). For instance, Ortiz et al. (2022) studied the application of the conventional Fenton process to the manipulation of different microplastics from real sources (PET, PE, PVC, PP, and EPS) by varying the concentrations of reagents and microplastics (Ortiz et al., 2022). The authors achieved a maximum efficiency of 18 % (expressed as weight loss, WL) for EPS weight reduction. The chemical composition of microplastics is highly correlated with the overall oxidation rate, with microplastics that contain aromatic rings in their structures (EPS and PET) being more vulnerable to oxidation compared to those formed by alkane chains (PE, PP, and PVC) (Ortiz et al., 2022). An example of a photo-Fenton process for microplastic pollution remediation was reported by Piazza et al. (2022). The authors trained the photo-Fenton process for the manipulation of commercially purchased PP and PVC microplastics for up to 30 days (Piazza et al., 2022). After seven days, an efficiency of 95 % reduction in the volume (RPV) of microparticles was achieved, with no release of toxic by-products for other living beings, according to experiments carried out with *Aliivibrio fischeri* and *D. magna* acute toxicity assays and *P. subcapitata* chronic toxicity assay. The thermal-Fenton process can reduce the reaction time necessary to achieve degradation and mineralisation. For example, Hu et al. (2022) subjected five types of microplastics (HDPE, LDPE, PVC, PP, and PS) to the thermal Fenton process for up to 16 h, varying the pH (0.7–3.0) and temperature (25–160 °C) (Hu et al., 2022). After 4 h, 95.9 % WL and 75.6 % mineralisation of microplastics were achieved at pH values of 1 and 160 °C, respectively.

Among AOP processes, photocatalysis has shown promise for the efficient removal of microplastics. Photocatalysis is a water treatment process that can be used in tertiary treatment WWTPs. It is based on the irradiation of a semiconductor (photocatalyst) with light and generation of oxidant radicals. When the photocatalyst interacts with photons with energies greater than its bandgap (E_g), the electrons (e^-) in the valence band are transferred to the conduction band, leaving behind a positive hole (h^+), as shown in Eq. (3). Holes react with H_2O or hydroxyl groups (OH^-) adsorbed on the surface to generate $OH^\bullet$, whereas electrons react with adsorbed oxygen to form hydroperoxyl/superoxide anion radicals ($HO_2^\bullet/O_2^{-\bullet}$), as shown in Eqs. (4) and (5). All these radicals are known as reactive oxygen species (ROS) and are mainly present on the surface of the photocatalyst. ROS can degrade complex organic pollutants into simpler subproducts or mineralise them into CO_2 and H_2O, as shown in Eq. (6) (Fig. 7).

$$\text{Photocatalyst} + h\nu \rightarrow h^{+} + e^{-} \tag{3}$$

$$h^{+} + H_2O\ (\text{or } OH^{-}) \rightarrow OH^{\cdot} \tag{4}$$

$$e^{-} + O_2 \rightarrow H\dot{O}_2/O_2^{-\cdot} \tag{5}$$

$$\text{Pollutant} + OH \rightarrow \text{Subproducts} \rightarrow CO_2 + H_2O \tag{6}$$

In recent years, numerous studies have focused on the photocatalytic degradation of microplastics, targeting various polymers, such as PE (Ariza-Tarazona et al., 2020, 2019; Tofa et al., 2019a, 2019b; Vital-Grappin et al., 2021), PS (Acuña-Bedoya et al., 2021; Chattopadhyay et al., 2023; Domínguez-Jaimes et al., 2021; Nabi et al., 2020), PP (Uheida et al., 2021), and PET (Ariza-Tarazona et al., 2023; Rojas-Guerrero et al., 2023; Zhou et al., 2022). However, there are challenges associated with the scalability of photocatalysis and the need for long irradiation times and harsh conditions to promote effective degradation. Achieving scalable and practical applications of this technology is a complex task that requires further research and development. Additionally, optimising the process to reduce irradiation times and minimise harsh conditions is essential to enhance its feasibility and efficiency in treating microplastic-contaminated wastewater.

An advantage of AOPs is that these technologies can achieve high rates of removal and mineralisation of microplastics, with limited or no release of toxic subproducts. Furthermore, it is possible to benefit from the use of subproducts such as H_2 fuel obtained from water hydrolysis (J. He et al., 2023; Qin et al., 2022) and, more recently, the transformation of microplastics into value-added functional carbons (Ren et al., 2024). Among the factors that most influence AOPs are the catalyst and pollutant concentrations, pH of the medium, temperature, reaction medium, reaction time, presence of other compounds in the medium, and particle size. More studies on the application of these processes under natural conditions (whether of the reaction medium or the source of microplastics) and on a larger scale are needed, in addition to analysing the toxicity of by-products after the processes and the mineralisation rate of microplastics.

Table 4 presents a selection of recent reports (2019 – date) regarding coagulation-flocculation-sedimentation, electrocoagulation, Fenton, and photocatalytic technologies for microplastic pollution remediation. Selection was performed to illustrate the wide variety of materials used to chemically remove, degrade, or mineralise microplastics achieving the highest removal efficiency. Coagulation using organic and inorganic coagulants allows the removal of a wide granulometric range of plastic particles (from 500 nm to 500 μm) of several chemical compositions and shapes. Although the efficiency was slightly increased by electrocoagulation, the size of the recovered microplastics greatly increased (up to 2 mm). Both Fenton-based methods and photocatalysis allow the degradation of microplastics of several sizes (below 725 ± 108 μm), shapes, and compositions. However, as a surface process that depends on the interaction of microplastics with surface-adsorbed photogenerated ROS, photocatalysis presents lower degradation efficiencies than Fenton-based processes for relatively large microplastics, for which adsorption on the surface of the photocatalyst is intrinsically impeded.

7.3. Biological processes

The remediation of microplastic pollution using biological processes can be achieved using bacteria, fungi, algae, insects, and enzymes.

7.3.1. Microbial degradation by bacteria and fungi

Bacteria and fungi play crucial roles in maintaining biogeochemical and nutrient cycling in the environment (S. Li et al., 2023). Bacteria are preeminent organisms for nutrient transformation and circulation in the environment and can decompose synthetic polymers because of their potential to metabolise long-chain fatty acids (S. Li et al., 2023). Degradation of microplastics using bacteria can be achieved using cultures from various sources, such as soil (Auta et al., 2022; Habib et al., 2020), landfill soil (Park and Kim, 2019; Tareen et al., 2022), marine environments (Nanthini Devi et al., 2021), and sediments (J. Yuan et al., 2022), worms (Kang et al., 2023), mud, and wastewater (Dehghanian et al., 2023). Fungi are sporulating eukaryotic organisms devoid of chloroplasts. They are heterotrophic organisms that absorb nutrients through endocytosis and exocytosis; therefore, some of the enzymes released by them can promote the degradation of microplastics (S. Li et al., 2023; Moyses et al., 2021; J. Zhang et al., 2020).

Microbial degradation of microplastics occurs in four stages: (i) the formation of microbiological membranes surrounding microplastics (biofilm formation), (ii) biodeterioration, (iii) biological fragmentation, and (iv) mineralisation (Nguyen et al., 2023). Biofilm formation is indispensable for the breakdown of plastics because it facilitates the adhesion of colonies to the surface of microplastics and promotes their persistence (S. Li et al., 2023). Microplastic surface properties such as free energy, roughness, electrostatic interaction, and hydrophobicity can influence biofilm formation (Nguyen et al., 2023). The biodeterioration stage is based on the production of internal and extracellular enzymes by microorganisms, and plays a particular role in the breakdown of microplastics (biological fragmentation) (Nguyen et al., 2023). Commonly reported microplastic-degrading enzymes include oxidoreductases, lipases, esterases, cutinases, laccases, peroxidases, carboxylesterases, keratinases, hydrolases, and proteases (Dehghanian et al., 2023; S. Li et al., 2023). In general, a single enzyme cannot completely degrade microplastics, whereas the action of multiple enzymes typically results in complete degradation (S. Li et al., 2023). Finally, mineralisation involves the formation of CO_2, H_2O, and CH_4. According to Yuan et al., the mechanism of microplastic mineralisation by microbes first

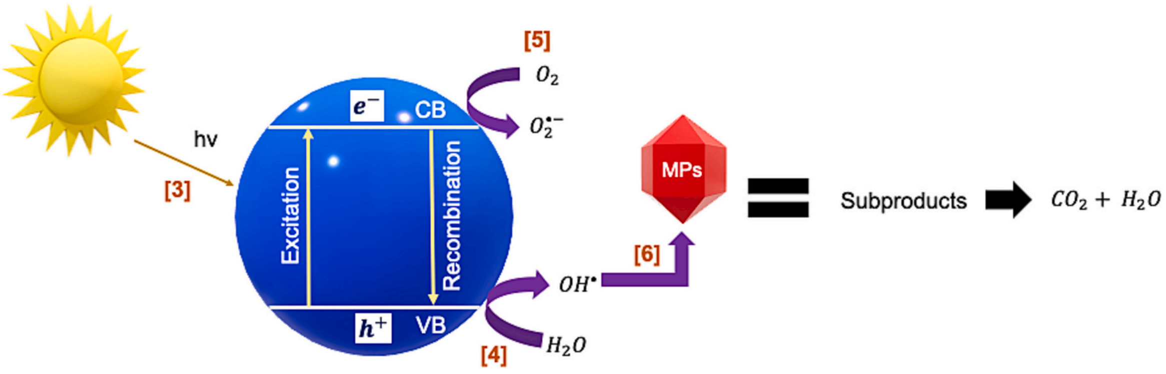


Fig. 7. Photocatalytic degradation and mineralisation of microplastics (MPs).

Table 4
Chemical processes for microplastic pollution remediation.

Chemical process	Material	Microplastic/nanoplastic characteristics			Nature of sample	Removal efficiency (%)	Reference
		Polymer	Size/ concentration	Shape			
Coagulation	Polyaluminum chloride (PAC) and $FeCl_3$	PS and PE	200–400 µm	Irregular fragments	Laboratory with water	77.8 % WL	(G. Zhou et al., 2021)
Coagulation	Tannic acid (TA)	PS and PE	0.5–125 µm	Spherical	Laboratory with ultrapure water	99.0 % FQA	(Park et al., 2021)
Coagulation	Polyaluminum sulfate (PAS)	PS	250–425 µm	Irregular fragments	Laboratory with ultrapure water	90.4 % WL	(Yao et al., 2023)
Coagulation	Anionic polyacrylamide (PAM), sodium alginate (SA) and activated silicic acid (ASA) combined with polyaluminum chloride (PAC)	PET	≤500 µm	Irregular fragments	Laboratory with water	91.5 % WL	(Yingshuang Zhang et al., 2021; Zhang et al., 2021a, 2021b)
Coagulation	$AlCl_3$	PET	500 ± 2.5 nm	No presented	Laboratory with ultrapure water	100.0 % WL	(Lu et al., 2021)
Coagulation	Crystal aluminum chloride	PS	2–5 µm	Spherical	Laboratory with deionized water	98.6 % FQA	(Xia et al., 2020)
Coagulation	Magnetic magnesium hydroxide coagulant (MMHC) and magnesium hydroxide coagulant (MHC)	PE	≤270 µm	No presented	Laboratory with simulated natural water conditions	87.1 % WL	(Yingshuang Zhang et al., 2021; Zhang et al., 2021a, 2021b)
Coagulation	Ferrate	PE and PET	40–300 µm	No presented	Natural surface water was taken from a river of Oncheoncheon, Republic of Korea	98.0 % PC	(Lee et al., 2023)
Electrocoagulation	Al and Fe anode	PE, PMMA, Cellulose acetate and PP	PE and PMMA (6.3–286.7 µm), Cellulose acetate and PP (1-2 mm)	Granular (PE and PMMA) and fibres (cellulose acetate and PP)	Laboratory with simulated wastewater conditions	93.2 %, 91.7 %, 98.2 % and 98,4 % WL	(Shen et al., 2022)
Electrocoagulation	Reactor made with stainless-steel outlet and the electrodes comprised an iron anode and a stainless-steel cathode	PA, PE, PET and PP	125–250 µm	Fibres and fragments	Laboratory with simulated wastewater conditions	PET with fragment form (96.7 %), PP with mixed form (91.3 %), PA with mixed form (88.0 %) and PE fragments (93.3 %) CP	(Senathirajah et al., 2023)
Electrocoagulation	Reactor made with stainless-steel valves and Al electrode	PET	25–1500 µm, 100 mg/L	Sheet	Synthetic solutions and wastewater samples from WWTP Rhode Island (USA)	98.5 % PC	(Elkhatib et al., 2021)
Electrocoagulation	Reactor equipped with electrode	No determined		Irregular fragments and fibres	Wastewater from a laundry located in Mersin, Turkey	98.0 % PC	(Akarsu and Deniz, 2021)
Electrocoagulation	EC/EF system equipped with electrodes Fe—Al and Al-Fe	PE and PVC	150–250 µm	No presented	Distilled water and wastewater by Konacık located around Bodrum, Muğla	100.0 % PC	(Akarsu et al., 2021)
AOPs - Fenton	ZnO nanorods coated with SnO_x($x < 2$) layer and decorated with zero valent iron (Fe^0) nanoparticles	PP and PVC	73–155 µm	Irregular fragments	Laboratory with deionized water	95.0 % WL	(Piazza et al., 2022)
AOPs - Fenton	Conventional Fenton	PET, PE, PVC, PP and EPS	27–335 µm	Irregular fragments	Laboratory with deionized water	18.0 % WL	(Ortiz et al., 2022)
AOPs - Fenton	Thermal Fenton reaction	HDPE, LDPE, PVC, PP and PS	≤254 µm	Irregular fragments	Laboratory with ultrapure water	95.9 % WL/M	(Hu et al., 2022)
AOPs - Photocatalysis	C,N-TiO_2	HDPE	725 ± 108 µm	Spherical	Laboratory with a buffer solution	75.4 % WL	(Ariza-Tarazona et al., 2020)
AOPs - Photocatalysis	ZnO	PP	154.8 ± 1.4 µm	Irregular fragments	Laboratory with a high pure water	65.0 % RPV	(Uheida et al., 2021)
AOPs - Photocatalysis	C,N-TiO_2	HDPE	725 ± 108 µm	Spherical	Laboratory with a buffer solution	71.8 % WL	(Vital-Grappin et al., 2021)
AOPs - Photocatalysis	g-C_3N_4/TiO_2	PE	50 mg	Fibre	Laboratory with water	89.0 % WL	(Zhong et al., 2023)
AOPs - Photocatalysis	Co_3O_4@Co$(OH)_2$	PS	0.9 µm	Spherical	Laboratory with water	40.0 % WL	(Greco et al., 2023)
AOPs - Photocatalysis	GO-TiO_2	PE	1 mm-300 µm	Spherical	Laboratory with deionized water	50.5 % WL	(Ugintė et al., 2023)

(continued on next page)

Table 4 (*continued*)

Chemical process	Material	Microplastic/nanoplastic characteristics			Nature of sample	Removal efficiency (%)	Reference
		Polymer	Size/ concentration	Shape			
AOPs - Photocatalysis	TiO_x/ZnO tetrapod	PS and PE	2 μm	Spherical, fibres and irregular fragments	Laboratory with deionized water	100.0 % WL	(Y. He et al., 2023)
AOPs - Photocatalysis	$FeCl_3$	PA6	600 nm-1.2 μm	Fibre	Laboratory with deionized water	94.0 % WL	(Zhong et al., 2024)

WL = weight loss (%); FQA = fluorescent quantitative analysis; PC = particle counter; M = mineralisation; RPV = reduction of particle volume; EC = electrocoagulation and EF = electroflotation.

involves their transformation into oligomers and monomers. Subsequently, intracellular or extracellular depolymerase enzymes are secreted, depending on the type of microorganism (Yuan et al., 2020). Finally, mineralisation converts short molecular chains that are small enough to pass through a semi-permeable membrane into CO_2, H_2O, and CH_4 (Nguyen et al., 2023). Physically, the microbial degradation of microplastics causes a decrease in the dry weight of polymers and physicochemical alterations, including modifications in surface morphologies.

The degradation accomplished by microbes is related to key characteristics, such as molecular weight, solubility, branching degree, crystallinity, and hydrophilicity of the polymers (S. Li et al., 2023). Pure bacterial cultures or bacterial consortia can be employed for the microbial degradation of microplastics (Dehghanian et al., 2023). However, it is known that in bacterial processes, a single-strain culture easily produces toxic substances in the later stages of degradation, which markedly impedes the growth of microorganisms (S. Li et al., 2023). Therefore, mixed microbial cultivation can eliminate the toxicity of metabolites and improve degradation efficiency (Dehghanian et al., 2023; S. Li et al., 2023). Similarly, mixed fungal strains have a synergistic effect on microplastic degradation (S. Li et al., 2023).

Although microbial degradation is a promising technology for microplastic pollution remediation, it is important to highlight that it can also promote the release of plastic particles smaller than those originally targeted for remediation. For instance, Jayan et al. found that while a novel isolate *Bacillus cereus* obtained from waste dump soil can biodegrade LDPE macroplastics (43 % WL in 120 days), the bacteria released an average of 50,930 ± 1464 microplastics/L during the same period (Jayan et al., 2023), and similar behaviours can be shown by microbes degrading relatively large microplastics. Therefore, these microbes should be incubated for extended periods in carbon-free media to continue biodegrading the released smaller plastic particles, and the release of nanoplastics should be monitored.

7.3.2. Adsorption and heterogeneous aggregation of microplastics by algae

Algae can not only collect and fix microplastics by interception, capture, and entanglement (adsorption) (Gao et al., 2020; S. Liu et al., 2023; Peller et al., 2021) but also through the formation of hetero-aggregates due to the secretion of extracellular substances from cells (Cheng and Wang, 2022; Cunha et al., 2019, 2020; S. Liu et al., 2023). According to S. Liu et al. (2023), these two pathways can be categorised as direct and indirect. In the direct pathway, microplastics can quickly adsorb onto the surface of algae, while nanoplastics can be absorbed and internalised by algal cells and transferred to various tissues. Large plastic particles (microplastics) remain on the surface because the epidermis and cell walls make it difficult for large particles to penetrate tissues, whereas smaller plastics (nanoplastics) are more likely to penetrate tissues. The surface roughness of plastics is positively correlated with the number of attached microalgae, and high-energy surfaces typically contribute to biofilm growth. Thus, microplastics with high surface roughness and hydrophilicity are expected to attach more easily to microalgae (S. Liu et al., 2023). The indirect pathway of microplastic collection by algae involves an extracellular polymer substance (EPS), a polymer with complex structures, and various physical and chemical properties (S. Liu et al., 2023). Under microplastic stimulation, algae can enhance the secretion and release of EPS, which captures microplastics by forming heterogeneous aggregates (Cheng and Wang, 2022; Cunha et al., 2019, 2020; S. Liu et al., 2023). Heteroaggregation promotes automatic precipitation, which does not require energy-intensive filtration or centrifugation (S. Li et al., 2023). The removal of microplastics by the formation of hetero-aggregations is repeatable, and the large-scale extension of this process is relatively simple. Moreover, extracellular polymers can enhance the adsorption of microplastics on solid surfaces and further reduce the number of free and suspended microplastics (S. Li et al., 2023).

Both adsorption and heterogeneous aggregation may be pathways for microalgae to reduce the concentration of microplastics in marine ecosystems. However, a disadvantage of this process is that turbulence can disrupt heterogeneous aggregates during wastewater treatment (S. Liu et al., 2023).

7.3.3. Biodegradation by insects

Insect larvae, such as *Tenebrio molitor* larvae (mealworms), a plastic-degrading macroinvertebrate, have recently been shown to degrade PVC, PS, and PLA microplastics (Peng et al., 2023, 2020). However, macroinvertebrates that ingest macroplastics or microplastics may simultaneously experience inflammatory responses and physical damage, possibly generating and releasing smaller microplastics or nanoplastics. For example, 31.5 μm PE microplastics were found to be digestively triturated into nanoplastics (<1 μm) in Antarctic krill (*Euphausia superba*), which increased the capacity of fragments to cross biological barriers or are egested as a mixture of triturated particles (Dawson et al., 2018). Kwak and An reported the earthworm-induced fragmentation of microplastics to nanoplastics. The authors exposed earthworms (*Eisenia andrei*) to 180–212 μm and 250–300 μm PE microplastics for 21 days and found that these soil invertebrates produced nanoplastics (180–364 nm) in their intestines, which were introduced into soils through cast excretion (Kwak and An, 2021).

7.3.4. Enzymatic degradation

Research has been conducted to identify the enzymes responsible for the biological degradation of polymers in several organisms, with the aim of further large-scale production using biotechnology (Cao et al., 2023; A. Zhang et al., 2023). Extracellular enzymes undergo oxidation, hydrolysis, and depolymerisation of long-chain polymers into a mixture of small-chain oligomers and monomers, while intracellular enzymes are involved in the assimilation and mineralisation of oligomers and monomers through aerobic and anaerobic processes (Kothawale et al., 2023). Hydrolysable polymers, such as PET and polyurethane (PUR), with ester bonds in their backbones are easily hydrolysed by enzymes, whereas non-hydrolysable polymers, such as PE, PVC, PS, and PP, which have carbon chains in their backbone, are less susceptible to enzymatic degradation (Kothawale et al., 2023).

Fig. 8 presents an overview of the biological processes involved in

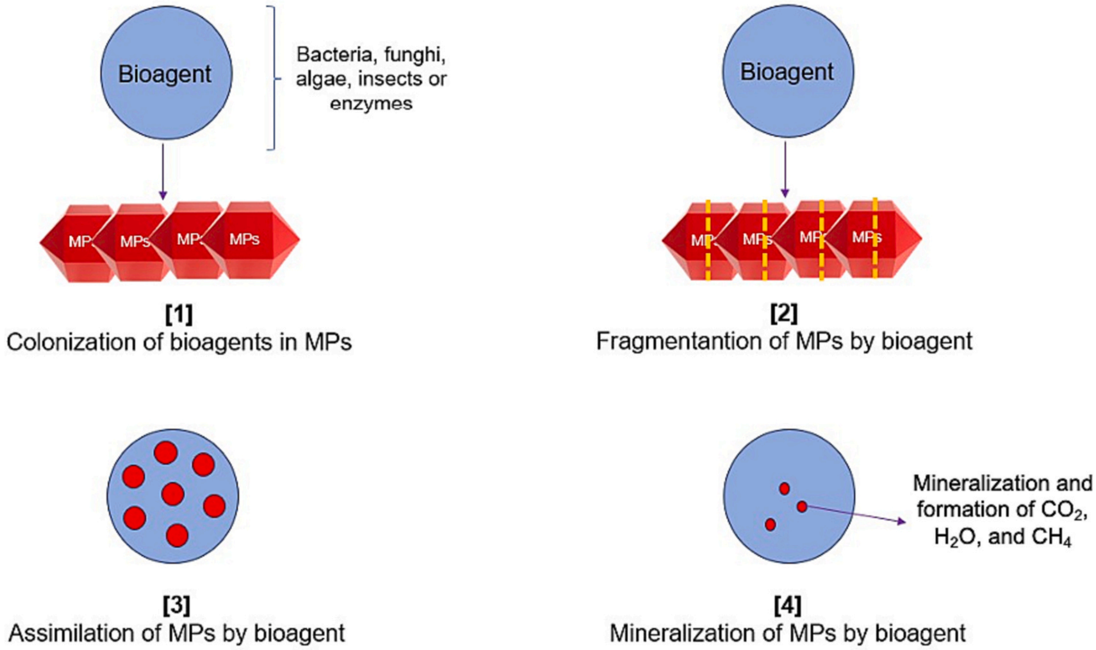


Fig. 8. Biological processes involved in the remediation of microplastic (MPs) pollution using bacteria, fungi, algae, insects, and enzymes (bioagents).

the remediation of microplastic pollution using bacteria, fungi, algae, insects, and enzymes.

Table 5 presents a selection of recent reports (2019 – date) regarding the use of bacteria, fungi, algae, insects, and enzymes for microplastic pollution remediation. Selection was performed to illustrate the wide variety of organisms used to biologically remove, degrade, or mineralise microplastics achieving the highest removal efficiency.

As shown in Table 5, bacteria and fungi are able to degrade either "pure" microplastics - i.e., commercially obtained - or real microplastics derived from post-consumer products or extracted from sludge or water samples. Although the advantages of microbial degradation by bacteria and fungi are the use of microplastics with large sizes (up to 5 mm) and some grade of artificial or environmental aging, the main disadvantage is the low remediation efficiencies achieved compared with those obtained by physical and chemical technologies. Table 5 also shows that adsorption and heterogeneous aggregation of microplastics by algae seems promising, but the reported qualitative evaluations of the efficiency of these processes make it difficult to make comparisons and propose improvements. Using insects for microplastic biodegradation can achieve high degradation efficiency, as presented in Table 5, but this should be done carefully because of the spread of insects. For instance, *Galleria mellonella* and *Plodia interpunctella* (both waxworms) can degrade PE and PS macroplastic films (Nguyen et al., 2023). However, as stated by Nguyen et al., some scientists have warned about the use of waxworms to remove plastic waste pollution because these worms naturally destroy hives. Thus, inadequate control of the treatment area during rearing may cause damage to the neighbouring ecosystem owing to the spread of insects (Nguyen et al., 2023). Finally, Table 5 shows that microplastic degradation can be carried out directly by enzymes secreted by microorganisms (Cao et al., 2023; A. Zhang et al., 2023) or combined with other inorganic nanomaterials, such as adhesive polydopamine magnetic microrobots (PDA)@Fe_3O_4 (H. Zhou et al., 2021).

7.4. Environmental education strategies and awareness campaigns

As presented in the previous sections, scientists worldwide are developing innovative ways to mitigate microplastic pollution through physical, chemical, and biological approaches. Although it is expected that the industry will develop alternative products to replace plastics and governments are already implementing measures towards microplastic bans (see Section 10), individuals should also adopt sustainable habits to limit microplastic pollution.

To achieve this goal, Grelaud and Ziveri conducted awareness campaigns (pilot actions) to reduce the amount of waste (including plastics and microplastics) entering the environment through beaches (Grelaud and Ziveri, 2020). The beach sites of Sicily, Malta, Crete, Rhodes, Cyprus, and Mallorca were selected. The sites where tourists represented most of the visitors were classified as impact sites, whereas the sites where locals represented most of the visitors were identified as control sites. The awareness campaigns were implemented during the summer of 2019 directly on sites or through social media or radio, installation of new trash bins for mixed or recyclable waste, or installation of new signs on existing bins. The results showed that awareness campaigns could be an efficient tool for reducing the amount of litter resulting from the recreational use of Mediterranean island beaches. Indeed, after the implementation of the pilot actions, the authors observed an average decrease of 52.5 % ± 20.8 % in the accumulation rate of the waste items that were most likely left on the beaches by visitors.

The awareness campaigns conducted by Grelaud and Ziveri highlighted the need for the public to be informed about the environmental impact of waste. In particular, the topic of microplastic waste and its impacts have only been included in awareness-raising campaigns such as iSea's "zeroplastic", or National Geographic's Planet or Plastic. However, microplastics are not included in any part of formal education worldwide. This is of concern because it has been reported that there is a lack of public knowledge concerning the sources and use of microplastics, highlighting the necessity for individuals to be well informed about environmental issues in order to acquire pro-environmental attitudes and behaviours. Charitou et al. (2021) investigated the knowledge and attitudes of the Greek public towards marine plastic pollution and the EU Single-Use Plastics Directive by interpreting the results of a questionnaire ($n = 374$) (Charitou et al., 2021). Their findings suggested that although the majority of the participants were informed about the impact and activities that lead to marine plastic pollution, there is a significant lack of knowledge about microplastic topics. Therefore, the authors suggest that the topic of microplastics should be integrated into the context of formal education.

Similar suggestions were made by other research groups. In a study

Table 5
Biological processes for microplastic pollution remediation.

Biological processes	Organism(s)/degrading enzyme	Microplastic/nanoplastic characteristics			Nature of sample	Removal efficiency (%)	Reference
		Polymer	Size/ concentration	Shape			
Bacteria							
Microbial degradation	Mesophilic mixed bacterial culture isolates obtained from a municipal landfill sediment (Incheon, Korea), particularly, *Bacillus* sp. and *Paenibacillus* sp./Enzyme not specified	PE	40–600 μm/1 % *w/v*	Irregular spheres	Commercially available plastics	14.7 % after 60 days	(Park and Kim, 2019)
Microbial degradation	Antarctic soil bacteria *Pseudomonas* sp. ADL15 and *Rhodococcus* sp. ADL36/ Enzyme not specified	PP	1 mm/0.1 g PP	Fragments	Commercially available plastics	The weight loss percentage of the PP microplastics by ADL15 and ADL36 after 40 days was 17.3 % and 7.3 %, respectively.	(Habib et al., 2020)
Microbial degradation	Hyperthermophilic bacteria in hyperthermophilic composting (*h*TC), particularly, *Thermus*, *Bacillus*, and *Geobacillus*/ Enzyme *not specified*	Full-scale test: PP, PE, PES, PS, PET Lab-scale test: PS	Full-scale test: ≤2.5 mm/7.4 ± 1.7 × 10^4 particles/kg dry sludge Lab-scale test: 100 mg PS/60 mL	Full-scale test: sludge-based microplastics. Lab-scale test: not-specified	Full-scale test: Fibre, foams, film, fragments. Lab-scale test: not-specified	Full-scale test (200 t): 43.7 % after 45 days of *h*TC. Lab-scale test: 7.3 % at 70 °C in 56 days	(Z. Chen et al., 2020)
Microbial degradation	*Bacillus paramycoides* and *Bacillus cereus* collected from Vaigai River, Madurai, India/Enzyme not specified	PP	–	–	–	*B. paramycoides*: 79.0 % in 21 days *B. cereus* + *B. paramycoides*: 78.6 % in 21 days	(Nanthini Devi et al., 2021)
Microbial degradation	*B. cereus*, *A. faecalis*, *B. sonorensis*, *S. epidermidis*, *B. vietnamensis*, *R. ruber*, *B. flexus*, *S. globispora*, *B. gottheilii* isolated from plastic/microplastic-inundated mangrove soil/ Enzyme not specified	PET and PS	2–5 mm, 0.5 g	Fragments	Artificially UV aged (2 days) secondary microplastics from commercial plastic products	PET: 18.0 % in 90 days PS: 15.0 % in 90 days	(Auta et al., 2022)
Microbial degradation	*Bacillus cereus* CH6 from lake sediments/Esterase	PS	0.5 g/L	Irregular spheres	Artificially UV (254 nm)-aged PS (96 h treatment)	10.7 % in 50 days. Average degradation rate of 0.967 mg/d.	(J. Yuan et al., 2022)
Microbial degradation	54 bacterial isolates from municipal landfill soil (Multan, Pakistan), including *Alcaligenes faecalis* (MK517568) and *Bacillus cereus* (MK517567)/AlkB family of enzymes, manganese peroxidase and laccase enzymes.	LLDPE, HDPE, PES	Not specified	Beads (LLDPE and HDPE) and fibres (PES)	Commercially available plastics	*Alcaligenes faecalis*: 3.5 % LLDPE 5.8 % HDPE and 17.3 % PES in 40 days. *Bacillus cereus*: 29.0 % PES in 40 days.	(Tareen et al., 2022)
Microbial degradation	*Enterobacter hormaechei* LG3 (CP118279.1), an anaerobic bacterial strain isolated from the gut of *Tenebrio molitor* larvae (mealworms)/Thiol peroxidase (*tpx*), alkyl hydroperoxide reductase C (*ahpC*) and bacterioferritin comigratory protein (*bcp*) degradative enzymes	PS	1 μm/0.075 % *w/v*	Foams, films and spheres	Commercially available plastics	PS film on FMM agar medium: ~3.0 % in 20–30 days.	(Kang et al., 2023)
Fungi							
Microbial degradation	*Aspergillus flavus* PEDX3 isolated from the guts of wax moth *Galleria mellonella*/ Laccase-like multicopper oxidases (LMCOs)	HDPE	≤200 μm/Not specified	Fragments	Commercially available plastics	3.9 % in 28 days	(J. Zhang et al., 2020)
Microbial degradation	*Aspergillus niger and Aspergillus fumigatus* from Ohiakwu River (Nigeria)/ Enzyme not specified	PP	≤11 μm/not specified	Not specified	Extracted from a water sample	PP 71.1 % (*A. niger*), 53.1 % and (*A. fumigatus*)	(Williams and Osahon, 2021)
Microbial degradation	*Fusarium oxysporum*, *Fusarium falciforme* and *Purpureocillum lilacinum* solated from an abandoned	LDPE	≤500 μm/5–10 g/L	Not specified	Commercially available PE granules	Qualitatively assessed after 30 days by FTIR (oxidation phenomena) and SEM	(Spina et al., 2021)

(continued on next page)

Table 5 (*continued*)

Biological processes	Organism(s)/degrading enzyme	Microplastic/nanoplastic characteristics			Nature of sample	Removal efficiency (%)	Reference
		Polymer	Size/ concentration	Shape			
	dumpsite in Tavernelle (Italy)/Enzyme not specified				(pulverized in liquid nitrogen)	(changes in the LDPE morphology)	
Microbial degradation	*P. simplicissimum* and isolated from wastes of a Brazilian babassu palm (*Attalea speciosa*) oil industry/lipase	PET	5 mm/8.33 g/L	Fragments	Post-consumer PET bottles cutted in squared fragments	3.1 % in 28 days	(Moyses et al., 2021)
Algae							
Heterogenous aggregation	*Microcystis panniformis and Scenedesmus* sp. *freshwater microalgae and marine Tetraselmis* sp. *and Gloeocapsa* sp. *microalgae*	PMMA and PS	≤250 μm/25 and 250 mg/L	Fragments	Fragmented by milling	Qualitatively assessed after 21 days by fluorescent microscopy and SEM. *Gloeocapsa* sp. presented excellent microplastics aggregation capabilities	(Cunha et al., 2019)
Heterogeneous aggregation/ bioflocculation	Freshwater *Cyanothece* sp. microalgae	PS	0.1 μm and 10 μm/1 and 10 mg/L	Spheres	Commercially available plastics	Qualitatively assessed after 14 days by fluorescent microscopy. Cyanothece sp. exhibits very favourable characteristics for hetero-aggregation and flocculation.	(Cunha et al., 2020)
Heterogeneous aggregation	*Scenedesmus abundans*	PS, PLA and poly(methyl methacrylate) (PMMA)	2 μm/90,000 microplastics/ mL	Irregular spheres	Commercially available plastics	PS 84.0 %, PLA 87.0 % and PMMA 98.0 %; in 6 days	(Cheng and Wang, 2022)
Adsorption	*Ulva prolifera* macroalgae from yellow Sea (China)	PET, PE, PP, PS, PVC, Nylon6	2–5 mm/	Fragments, pellets, foam, fibres	Recovered from sea water samples	Estimations of approximately 35.6 tons microplastics/year removed from the Yellow Sea	(Gao et al., 2020)
Adsorption	Fresh and aged *Cladophora green algae from Great Lakes (USA)*	PES (pristine and oxidized) and acrylic		Fibres		Qualitatively assessed after 14 days by microscopic analyses. *Cladophora* algae interacted with microplastics	(Peller et al., 2021)
Macroinvertebrates							
Biodegradation	*Tenebrio molitor* (Coleoptera: Tenebrionidae) larvae/ Enzyme not specified	PVC	70–150 μm/ 1.21–5.0 g PVC		Commercially available powders	Gel permeation chromatography (GPC) analysis indicated a decrease in the M_w, M_n and M_z by 33.4 %, 32.8 %, and 36.4 %, respectively, demonstrating broad depolymerization in 16 days	(Peng et al., 2020)
Biodegradation	*Tenebrio molitor* larvae (mealworms)/Enzyme not specified	PVC, PS and PLA	<300 μm	Not specified	Commercially available powders	85.2 ± 1.2 % PLA, 67.7 ± 1.8 % PS, and 58.2 ± 1.5 % PVC in 42 days by the larvae fed with plastics only. 76.5 ± 0.4 % PLA, 62.5 ± 0.1 % PS, and 49.6 ± 1.0 % PVC in 42 days by the larvae fed with plastics plus bran.	(Peng et al., 2023)
Enzymes							
Enzymatic degradation	Lipase immobilized onto adhesive polydopamine magnetic microrobots (PDA) @Fe_3O_4	PCL	Not specified	Fragments	Not specified	Qualitatively assessed after 24 h by microscopic analyses. PCL morphologically changed after exposere to lipase immobilized onto PDA@Fe_3O_4	(H. Zhou et al., 2021)
Enzymatic degradation	Cold-active degrading laccase PsLAC InaKN-mediated *Escherichia coli* -surface display system	LDPE	1000 μm/0.25 g/ L	Not specified	Commercially available plastic particles	66.0 % in 144 h	(A. Zhang et al., 2023)
Enzymatic degradation	DuraPETase secreted from *Comamonas testosteroni* CNB-1	PET	425 μm/100 mg/ 100 mL	Fragments	Commercially available plastic	9.0 % in 9 days	(Cao et al., 2023)

FMM = fungal minimum medium and PCL = polycaprolactone.

that evaluated the recognition and behaviours towards microplastics and zero waste among 196 college students at a university in G Metropolitan City (Republic of Korea), Choi et al. found that zero-waste behaviour was related to the recognition of the health impact of microplastics and attitudes towards separating disposables (Choi et al., 2022). In agreement with the suggestions made by Charitou et al., the authors concluded that education programs are needed to improve awareness of microplastic health effects and attitudes towards separating disposables. Through a preliminary survey that assessed awareness, attitudes, behaviours, and opinions pertaining to plastic and microplastic pollution among 220 students in India, Dowarah et al. also found that microplastic pollution has not been sufficiently registered in the minds of people as an area of enhanced concern (Dowarah et al., 2022). The authors suggested that issues about plastic pollution should be included as part of both the social sciences and physical sciences curricula in schools. In their study that assessed the willingness and motivation of 276 individuals within the American Farm School and collaborating academic institutions to change daily habits to minimise plastic and microplastic pollution, Willis and Fytianos found that it is crucial to combine any new microplastic mitigation measures or policies with proper education about why these measures are being made, so as to raise awareness and receptivity to those who are not familiar with microplastic pollution (Willis and Fytianos, 2022). There is likely an overlap between having heard little or nothing about microplastics and being unwilling to take action to mitigate microplastic pollution. Similarly, Garcia-Vazquez et al. (2023) suggested that consumers in Spain could reduce microplastic pollution by adopting *R-behaviours*, such as *reducing* the consumption of plastic, *refusing* products with microplastics, *replacing* them with green products, and *recycling* (Garcia-Vazquez et al., 2023). The authors measured the individual's willingness ($n = 671$) to adopt R-behaviours and the perceived level of environmental responsibility through online images and short messages to promote microplastic conscious behaviour. According to their results, R-behaviours could be achieved through education campaigns that prioritise the sense of environmental responsibility and evoke environmental health instead of threats to wildlife.

As evidenced by previous studies, the accountability of individuals requires reliable and easy-to-understand information about sources, contamination, fate, and effects of microplastics in the environment. Microplastic education is acclaimed as a potential tool to achieve this goal; however, student-centred research to raise awareness of this theme is limited in the literature. For example, in an attempt to integrate microplastics into formal education, Raab and Bogner developed a consciousness-raising module for primary education named "Plastic Detectives – The Search for Plastic" (Raab and Bogner, 2020). Such modules are focused on student-centred activities, different tasks regarding sources in everyday life, sinks in aquatic ecosystems, effects on marine animals, and prevention strategies for microplastics. The goal of the module is to offer an appropriate overview that enables students to ponder their purchase decisions and potentially limit microplastic pollution in everyday life.

Following a similar principle, in 2021, Oliani and Cedillo-González carried out an awareness campaign focused on marine microplastic pollution through a seven-chapter column in an Italian children newspaper from 6 to 11 years of age (Oliani and Cedillo-González, 2021). The column, through its main character named "Pelucco" (a PES microplastic fibre), was specifically designed to teach children how microplastic fibres released from the washing cycles of synthetic textiles travel through pipes and rivers and reach the ocean. The same story was further developed on the book "Pelucco: A Microplastic's Journey" (Cedillo-González and Oliani, 2023; Oliani and Cedillo-González, 2022a), which explains to children the mechanisms of introduction of microplastics into different aquatic environments, highlighting how these pollutants travel through pipes, sewer networks, WWTPs and rivers, reaching not only the oceans but also land, air and biota. The story concludes with tips, practical advice, and daily actions to decrease microplastics' input into the oceans. The story was tested in two groups of Italian children aged 3–6 years ($n = 115$) and children aged 6–11 years ($n = 42$). The questionnaires revealed that before hearing the story, almost 94 % of the children were unaware of microplastic pollution. After hearing Pelucco's story, the authors found that 100 % of children were able to correctly describe the generation of microplastics from several plastic wastes and even suggested strategies to stop microplastic pollution in the ocean (Oliani and Cedillo-González, 2022b, 2022c).

Finally, Bettencourt et al. reported an integrative, student-centred, and over weeks educational intervention to raise awareness of marine litter for 1st cycle to high school students (7 to 18 years old) that compared pre- and post-intervention results (Bettencourt et al., 2023). Different learning skills were fostered through theoretical, laboratory, and hands-on activities, and students participated in a beach clean-up to summarise the classroom's learning in loco. Through pre- and post-questionnaires, the authors found that students' knowledge, perceptions, and behavioural intentions changed, and that their intervention positively impacted schoolchildren's literacy. The beach clean-up action recapped the classroom's learning and gave students a better idea of the amount and type of litter on beaches and the possible sources and pathways of the same debris.

Microplastic research frequently incorporates citizen science to assist data collection. For instance, Ershova et al. (2021) reported that 200 volunteers including local residents, schoolchildren and students from polar communities from the Arkhangelsk region participated in a field expedition in the Russian Arctic held by a group of scientists and members of the "Clean North-Clean Country" and "Ecopatrol" NGOs (Ershova et al., 2021). This study aimed to monitor microplastic pollution and train volunteers in microplastic sampling and litter separation for different plastic categories. The fieldwork diary broadcasted online in social networks allowed viewers to "live through" the expedition, to experience the fieldwork, and to learn skills of living in nature while minimising the personal footprint. Combining conventional science with citizen science has been demonstrated not only to be a good approach to teaching microplastic pollution to individuals, but, according to Collier et al., citizen science-inspired activities within microplastic research projects can also provide opportunities for greater societal inclusion in science by involving volunteers and increasing science capital in individuals with fewer science experiences (Collier et al., 2023). To achieve this goal, the authors designed three activities for high school students to extract, quantify, and observe microplastics from personal care products, water, and sediment samples. Such activities were aimed at increasing students' environmental stewardship of microplastic pollution.

8. Valorisation of microplastics

Valorisation involves developing technologies and processes to recover and recycle microplastics from diverse sources, including wastewater treatment plants, plastic waste, textile microfibers and marine litter. By transforming microplastics into valuable resources, such as new plastic products or alternative materials, valorization strategies significantly reduce the demand for virgin plastics and mitigate further pollution.

A notable application of valorization of fibre microplastics is their application as secondary raw materials in the building sector or as raw materials for producing oil, gas, and char through pyrolysis. For instance, Malchiodi et al. investigated the direct reuse of microfibres in fibre-reinforced cementitious composites (FRCs) (Malchiodi et al., 2022), finding that including textile waste microfibres improved Portland cement's thermal-insulating and mechanical properties. Belzagui et al. proposed the immobilisation of fibre microplastics in a polymeric matrix, turning them into composites (Belzagui et al., 2022). Abdelkarim (2023) proposed the valorisation of microplastics within the building sector through their use as inert materials in cementitious matrices and found that this function depends on both the granulometric distribution of plastics and their surface characteristics, which may or may not promote adhesion between the plastics and cement (Abdelkarim, 2023).

Research has also been conducted on the use of fibre microplastics as a renewable energy source. Yousef et al. used lint-microfibres generated during clothes drying, composed mainly of cotton, polyester, and lignin, to generate three main energy products (oil, gas, and char) using pyrolysis treatment in a pilot plant (Yousef et al., 2021). Their results showed that lint-microfibres could thermally decompose into energy products with a 65 %–78.4 % conversion rate. Toluene was the primary compound in the biogas and bio-oil obtained at 500 °C, with 93 and 33 % concentrations, respectively.

Microbiological and photochemical processes have also been used to valorise microplastics. For instance, LDPE microplastics have been converted into biodegradable polyhydroxyalkanoate polymers using *C. necator* H16, *P. putida* LS46, *A. pittii* IRN19, and *C. necator* bacterial strains (Montazer et al., 2019). *C. vulgaris* can be used as a carbon source for degradation products derived from the catalytic oxidation and hydrothermal hydrolysis of cosmetic-derived PE microplastics over magnetic spring-like carbon nanotubes (Kang et al., 2019). Polyester fibre- and soybean oil-contaminated PET microplastics can be converted into hydrogen (H_2) fuel and a variety of organic compounds by photoreforming over a carbon nitride/nickel phosphide catalyst (Uekert et al., 2019) or by photocatalysis over M-2/$Zn_{0.6}Cd_{0.4}S$ (Cao et al., 2022).

Despite these promising findings, the valorization of microplastics is still in its early stages (Cholewinski et al., 2022), but these innovative approaches show the potential of valorization in turning microplastics into valuable resources while promoting sustainability and circularity in the plastic industry.

9. History of plastics and evolution of the research in microplastic pollution

To understand the evolution of research on microplastic pollution, it is necessary to begin with the history of what has already been addressed on the subject, highlighting the main milestones. In this section, we present a brief history of the first discovery of plastics that will allow us to understand the reasons for the increase in their production worldwide, leading to microplastic pollution.

The invention of plastic is presented in a divergent way in the literature, as there are records of the polymerisation of styrene in 1839, but it was not commercially developed until 1930 and, therefore, was not considered the first polymeric synthesis (Rasmussen, 2018). Most of the scientific community adopted bakelite as the first plastic developed in history by Belgian-American chemist Leo Baekeland in 1907. In addition to creating bakelite, Baekeland introduced the first definition of plastic, which refers to a material capable of undergoing deformation without breaking (Mossman, 2017). However, this article treats polystyrene as the first synthetic polymer (plastic) in history. Eduard Simon, a German apothecary, distilled an oily substance from storax (resin from a tree) and named it “styrol”. After several months, he observed that the oil turned into a colourless gelatinous substance that was no longer solubilised in alcohol or ether and was as rigid as rubber. Simon believed that this transformation occurred because of combined environmental factors and named the new substance “styrol oxide”, now known as polystyrene (PS) (Rasmussen, 2018).

From the discovery of plastic until the 1950s, plastic production was approximately 4–8 million tons (Geyer, 2020). From then on, this number increased exponentially, inaugurating the Anthropocene period (Geyer, 2020). Recently, scientists related this period to the so-called “Plastic Age” (Chang et al., 2022; Geyer, 2020; Shekhar et al., 2022). Plastics are highly versatile owing to their properties such as low density, low production cost, low electrical conductivity, and high corrosion resistance. These properties make plastic a highly attractive material for various applications (Frias and Nash, 2019). However, owing to their versatility, the production and consumption of plastics has not kept up with the possibility of environmentally appropriate disposal and treatment, causing numerous impacts on the environment and health of living beings (Chamas et al., 2020; Ge et al., 2023; H. Liu et al., 2023; Ray et al., 2022).

Given the importance of the topic, on 5 June 2023 World Environment Day was celebrated for the fiftieth time with the theme “Pollution caused by plastics”. According to the UNEP, approximately 430 million tons of plastic are produced annually, two-thirds of single-use plastics, and soon become waste (United Nations Environment Programme (UNEP), 2023). Of these, only 46 % are adequately disposed in landfills, but decomposition takes a long time, from 10 to 1000 years, depending on the chemical composition (Chamas et al., 2020). During this period, many plastic waste fragments or decompose into microplastics (Arthur et al., 2009). Therefore, microplastics are present in all biosphere compartments (air, water, and soil) and interact with other hazardous substances, further increasing their danger to the environment and living beings (Alimi et al., 2018; Chamas et al., 2020; Ge et al., 2023; Hurley and Nizzetto, 2018; Koelmans et al., 2019; Vethaak and Legler, 2021).

9.1. Main focus and evolution of research in the field of microplastic pollution

To contextualise the first research related to microplastics and its current status, including gaps and future perspectives, it is important to present a short bibliometric study. The bibliometric review highlights that sufficient knowledge regarding microplastic pollution already exists and that the conclusions of all those works should be taken into account when developing holistic remediation strategies. Additionally, we consider important to contextualise ERCs on other microplastic-related minimally explored topics, as this will allow them to perform research with greater impact and innovation within the field. Furthermore, no other bibliometric study on this topic has brought together such broad research in terms of the number of journals included in this work.

In December 2023, a survey was carried out in 395 journal databases, including Scopus, Web of Science, PubMed, ERIC, IEEE Xplore, ScienceDirect, Directory of Open Access Journals (DOAJ), and SpringerLink, to determine the number of peer-reviewed articles based on the most used keywords in articles in the area together with the term “microplastics”. The results are shown in Fig. 9. From Fig. 9, it can be observed that the number of articles related to microplastics in the marine environment (ocean and sea) was much greater than those related to soil (soil and landfill) and air (air and atmosphere). In addition, research related to health (“human”, “health”, “ingestion”, and “inhalation”) still walks at a slower pace, as well as government policies (“law” and “policy”). It is also verified that there are many publications related to the terms “contamination” and “pollution”, but few that address the association with organic pollutants, climate change and removal from the environment (“organic pollutants”, “climate change”, and “removal”). This finding highlights the need for further research on these topics.

Fig. 10 presents the number of peer-reviewed articles with the most frequent terms in the articles raised in Fig. 9, grouped by environment (aquatic, 10a; terrestrial, 10b; and atmospheric, 10c). For this survey, the same methodology as in Fig. 9 was used. As shown in Fig. 10a, the number of articles in the marine environment is much greater than that in freshwater environments, probably because of the global distribution of these types of water. Approximately 3 % of the world's water is fresh, of which 69 % is difficult to access (groundwater and glaciers)

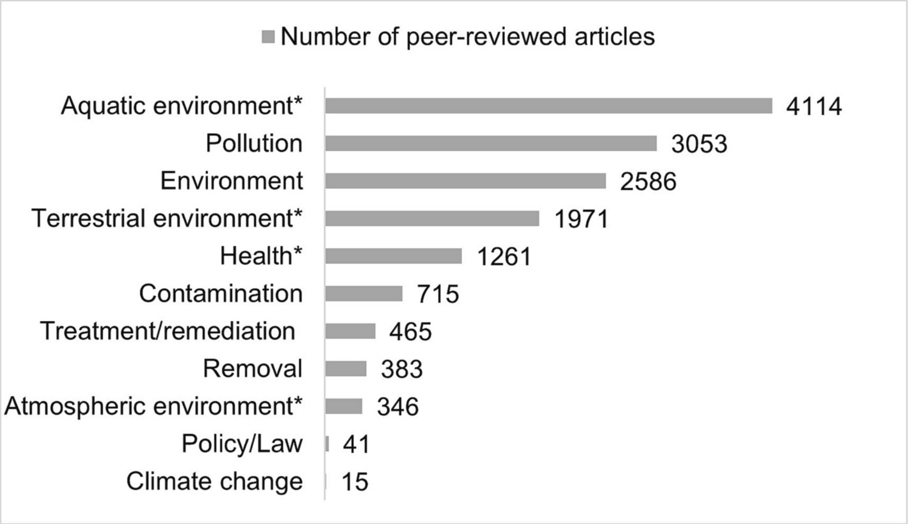


Fig. 9. A survey of peer-reviewed articles based on a combination of terms associated with microplastics was conducted on 20 December 2023 in 395 journal databases. The terms marked with (*) represent the sum of the other terms.

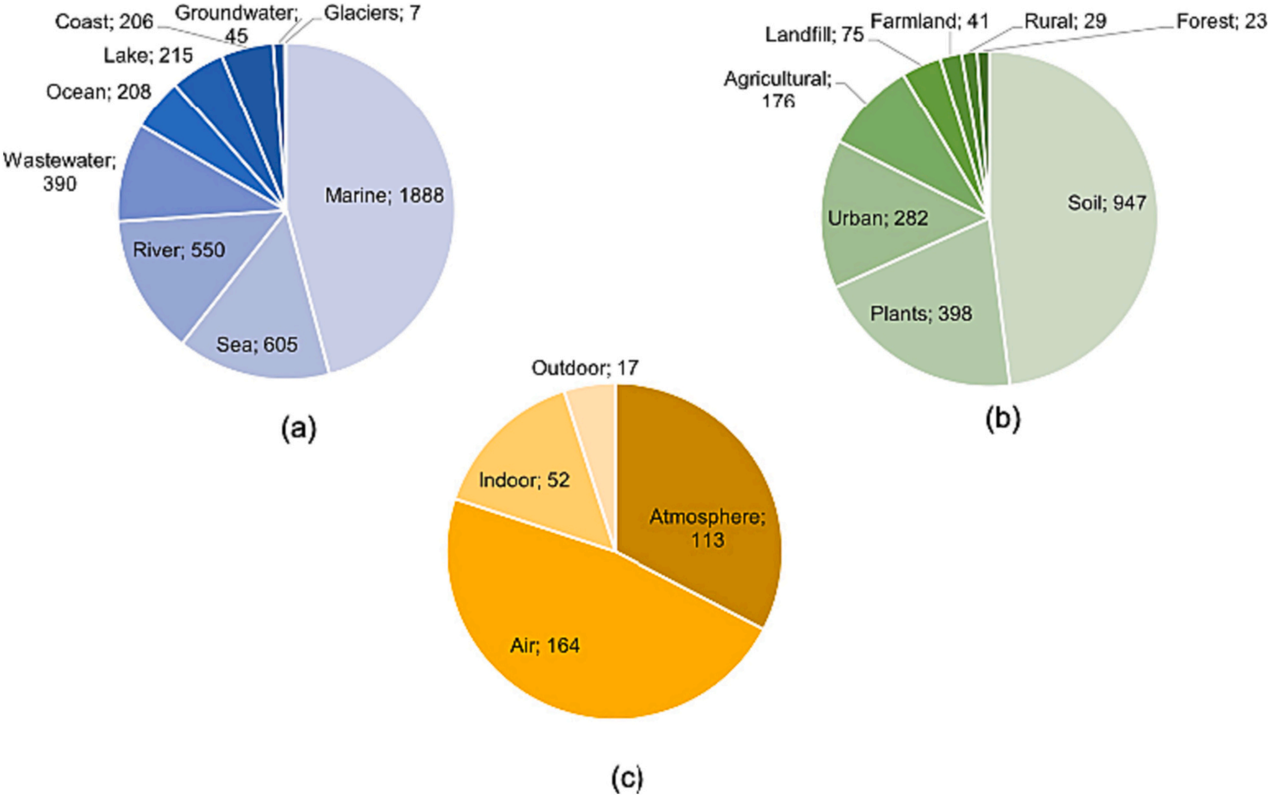


Fig. 10. The number of peer-reviewed articles that link the term "microplastic" with the keywords in the chart referring to (a) aquatic environment, (b) terrestrial environment, and (c) atmospheric environment by December 2023.

(Ministério da Integração e do Desenvolvimento Regional, 2023). For microplastics in the soil, it should be noted that the oldest article was published in 2012. That is, we have little more than a decade of information on these environments and in a much smaller number than that recorded in marine environments (4114 versus 2586), as shown in Figs. 9 and 10b. Regarding the atmospheric environment, the first publications were published eight years ago, and since then, researchers have sought to standardise sampling. Therefore, the number of articles was even smaller than that of the first two (Figs. 9 and 10c).

The first reports of the presence of microplastics in the environment were studied in marine aquatic environments in the 1970s (Carpenter et al., 1972; Carpenter and Smith, 1972). In 1972, Carpenter et al. documented, for the first time, the presence of plastic fragments from 0.25 to 0.50 cm in diameter and approximately 290 g.km^{-2} in the Sargasso Sea (located in the middle of the North Atlantic Ocean) (Carpenter and Smith, 1972). In a second article published by Carpenter et al., a few months later, the authors detected the presence of polystyrene spheres approximately 5 mm in diameter on the south coast of England. They verified that in addition to the bacterial biofilm, these particles absorbed polychlorinated biphenyls (PCBs) at a concentration of 5 ppm

(Carpenter et al., 1972). The authors identified eight out of 14 species of fish that consumed these identical particles and, in the case of smaller species, there was intestinal obstruction. In recent years, research in marine aquatic environments, such as oceans and seas, has continued to focus on detecting the presence of microplastics (Enders et al., 2015; Isobe et al., 2017; Kanhai et al., 2020; Qi et al., 2022), in addition to analysing their association with POPs and their impact on the environment and health of marine animals. In addition, the issue of dispersion of microplastics found in marine environments into the atmosphere has been raised (Allen et al., 2020). Investigations in freshwater aquatic environments began in 2013 and have been reported in several locations, such as groundwater (Esfandiari et al., 2022; Kim and Lee, 2020; Panno et al., 2019), glaciers (Ambrosini et al., 2019; Cabrera et al., 2022; Crosta et al., 2022), lakes (Imhof et al., 2013; Neelavannan et al., 2022), and rivers (Kiss et al., 2021; Mani et al., 2015; Sanchez et al., 2014).

Soil is considered one of the largest microplastic reserves in the world (Barnes et al., 2009; He et al., 2019; Hurley and Nizzetto, 2018; United Nations Environment Programme (UNEP), 2018), in addition, to being a significant source of transport to the acquatic environments via atmospheric dispersion (Liu et al., 2019b; Ta and Babel, 2023; Yang et al., 2023). Among other reasons, this phenomenon occurs (especially in agricultural areas) owing to the use of cover films to improve soil moisture and heat retention, organic fertiliser, and artificial irrigation (Jia et al., 2022).

Recent studies have shown that microplastics can alter the physicochemical properties of the soil and interact with microorganisms (Khan et al., 2023), in addition to affecting plant development (He et al., 2021) and the health of living beings (Vethaak and Legler, 2021; Yee et al., 2021) owing to bioaccumulation in food chains. Research related to microplastics in the terrestrial environment is focused on the occurrence, sorption, transport, and possible impacts of other pollutants on these ecosystems (Khan et al., 2023; Xu et al., 2020; Yang et al., 2023). Among the key terms shown in Fig. 10b, there is a greater number of articles published with the terms “soil” and “plants” when compared to the others, since in many cases research uses several sampling regions that may be inserted in different environments (urban or rural/agricultural). It should be noted that there are only 38 peer-reviewed articles that correlate different land uses with the presence of microplastics, most of which, including the most recent ones, are concentrated in the Asian continent (Feng et al., 2023; Z. Li et al., 2023; Qiu et al., 2023; Ta and Babel, 2023; Xue et al., 2023; Ye and Pei, 2023; M. Zhang et al., 2023). Furthermore, Khan et al. indicated other gaps that can be filled in future studies, among which are highlighted: (I) correlating the mechanical properties and morphology of microplastics with different changes in soil composition quality; (II) studying the mechanisms of transport and accumulation of microplastics in plants; (III) investigating the accumulation of microplastics in plant roots and the inhibition of their growth; (IV) developing technologies for quantification of microplastics and microplastics-derived carbon in soils to assess their contribution and fundamental role in element cycling; and (V) proposing new simplified standardised sampling techniques (Khan et al., 2023).

The first publications aimed to identify microplastics in the atmospheric environment were reported by the research groups of Dris et al. (2017, 2016, 2015); Wesch et al. (2017); Abbasi et al. (2019) and K. Liu et al. (2019).

Similar to the first publications, most of the published works continue to focus on the detection of microplastics in the environment, in addition to research into possible sources, transport, and impacts associated with health. Fig. 10.c presents the main key terms that appear in peer-reviewed articles on atmospheric microplastics. In most of these articles, either the term “air” or “atmosphere” appears, or both. Regarding the terms “indoor” and “outdoor”, there is a higher prevalence of the former; there are studies that use them together, that is, to compare the concentration of microplastics in indoor and outdoor environments in the same region (Amato-Lourenço et al., 2022; Liao et al., 2021). Some studies stand out that do not have the same focus, such as that of Ortega and Cortés-Arriagada (2023), who investigated the sorption of atmospheric pollutants from microplastics (Ortega and Cortés-Arriagada, 2023), and Wang et al., 2023 (Wang et al., 2023), who studied the change in the physicochemical properties of microplastics (PE, PS, and PVC) from solar photoirradiation and contact with air humidity (in different percentages). There is a demand for studies that (I) identify the presence of microplastics in the atmosphere and correlate them with greenhouse gas emissions, (II) evaluate the influence of microplastics (associated or not with other pollutants) on nutrient cycling, and (III) propose new simplified standardised sampling techniques.

Over the years, in addition to continuing this type of investigation, researchers have proposed simplified sampling methods (Prata et al., 2020), the association of these particles with other pollutants, and the harm to human health (Akhbarizadeh et al., 2021). A work worth mentioning is that of Liao and Chen, who presented four types of biodegradable plastics subjected to photodegradation. The authors indicated that biodegradable plastics have low degradability in soil and air (441 ± 326 and 2103 ± 131 item/g plastic, respectively). In addition, microplastics are highly formed in the soil (2103 ± 131 item/g original plastic) and air (441 ± 326 item/g original plastic) (Liao and Chen, 2021).

Fig. 11 shows the number of articles related to the biota and the health of living beings. Regarding the ingestion and interaction of these particles by living beings, the first record is from the work of Volkheimer, who compared the ingestion and digestion of PVC pellets and potato starch granules in various animals (rats, pigs, rabbits, chickens, and dogs) in 1975 (Volkheimer, 1975). The authors found the presence of microplastics in various fluids (urine, milk, cerebrospinal fluid, and others), including the bloodstream, which, after a specific time, is disseminated to all organs. However, the effects of ingestion of these microparticles on animal health have not been studied. This story is more recent in humans. In 2014, microplastics were identified in bivalves grown for human consumption (Van Cauwenberghe and Janssen, 2014). Researchers have already detected the presence of microplastics (>50 μm) in placentas (Braun et al., 2021; Ragusa et al., 2021; Zhu et al., 2023) and meconium (Braun et al., 2021) of newborns, in addition to the discussion of possible effects on human health (Vethaak and Legler, 2021).

In the Technical Memorandum of the National Oceanic and Atmospheric Administration of 2009 (Arthur et al., 2009), some gaps in studies carried out at that time were presented that, until today, have not been filled. One is the cataloguing of primary microplastics, including their physicochemical properties, to allow the measurement of environmental impacts. In addition to being pioneering and essential, a study such as this would serve as a basis for formulating laws and policies to protect the environment (or for improving laws and policies that already exists in some countries). Another gap is the understanding of the synergistic effect between POPs and microplastics in living beings. The Technical Memorandum also highlights the need to (a) explore different technologies that remove microplastics already present in different environments and (b) identify ways of processing plastics that do not release microplastics into the environment.

10. Microplastics and environmental governance

Because of the harmful effects of microplastics on ecosystems and human health, many countries and international organisations have taken action to create a regulatory response to microplastics in the environment, with the primary aim of reducing the generation and release of microplastics into the environment and mitigating their impact.

In this sense, two general approaches have been proposed to properly regulate microplastics. The first focuses on removing the sources of intentionally produced microplastics for consumer use and production

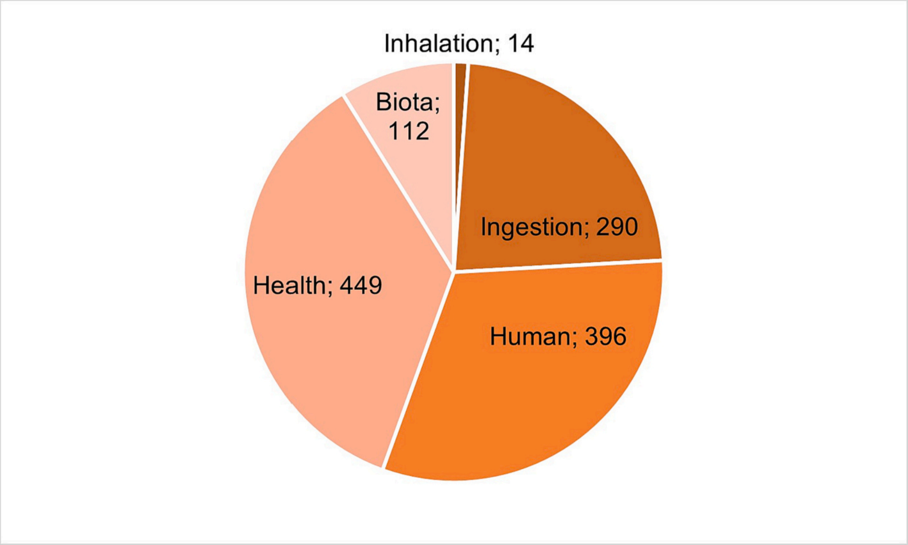


Fig. 11. The number of peer-reviewed articles that link the term "microplastic" with the keywords in the chart referring to biota and by December 2023.

chains. The second approach focuses on implementing monitoring programs and regulations to better understand the nature and extent of microplastic issues (Metzler and Simbeck, 2022).

In Europe, the regulation of microplastics started in 2013, when the Netherlands reported that microplastic litter represented a growing environmental problem, as observed in mussels from the Dutch province of Zeeland (EURACTIV, 2013; General Secretariat Council of the European Union, 2023). From there, a joint statement by Belgian, Dutch, Austrian and Swedish delegations urged the Council of the European Union to eliminate microplastics in cosmetic products (General Secretariat Council of the European Union, 2014). Initial efforts by the European Commission to reflect on potential responses to the public policy challenges posed by plastic waste derived in the publication of the GREEN PAPER On a European Strategy on Plastic Waste in the Environment (European Comission, 2013). Meanwhile, other member states have begun their initiatives to regulate microplastics. For example, in 2017, a decree was published in France banning the use of microbeads in exfoliating and cleaning cosmetic products (Journal officiel "Lois et Décrets," 2017). The same happened in 2018, when Sweden banned the sale of cosmetic products (KEMI Swedish Chemicals Agency, 2023). Later that year, the UK issued a sales ban on products containing any plastic particles, prohibiting retailers in England and Scotland from selling such products (UK department for Environment, Food, and Rural Affairs and The Rt Hon Michael Gove, 2018). In recent years, many countries, such as New Zealand (New Zeland Legislation, 2017), Portugal (Diário da República, 2021), and Argentina (Boletín Oficial de la República Argentina, 2020), have adopted this strategy, imposing restrictions on the use of microplastics in cosmetics and other products.

While all of these measures took place in 2017, the European Commission requested the European Chemical Agency (ECHA) to elaborate regulatory actions to address microplastic pollution. In this manner, in 2020, ECHA proposed extensive restrictions on microplastics in products placed on the European Union (EU) and European Economic Area (EEA) markets banning the addition of microplastics to many commercial products (ECHA Committe for Risk Assessment (RAC) and ECHA Committee for Socio-economic Analysis (SEAC), 2020). This restriction proposal was developed in the context of the EU Plastics Strategy (European Comission, 2018) and the Circular Economy Action Plan (European Comission, 2015) to reach 2030 sustainable development goals, global climate commitments, and the EU's industrial policy objectives. In September 2022, the European Commission published a draft proposal amending Annex XVII to Regulation (EC) No 1907/2006 to limit intentionally added microplastics in various products (European Comission, 2022). However, considering that the transitional period for the implementation of this regulation was too long, several beauty brands and associations (Rethink Plastic Alliance, 2023), at the same time that the Netherlands and Denmark, France, Germany, and Luxembourg (Zaken, 2023) have signed open letters to the European Commission (EC) calling for a faster and more complete ban by the European Chemical Agency. On 27 April 2023, the REACH Committee voted in favour of the Commission's proposal (European Comission, 2023).

Similar efforts have been made in the United States to regulate the impact of microplastic pollution. The Microbead-Free Waters Act of 2015 (United States of America 114th Congress, 2015) prohibits the sale or distribution of rinse-off cosmetics containing plastic microbeads. In January 2018, the Canadian government amended the Canadian Environmental Protection Act of 1999 to include Microbeads in Toiletries Regulations, which was published in the Canada Gazette, Part II: Vol. 151, No. 12–14 June 2017 (Government of Canada, 2017). However, a differentiating factor is that these countries are moving into implementing monitoring programs and regulations to understand the nature and extent of microplastic pollution. This approach started in 2018 when California passed Senate Bill 1422 (SB1422) (California Legislative Information, 2018), an extension of the 1974 Safe Drinking Water Act, a federal statute requiring the monitoring and public notification of drinking water contaminants, requiring the State Water Resources Control Board (SWRCB) to define microplastics in drinking water by 1 July 2020, and on or before 1 July 2021, to adopt a standard methodology to be used in the testing of drinking water for microplastics. On 7 September 2022 California's SWRCB approved the initial requirements for testing microplastics in drinking water, becoming the first government in the world to establish health-based guidelines for acceptable levels of microplastics in drinking water (California Legislative Information, 2018). However, there is no EPA-approved method to identify the many types of microplastics in drinking water and no standardised water treatment method for removing microplastics from the public water supply. Therefore, authorities have developed a two-step, four-year plan for monitoring and reporting microplastics systematically and harmonised. The first phase of the test is scheduled between the fall of 2023 and the fall of 2025 ("STATE WATER RESOURCES CONTROL BOARD RESOLUTION NO. 2022-0032," n.d., pp. 2022–0032). Nevertheless, these efforts have not yet covered the public's expectations about microplastics' ecological and human health risks, as the EPA has not yet developed regulations concerning the release of microplastics into the environment. This has resulted in >70 US lawmakers urging the

EPA to boost regulation of microplastic pollution ("quill-letter-l11195-epa-microplastic-actions-version-3-05-12-2023-09-36-am," n.d.).

As microplastic pollution problems become more extensive, implementing more laws to mitigate their presence in the environment has become a priority. For instance, the United Nations Environmental Assembly (UNEA) hosted a meeting with the Heads of State, Ministers of Environment, and representatives from 175 countries to discuss a historic resolution that seeks to end plastic pollution and forge an international legally binding agreement by 2024 (United Nations Environment Assembly of the United Nations Environment Programme, 2022). Nevertheless, many countries have begun developing policies to regulate the use and disposal of single-use plastics. For example, the European Union issued Directive (EU) 2019/904 on reducing the impact of certain products on the environment, commonly known as the Single-Use Plastic Directive (Directive (EU*) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment (Text with EEA relevance)*, 2019). This directive was later reinforced by laying down rules on harmonised marking specifications on single-use plastic products Commission Implementing Regulation (EU) 2020/2151 on 17 December 2020 (Commission Implementing Regulation (EU) *2020/2151 of 17 December 2020 laying down rules on harmonised marking specifications on single-use plastic products listed in Part D of the Annex to Directive (EU) 2019/904 of the European Parliament and of the Council on the reduction of the impact of certain plastic products on the environment (Text with EEA relevance)*, 2020). Other countries have begun to follow this strategy by banning certain single-use plastic items. For example, from 1 October 2023 businesses in England must no longer supply, sell, or offer particular single-use plastic items (Department for Environment, Food & Rural Affairs, 2018). Similarly, on 1 January 2021 a plastic ban took effect in China that prohibited restaurants nationwide from providing single-use plastic straws and stores in major cities from providing plastic shopping bags (Library of the Congress, n.d.). In this regard, China expects to effectively control plastic pollution by 2025, substantially reduce plastic waste in key cities' landfills, and establish a complete plastics management system (The State Council and The people's republic of china, 2020).

11. Recommendations for the holistic development of innovative microplastic pollution remediation technologies

The origin, composition, particle size, and shape of microplastics are important factors to consider when developing physical, chemical, biological (or even combined) remediation strategies for microplastic pollution. Therefore, ERCs interested in developing innovative and efficient microplastic remediation technologies should consider all these critical aspects that characterise microplastic pollution.

For instance, the success of the physical removal of microplastics from aquatic environments depends on both the characteristics of the materials and target pollutants. Instead, strategies involving chemical or biological transformations can produce two types of products: innocuous substances, such as CO_2, water, or biodegradable organic molecules, and toxic subproducts, such as nanoplastics or chemicals. The nature of the obtained products depends on both the transformation conditions (temperature, pH, oxygen or concentration, among others) and, more importantly, on the wide range of characteristics of the targeted microplastics (origin, composition, size, shape, degree of aging, biofouling, and adsorption of pollutants). The efficiency of innovative remediation technologies should be tested using microplastic models that adequately reflect the wide variety of physicochemical surface and bulk properties of microplastics present in the environment, instead of *pure* micron-sized polymers without antioxidants, flame retardants, plasticisers, pigments, UV absorbers, or other additives present in plastic formulations.

The physicochemical properties of microplastics present in the environment are not static, as they undergo dynamic transformations due to environmental aging, biofouling, partial digestion by some organisms, the adhesion of organic pollutants, and their transfer to one environmental compartment to another. Thus, the efficiency of any novel remediation technology should not be affected by such dynamic transformation. However, depending on the specific working principle of each remediation strategy, changes in the physicochemical properties of microplastics can affect their efficiency. An example of this concept was illustrated by Llorente-García et al. (2020), who investigated the efficiency of the photocatalytic degradation of PE microplastics and its relationship with their buoyancy (which in real environmental conditions may depend on their changes in density due to aging and biofouling) and shape. The authors found that for remediation strategies based on photocatalysis, floating film-shaped LDPE microplastics prevented the correct absorption of photons by the semiconductor, a condition that negatively affected ROS generation and microplastic degradation (Llorente-García et al., 2020).

The particle size of microplastics can also influence the choice of a remediation strategy or influence its efficiency. For example, a proposal for the recovery of microplastics for their valorization within the building sector implies their use as inert materials in cementitious matrices, but this function depends on both the granulometric distribution of plastics and their surface characteristics, which may or may not promote the adhesion between plastics and cement (Abdelkarim, 2023). The mechanical properties of plastics should also be considered when investigating mitigation proposals, because breakage can lead to the formation of nanoplastics. For instance, although WWTPs play a crucial role as the first line of defense to prevent microplastics from entering aquatic environments, it has been discovered that microplastics can break down into nanoplastics and change their surface characteristics during different treatment stages (Magni et al., 2019). These nanoplastics, with their increased surface area, cannot only adsorb the pollutants eventually present in the ecosystem where they are being introduced (Hamidian et al., 2021), but have also shown a greater potential to be transferred through the trophic chain up to humans (Xu et al., 2022). The accidental release of nanoparticles from inadequate remediation strategies should also be avoided to comply with the monitoring programs and regulations that some countries and international organisations have implemented to mitigate the impact of microplastics.

The introduction of microplastics within environmental compartments and their transfer between them is an important phenomenon that should be considered to avoid the design of proposals to manage microplastic waste based on the removal of these pollutants from one environmental compartment (for example, water) and their storage in another (usually land). The best example of this situation is illustrated by WWTPs, which may not capture all microplastics because of their small size and the limitations of existing treatment processes, making them a source of microplastic pollution in aquatic systems. As revised by Iyare et al. in 2020 (Iyare et al., 2020), depending on the use of primary and secondary tertiary treatments, up to 94 % of microplastics present in influents can be removed. Although this removal efficiency may seem satisfactory, considering the large effluent volumes, this represents a high amount of microplastics that still find their way into aquatic systems. Moreover, the microplastics captured in wastewater treatment plants are typically retained in sewage sludge, which is later disposed of in landfills (Magnusson and Norén, 2014). This type of unintentional transfer of microplastics between environmental compartments can worsen microplastic pollution and impact climate change. For instance, the size, bulk, and surface physicochemical properties of microplastics may change because of the mechanism used for recovery, and these modified microplastics can show higher toxicity to ecosystems. Moreover, if microplastics recovered from land or aquatic environments are not correctly managed or stored and are accidentally introduced into the atmosphere, atmospheric transport can cause microplastic pollution in susceptible receptor regions, where microplastics may cause accelerated warming or disturb carbon cycle patterns.

Photocatalysis is an example of a chemical remediation strategy that involves most critical aspects of microplastic pollution. The successful application of photocatalysis to transform pollutants into innocuous CO_2 and water should be engineered by considering the target pollutant. For instance, microplastics present a series of inherent characteristics that are not always present in other common water-soluble pollutants such as dyes, alcohols, and pharmaceutical products. Microplastics are insoluble solids (in water) composed of polymers made of highly recalcitrant chemical structures that contain bonds that are difficult to break. As secondary microplastics present in the environment originate from the breakage of conventional plastic products, the antioxidants and other additives contained in their formulations may affect the degradation or mineralisation efficiency. Additionally, microplastics are huge regarding the particle or pore sizes of common photocatalysts (i.e. PE microplastics present in some commercial scrub formulations are roughly 17,000-fold the size of Degussa P25 TiO_2 nanoparticles (Llorente-García et al., 2020), which is a reference photocatalyst used worldwide). Thus, the adsorption of most microplastics on nanosized photocatalysts, which is required for their interaction with photogenerated ROS, is disadvantageous. The surface characteristics of microplastics should also be considered when selecting semiconductors for photocatalysis. Microplastics are typically hydrophobic; however, environmental aging can turn them hydrophilic owing to the formation of substances containing C═O bonds on their surfaces. These changes in wettability may affect the interaction between the semiconductor and microplastics, as the photocatalytic degradation of microplastics starts from the surface and proceeds towards the bulk of the particles. The presence of POPs or biofilms on the surface of microplastics may also affect the joining of the photocatalyst and the overall efficiency of the process. Finally, depending on the polymer type, the characteristics of the reaction medium (pH, temperature or oxygen concentration), and reaction time, photocatalytic oxidation can follow degradation paths that may lead to the production of toxic chemicals. Thus, the release of microplastic-free effluents into the environment without proper control of the outcomes of photocatalysis can damage the environment and humans.

When thinking in remediation proposals for microplastic pollution, we suggest ERCs to combine the physical, chemical, and biological technologies with educational mitigation strategies aimed at enhancing individuals' motivation and sense of responsibility regarding this complex pollution issue.

12. Conclusions

When examining their entire life cycle, it should be recognised that plastics negatively impact the environment and society at every stage, from the extraction of raw materials and manufacturing of products to consumption and disposal. Microplastics are a particular type of plastic waste, and the challenges of microplastic pollution are related to the complex relationships between the microplastic generation mechanisms, their physicochemical properties, their interactions with other pollutants and microorganisms, the changes in their properties with aging, and their small sizes that facilitate their diffusion and transportation between the air, water, land, and biota, thereby promoting their ubiquity. Furthermore, microplastics have a negative influence on society. ERCs constitute an essential part of the scientific community committed to overcoming the challenges of plastic pollution with their new ideas and innovative scientific perspectives for the development of remediation strategies for microplastic pollution. However, owing to the enormous amount of available information, it may be difficult for ERCs to determine the complexity of this environmental issue and design remediation proposals appropriately targeted for microplastic pollutants. The overall information presented here and the recommendations for holistic microplastic pollution remediation strategies can help ERCs to conceive highly innovative remediation technologies from a integrated perspective, considering their environmental, social, and practical dimensions while fulfilling the current government policies to manage microplastic waste. In this way, novel research performed by ERCs can provide stakeholders with concrete technologies to restore the health and well-being of the environment and people that coexist with microplastic pollution.

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CRediT authorship contribution statement

Nicoly Milhardo Lourenço Nohara: Investigation, Visualization, Writing – original draft, Writing – review & editing. **Maria Camila Ariza-Tarazona:** Investigation, Writing – original draft. **Eduardo Rezende Triboni:** Investigation, Writing – original draft. **Evandro Luís Nohara:** Investigation, Writing – original draft, Writing – review & editing. **Juan Francisco Villarreal-Chiu:** Investigation, Writing – original draft. **Erika Iveth Cedillo-González:** Conceptualization, Investigation, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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Data availability

Data will be made available on request.

References

Abbasi, S., Keshavarzi, B., Moore, F., Turner, A., Kelly, F.J., Dominguez, A.O., Jaafarzadeh, N., 2019. Distribution and potential health impacts of microplastics and microrubbers in air and street dusts from Asaluyeh County, Iran. Environ. Pollut. 244, 153–164. https://doi.org/10.1016/j.envpol.2018.10.039.

Abdelkarim, F., 2023. Utilizzo di Microplastiche Come Inerte Nelle Malte: Caso Studio. University of Modena and Reggio Emilia, Modena.

Abihssira-García, I.S., Kögel, T., Gomiero, A., Kristensen, T., Krogstad, M., Olsvik, P.A., 2022. Distinct polymer-dependent sorption of persistent pollutants associated with Atlantic salmon farming to microplastics. Mar. Pollut. Bull. 180, 113794 https://doi.org/10.1016/j.marpolbul.2022.113794.

Acuña-Bedoya, J.D., Luévano-Hipólito, E., Cedillo-González, E.I., Domínguez-Jaimes, L. P., Hurtado, A.M., Hernández-López, J.M., 2021. Boosting visible-light photocatalytic degradation of polystyrene nanoplastics with immobilized CuxO obtained by anodization. J. Environ. Chem. Eng. 9, 106208 https://doi.org/10.1016/j.jece.2021.106208.

Ahmad, M., Chen, J., Khan, M.T., Yu, Q., Phairuang, W., Furuuchi, M., Ali, S.W., Nawab, A., Panyametheekul, S., 2023. Sources, analysis, and health implications of atmospheric microplastics. Emerging Contaminants 9, 100233. https://doi.org/10.1016/j.emcon.2023.100233.

Akarsu, C., Deniz, F., 2021. Electrocoagulation/electroflotation process for removal of organics and microplastics in laundry wastewater. CLEAN–Soil, Air, Water 49, 2000146. https://doi.org/10.1002/clen.20200 0146.

Akarsu, C., Kumbur, H., Kideys, A.E., 2021. Removal of microplastics from wastewater through electrocoagulation-electroflotation and membrane filtration processes. Water Sci. Technol. 84, 1648–1662. https://doi.org/10.2166/wst.2021.356.

Akhbarizadeh, R., Dobaradaran, S., Amouei Torkmahalleh, M., Saeedi, R., Aibaghi, R., Faraji Ghasemi, F., 2021. Suspended fine particulate matter (PM2.5), microplastics (MPs), and polycyclic aromatic hydrocarbons (PAHs) in air: their possible relationships and health implications. Environ. Res. 192, 110339 https://doi.org/10.1016/j.envres.2020.110339.

Alimi, O.S., Farner Budarz, J., Hernandez, L.M., Tufenkji, N., 2018. Microplastics and nanoplastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport. Environ. Sci. Technol. 52, 1704–1724. https://doi.org/10.1021/acs.est.7b05559.

Allen, S., Allen, D., Moss, K., Roux, G.L., Phoenix, V.R., Sonke, J.E., 2020. Examination of the ocean as a source for atmospheric microplastics. PLoS One 15, e0232746. https://doi.org/10.1371/journal.pone.023 2746.

Amato-Lourenço, L.F., dos Santos Galvão, L., Wiebeck, H., Carvalho-Oliveira, R., Mauad, T., 2022. Atmospheric microplastic fallout in outdoor and indoor environments in São Paulo megacity. Sci. Total Environ. 821, 153450 https://doi.org/10.1016/j.scitotenv.2022.153450.

Ambrosini, R., Azzoni, R.S., Pittino, F., Diolaiuti, G., Franzetti, A., Parolini, M., 2019. First evidence of microplastic contamination in the supraglacial debris of an alpine glacier. Environ. Pollut. 253, 297–301. https://doi.org/10.1016/j.envpol.2019.07.005.

Andersen, I., 2020. The Triple Planetary Crisis: Forging a New Relationship Between People and the Earth [WWW Document]. UNEP. URL http://www.unep.org/news-and-stories/speech/triple-planetary-crisis-forging-new-relationship-between-people-and-earth (accessed 1.23.23).

Andrady, A., 2008. Fate of plastics debris in the marine environment. In: Proceedings of the International Research Workshop on the Occurrence, Effects and Fate of Microplastic Marine Debris. NOAA Technical Memorandum NOS-OR&R-30.

Andrady, A.L., 2011. Microplastics in the marine environment. Mar. Pollut. Bull. 62, 1596–1605. https://doi.org/10.1016/j.marpolbul.2011.05.030.

Arhant, M., Le Gall, M., Le Gac, P.-Y., Davies, P., 2019. Impact of hydrolytic degradation on mechanical properties of PET-towards an understanding of microplastics formation. Polym. Degrad. Stab. 161, 175–182. https://doi.org/10.1016/j.polymdegradstab. 2019.01.021.

Ariza-Tarazona, M.C., Villarreal-Chiu, J.F., Barbieri, V., Siligardi, C., Cedillo-González, E.I., 2019. New strategy for microplastic degradation: green photocatalysis using a protein-based porous N-TiO2 semiconductor. Ceramics International, A Selection of Papers Presented at CIMTEC 2018 (45), 9618–9624. https://doi.org/10.1016/j.ceramint.2018.10.208.

Ariza-Tarazona, M.C., Villarreal-Chiu, J.F., Hernández-López, J.M., Rivera De la Rosa, J., Barbieri, V., Siligardi, C., Cedillo-González, E.I., 2020. Microplastic pollution reduction by a carbon and nitrogen-doped TiO2: effect of pH and temperature in the photocatalytic degradation process. J. Hazard. Mater. 395, 122632 https://doi.org/10.1016/j.jhazmat.2020.122632.

Ariza-Tarazona, M.C., Siligardi, C., Carreón-López, H.A., Valdéz-Cerda, J.E., Pozzi, P., Kaushik, G., Villarreal-Chiu, J.F., Cedillo-González, E.I., 2023. Low environmental impact remediation of microplastics: visible-light photocatalytic degradation of PET microplastics using bio-inspired C,N-TiO2/SiO2 photocatalysts. Mar. Pollut. Bull. 193, 115206 https://doi.org/10.1016/j.marpolbul.2023.1 15206.

Arthur, C., Baker, J., Bamford, H., 2009. Proceedings of the International Research Workshop on the Occurrence, Effects and Fate of Microplastic Marine Debris. NOAA Technical Memorandum NOS-OR&R-30.

Auta, H.S., Abioye, O.P., Aransiola, S.A., Bala, J.D., Chukwuemeka, V.I., Hassan, A., Aziz, A., Fauziah, S.H., 2022. Enhanced microbial degradation of PET and PS microplastics under natural conditions in mangrove environment. J. Environ. Manag. 304, 114273 https://doi.org/10.1016/j.jenvman.2021.114273.

Bank, M.S., Hansson, S.V., 2019. The plastic cycle: a novel and holistic paradigm for the Anthropocene. Environ. Sci. Technol. 53, 7177–7179. https://doi.org/10.1021/acs.est.9b02942.

Bank, M.S., Hansson, S.V., 2022. The microplastic cycle: an introduction to a complex issue. In: Bank, M.S. (Ed.), Microplastic in the Environment: Pattern and Process, Environmental Contamination Remediation and Management. Springer International Publishing, Cham, pp. 1–16. https://doi.org/10.1007/978-3-030-78627-4_1.

Barnes, D.K.A., Galgani, F., Thompson, R.C., Barlaz, M., 2009. Accumulation and fragmentation of plastic debris in global environments. Philos. Trans. R. Soc. B 364, 1985–1998. https://doi.org/10.1098/rstb.2008.0205.

Belzagui, F., Gutiérrez-Bouzán, C., Carrillo-Navarrete, F., 2022. Novel treatment to immobilize and use textiles microfibers retained in polymeric filters through their incorporation in composite materials. Polymers 14, 2971. https://doi.org/10.3390/polym14152971.

Berger, E., Potouridis, T., Haeger, A., Püttmann, W., Wagner, M., 2015. Effect-directed identification of endocrine disruptors in plastic baby teethers. J. Appl. Toxicol. 35, 1254–1261. https://doi.org/10.1002/jat.3159.

Bergmann, M., Mützel, S., Primpke, S., Tekman, M.B., Trachsel, J., Gerdts, G., 2019. White and wonderful? Microplastics prevail in snow from the Alps to the Arctic. Sci. Adv. 5, eaax1157 https://doi.org/10.1126/sciadv.aax1157.

Bettencourt, S., Freitas, D.N., Lucas, C., Costa, S., Caeiro, S., 2023. Marine litter education: from awareness to action. Mar. Pollut. Bull. 192, 114963 https://doi.org/10.1016/j.marpolbul.2023.114963.

Blair Crawford, C., Quinn, B., 2016. Microplastic Pollutants. Elsevier Limited.

Boletín Oficial de la República Argentina, 2020. Productos Cosméticos y Productos de Higiene Oral de Uso Odontológico-Ley 27602.

Brahney, J., Mahowald, N., Prank, M., Cornwell, G., Klimont, Z., Matsui, H., Prather, K.A., 2021. Constraining the atmospheric limb of the plastic cycle. Proc. Natl. Acad. Sci. 118, e2020719118 https://doi.org/10.1073/pnas.2020719118.

Braun, T., Ehrlich, L., Henrich, W., Koeppel, S., Lomako, I., Schwabl, P., Liebmann, B., 2021. Detection of microplastic in human placenta and meconium in a clinical setting. Pharmaceutics 13, 921. https://doi.org/10.3390/pharmaceutics13070921.

Cabrera, M., Moulatlet, G.M., Valencia, B.G., Maisincho, L., Rodríguez-Barroso, R., Albendín, G., Sakali, A., Lucas-Solis, O., Conicelli, B., Capparelli, M.V., 2022. Microplastics in a tropical Andean Glacier: a transportation process across the Amazon basin? Sci. Total Environ. 805, 150334 https://doi.org/10.1016/j.scitotenv.2021.150334.

Cai, Y., Wu, J., Lu, J., Wang, J., Zhang, C., 2021. Fate of microplastics in a coastal wastewater treatment plant: microfibers could partially break through the integrated membrane system. Front. Environ. Sci. Eng. 16, 96. https://doi.org/10.1007/s11783-021-1517-0.

California Legislative Information, 2018. Bill Text-SB-1422 California Safe Drinking Water Act: microplastics [WWW Document]. URL. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB1422 (accessed 6.30.23).

Calil, J., Gutiérrez-Graudiņš, M., Munguía, S., Chin, C., 2021. Neglected: Environmental Justice Impacts of Marine Litter and Plastic Pollution. United Nations Environment Programme (UNEP), Nairobi, Kenya.

Callister, W.D., Rethwisch, D.G., 2019. Materials Science and Engineering: An Introduction, 10th ed. Wiley.

Cao, B., Wan, S., Wang, Y., Guo, H., Ou, M., Zhong, Q., 2022. Highly-efficient visible-light-driven photocatalytic H2 evolution integrated with microplastic degradation over MXene/ZnxCd1-xS photocatalyst. J. Colloid Interface Sci. 605, 311–319. https://doi.org/10.1016/j.jcis.2021.07.113.

Cao, Z., Xia, W., Wu, S., Ma, J., Zhou, X., Qian, X., Xu, A., Dong, W., Jiang, M., 2023. Bioengineering Comamonas testosteroni CNB-1: a robust whole-cell biocatalyst for efficient PET microplastic degradation. Bioresources and Bioprocessing 10, 94. https://doi.org/10.1186/s40643-023-00715-7.

CAPES Brazilian tool, 2023. Portal de Periódicos da CAPES.

Caputo, F., Vogel, R., Savage, J., Vella, G., Law, A., Della Camera, G., Hannon, G., Peacock, B., Mehn, D., Ponti, J., Geiss, O., Aubert, D., Prina-Mello, A., Calzolai, L., 2021. Measuring particle size distribution and mass concentration of nanoplastics and microplastics: addressing some analytical challenges in the sub-micron size range. J. Colloid Interface Sci. 588, 401–417. https://doi.org/10.1016/j.jcis.2020.12.039.

Carney Almroth, B.M., Åström, L., Roslund, S., Petersson, H., Johansson, M., Persson, N.-K., 2018. Quantifying shedding of synthetic fibers from textiles; a source of microplastics released into the environment. Environ. Sci. Pollut. Res. 25, 1191–1199. https://doi.org/10.1007/s11356-017-0528-7.

Carpenter, E.J., Smith, K.L., 1972. Plastics on the Sargasso Sea surface. Science 175, 1240–1241. https://doi.org/10.1126/science.175.4027.1240.

Carpenter, E.J., Anderson, S.J., Harvey, G.R., Miklas, H.P., Peck, B.B., 1972. Polystyrene spherules in coastal waters. Science 178, 749–750. https://doi.org/10.1126/science.178.4062.749.

Cedillo-González, E., Oliani, P., 2023. Pelucco: A Microplastic's Journey. Amazon KDP. ISBN-13 979-8860263468 ↱ : .

Cedillo-González, E.I., Siligardi, C., 2023. Towards a microplastic-free ocean: green photocatalysis for mitigation of micro- and nanoplastic marine pollution. In: Cocca, M., Ambrogi, V., Avolio, R., Castaldo, R., Errico, M.E., Gentile, G. (Eds.), Proceedings of the 3rd International Conference on Microplastic Pollution in the Mediterranean Sea. Springer Water. Springer International Publishing, Cham, pp. 125–132. https://doi.org/10.1007/978-3-031-34455-8_18.

Chabi, K., Li, J., Ye, C., Kiki, C., Xiao, X., Li, X., Guo, L., Gad, M., Feng, M., Yu, X., 2024. Rapid sand filtration for <10 μm-sized microplastic removal in tap water treatment: efficiency and adsorption mechanisms. Sci. Total Environ. 912, 169074 https://doi.org/10.1016/j.scitotenv.2023.169074.

Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J.H., Abu-Omar, M., Scott, S.L., Suh, S., 2020. Degradation rates of plastics in the environment. ACS Sustain. Chem. Eng. 8, 3494–3511. https://doi.org/10.1021/acssuschemeng.9b06635.

Chang, X., Fang, Y., Wang, Y., Wang, F., Shang, L., Zhong, R., 2022. Microplastic pollution in soils, plants, and animals: a review of distributions, effects and potential mechanisms. Sci. Total Environ. 850, 157857 https://doi.org/10.1016/j.scitotenv.2022.157857.

Charitou, A., Naasan Aga-Spyridopoulou, R., Mylona, Z., Beck, R., McLellan, F., Addamo, A.M., 2021. Investigating the knowledge and attitude of the Greek public towards marine plastic pollution and the EU Single-Use Plastics Directive. Mar. Pollut. Bull. 166, 112182 https://doi.org/10.1016/j.marpolbul.2021.112182.

Chattopadhyay, P., Ariza-Tarazona, M.C., Cedillo-González, E.I., Siligardi, C., Simmchen, J., 2023. Combining photocatalytic collection and degradation of microplastics using self-asymmetric Pac-Man TiO2. Nanoscale 15, 14774–14781. https://doi.org/10.1039/D3NR01512B.

Chen, Q., Allgeier, A., Yin, D., Hollert, H., 2019. Leaching of endocrine disrupting chemicals from marine microplastics and mesoplastics under common life stress conditions. Environ. Int. 130, 104938 https://doi.org/10.1016/j.envint.2019.104938.

Chen, Y.-J., Chen, Y., Miao, C., Wang, Y.-R., Gao, G.-K., Yang, R.-X., Zhu, H.-J., Wang, J.-H., Li, S.-L., Lan, Y.-Q., 2020a. Metal–organic framework-based foams for efficient microplastics removal. J. Mater. Chem. A 8, 14644–14652. https://doi.org/10.1039/D0TA04891G.

Chen, G., Feng, Q., Wang, J., 2020b. Mini-review of microplastics in the atmosphere and their risks to humans. Sci. Total Environ. 703, 135504 https://doi.org/10.1016/j.scitotenv.2019.135504.

Chen, Z., Zhao, W., Xing, R., Xie, S., Yang, X., Cui, P., Lü, J., Liao, H., Yu, Z., Wang, S., Zhou, S., 2020c. Enhanced in situ biodegradation of microplastics in sewage sludge using hyperthermophilic composting technology. J. Hazard. Mater. 384, 121271 https://doi.org/10.1016/j.jhazmat.2019. 121271.

Cheng, Y.-R., Wang, H.-Y., 2022. Highly effective removal of microplastics by microalgae Scenedes-mus abundans. Chem. Eng. J. 435, 135079 https://doi.org/10.1016/j.cej.2022.135079.

Cheung, P.K., Fok, L., 2017. Characterisation of plastic microbeads in facial scrubs and their estimated emissions in Mainland China. Water Res. 122, 53–61. https://doi.org/10.1016/j.watres.2017. 05.053.

Choi, E.-H., Lee, H., Kang, M.-J., Nam, I., Moon, H.-K., Sung, J.-W., Eu, J.-Y., Lee, H.-B., 2022. Factors affecting zero-waste behaviours of college students. Int. J. Environ. Res. Public Health 19, 9697. https://doi.org/10.3390/ijerph19159697.

Cholewinski, A., Dadzie, E., Sherlock, C., Anderson, W.A., Charles, T.C., Habib, K., Young, S.B., Zhao, B., 2022. A critical review of microplastic degradation and material flow analysis towards a circular economy. Environ. Pollut. 315, 120334 https://doi.org/10.1016/j.envpol.2022.120334.

Chubarenko, I., Bocherikova, I., Esiukova, E., Isachenko, I., Kupriyanova, A., Lobchuk, O., Fetisov, S., 2023. Microplastics in sea ice: a fingerprint of bubble flotation. Sci. Total Environ. 892, 164611 https://doi.org/10.1016/j.scitotenv.2023.164611.

Cole, M., Lindeque, P., Halsband, C., Galloway, T.S., 2011. Microplastics as contaminants in the marine environment: a review. Mar. Pollut. Bull. 62, 2588–2597. https://doi.org/10.1016/j.marpolbul. 2011.09.025.

Collier, K.M., McCance, K., Jackson, S., Topliceanu, A., Blanchard, M.R., Venditti, R.A., 2023. Observing microplastics in the environment through citizen-science-inspired laboratory investigations. J. Chem. Educ. 100, 2067–2079. https://doi.org/10.1021/acs.jchemed.2c01078.

Commission Implementing Regulation (EU) 2020/2151 of 17 December 2020 laying down rules on harmonised marking specifications on single-use plastic products listed in Part D of the Annex to Directive (EU) 2019/904 of the European Parliament and of the Council on the reduction of the impact of certain plastic products on the environment (Text with EEA relevance), 2020. OJ L.

Crosta, A., De Felice, B., Antonioli, D., Chiarcos, R., Perin, E., Ortenzi, M.A., Gazzotti, S., Azzoni, R.S., Fugazza, D., Gianotti, V., Laus, M., Diolaiuti, G., Pittino, F., Franzetti, A., Ambrosini, R., Parolini, M., 2022. Microplastic contamination of supraglacial debris differs among glaciers with different anthropic pressures. Sci. Total Environ. 851, 158301 https://doi.org/10.1016/j.scitotenv.2022. 158301.

Cruz-Salas, A.A., Velasco-Pérez, M., Mendoza-Muñoz, N., Vázquez-Morillas, A., Beltrán-Villavicencio, M., Alvarez-Zeferino, J.C., Ojeda-Benítez, S., 2023. Sorption of total petroleum hydrocarbons in microplastics. Polymers 15, 2050. https://doi.org/10.3390/polym15092050.

Cunha, C., Faria, M., Nogueira, N., Ferreira, A., Cordeiro, N., 2019. Marine vs freshwater microalgae exopolymers as biosolutions to microplastics pollution. Environ. Pollut. 249, 372–380. https://doi.org/10.1016/j.envpol.2019.03.046.

Cunha, C., Silva, L., Paulo, J., Faria, M., Nogueira, N., Cordeiro, N., 2020. Microalgal-based biopolymer for nano- and microplastic removal: a possible biosolution for wastewater treatment. Environ. Pollut. 263, 114385 https://doi.org/10.1016/j.envpol.2020.114385.

Dawson, A.L., Kawaguchi, S., King, C.K., Townsend, K.A., King, R., Huston, W.M., Bengtson Nash, S.M., 2018. Turning microplastics into nanoplastics through digestive fragmentation by Antarctic krill. Nat. Commun. 9, 1001. https://doi.org/10.1038/s41467-018-03465-9.

Dehghanian, Z., Asgari Lajayer, B., Biglari Quchan Atigh, Z., Nayeri, S., Ahmadabadi, M., Taghipour, L., Senapathi, V., Astatkie, T., Price, G.W., 2023. Micro (nano) plastics uptake, toxicity and detoxification in plants: challenges and prospects. Ecotoxicol. Environ. Saf. 268, 115676 https://doi.org/10.1016/j.ecoenv.2023.115676.

Department for Environment, Food & Rural Affairs, 2018. Single-use plastics ban: plates, bowls, trays, containers, cutlery and balloon sticks [WWW document]. GOV.UK. URL https://www.gov.uk/guidance/single-use-plastics-ban-plates-bowls-trays-containers-cutlery-and-balloon-sticks (accessed 6.30.23).

Diário da República, 2021. Decreto-Lei n.º 69/2021, de 30 de julho.

Ding, H., Zhang, J., He, H., Zhu, Y., Dionysiou, D.D., Liu, Z., Zhao, C., 2021. Do membrane filtration systems in drinking water treatment plants release nano/microplastics? Sci. Total Environ. 755, 142658 https://doi.org/10.1016/j.scitotenv.2020.142658.

Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment (Text with EEA relevance), 2019, OJ L.

Dissanayake, P.D., Kim, S., Sarkar, B., Oleszczuk, P., Sang, M.K., Haque, M.N., Ahn, J.H., Bank, M.S., Ok, Y.S., 2022. Effects of microplastics on the terrestrial environment: a critical review. Environ. Res. 209, 112734 https://doi.org/10.1016/j.envres.2022.112734.

Domínguez-Jaimes, L.P., Cedillo-González, E.I., Luévano-Hipólito, E., Acuña-Bedoya, J. D., Hernández-López, J.M., 2021. Degradation of primary nanoplastics by photocatalysis using different anodized TiO2 structures. J. Hazard. Mater. 413, 125452 https://doi.org/10.1016/j.jhazmat.2021. 125452.

Dowarah, K., Duarah, H., Devipriya, S.P., 2022. A preliminary survey to assess the awareness, attitudes/behaviours, and opinions pertaining to plastic and microplastic pollution among students in India. Mar. Policy 144, 105220. https://doi.org/10.1016/j.marpol.2022.105220.

Dris, R., Gasperi, J., Rocher, V., Saad, M., Renault, N., Tassin, B., Dris, R., Gasperi, J., Rocher, V., Saad, M., Renault, N., Tassin, B., 2015. Microplastic contamination in an urban area: a case study in Greater Paris. Environ. Chem. 12, 592–599. https://doi.org/10.1071/EN14167.

Dris, R., Gasperi, J., Saad, M., Mirande, C., Tassin, B., 2016. Synthetic fibers in atmospheric fallout: a source of microplastics in the environment? Mar. Pollut. Bull. 104, 290–293. https://doi.org/10.1016/j.marpolbul.2016.01.006.

Dris, R., Gasperi, J., Mirande, C., Mandin, C., Guerrouache, M., Langlois, V., Tassin, B., 2017. A first overview of textile fibers, including microplastics, in indoor and outdoor environments. Environ. Pollut. 221, 453–458. https://doi.org/10.1016/j.envpol.2016.12.013.

ECHA Committe for Risk Assessment (RAC), ECHA Committee for Socio-economic Analysis (SEAC), 2020. Opinion on an Annex XV Dossier Proposing Restrictions on Intentionally-added Microplastics.

Edo, C., Fernández-Alba, A.R., Vejsnæs, F., van der Steen, J.J.M., Fernández-Piñas, F., Rosal, R., 2021. Honeybees as active samplers for microplastics. Sci. Total Environ. 767, 144481 https://doi.org/10.1016/j.scitotenv.2020.144481.

Elizalde-Velázquez, A., Subbiah, S., Anderson, T.A., Green, M.J., Zhao, X., Cañas-Carrell, J.E., 2020. Sorption of three common nonsteroidal anti-inflammatory drugs (NSAIDs) to microplastics. Sci. Total Environ. 715, 136974 https://doi.org/10.1016/j.scitotenv.2020.136974.

Elkhatib, D., Oyanedel-Craver, V., Carissimi, E., 2021. Electrocoagulation applied for the removal of microplastics from wastewater treatment facilities. Sep. Purif. Technol. 276, 118877 https://doi.org/10.1016/j.seppur.2021.118877.

Enders, K., Lenz, R., Stedmon, C.A., Nielsen, T.G., 2015. Abundance, size and polymer composition of marine microplastics ≥10μm in the Atlantic Ocean and their modelled vertical distribution. Mar. Pollut. Bull. 100, 70–81. https://doi.org/10.1016/j.marpolbul.2015.09.027.

Eriksen, M., Lebreton, L.C.M., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., Galgani, F., Ryan, P.G., Reisser, J., 2014. Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PLoS One 9, e111913. https://doi.org/10.1371/journal.pone.011 1913.

Ershova, A., Makeeva, I., Malgina, E., Sobolev, N., Smolokurov, A., 2021. Combining citizen and conventional science for microplastics monitoring in the White Sea basin (Russian Arctic). Mar. Pollut. Bull. 173, 112955 https://doi.org/10.1016/j.marpolbul.2021.112955.

Esfandiari, A., Abbasi, S., Peely, A.B., Mowla, D., Ghanbarian, M.A., Oleszczuk, P., Turner, A., 2022. Distribution and transport of microplastics in groundwater (Shiraz aquifer, Southwest Iran). Water Res. 220, 118622 https://doi.org/10.1016/j.watres.2022.118622.

EURACTIV, 2013. Dutch want their mussels free from micro-plastic litter, call on EU to act [WWW document]. www.euractiv.com. URL. https://www.euractiv.com/section/science-policymaking/news/dutch-want-their-mussels-free-from-micro-plastic-litter-call-on-eu-to-act/ (accessed 6.30.23).

European Comission, 2013. GREEN PAPER on a European Strategy on Plastic Waste in the Environment.

European Comission, 2015. First circular economy action plan [WWW document]. URL https://environment.ec.europa.eu/topics/circular-economy/first-circular-economy-action-plan_en (accessed 6.30.23).

European Comission, 2018. Plastics strategy [WWW document]. URL. https://environment.ec.europa.eu/strategy/plastics-strategy_en.

European Comission, 2022. Comitology Register-COMMISSION REGULATION (EU) …/… of XXX amending Annex XVII to Regulation (EC) No 1907/2006 of the European Parliament and of the Council concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) as regards synthetic polymer microparticles [WWW document]. URL. https://ec.europa.eu/trans-parency/comitology-register/screen/documents/083921/1/consult?lang=en.

European Comission, 2023. REACH committee votes to restrict intentional microplastics [WWW document]. URL. https://single-market-economy.ec.europa.eu/news/reach-committee-votes-restrict-intentional-microplastics-2023-04-27_en (accessed 6.30.23).

Evangeliou, N., Grythe, H., Klimont, Z., Heyes, C., Eckhardt, S., Lopez-Aparicio, S., Stohl, A., 2020. Atmospheric transport is a major pathway of microplastics to remote regions. Nat. Commun. 11, 3381. https://doi.org/10.1038/s41467-020-17201-9.

Farooq, M.U., Jalees, M.I., Qurat-ul-Ain, Hussain, G., Anis, M., Islam, U., 2021. Health risk assessment of endocrine disruptor bisphenol A leaching from plastic bottles of milk and soft drinks. Environ. Sci. Pollut. Res. 28, 57090–57098. https://doi.org/10.1007/s11356-021-14653-4.

Feng, X., Long, R., Liu, C., Liu, X., 2022. Visible-light-driven removal of tetracycline hydrochloride and microplastics (HDPE) by nano flower hybrid heterojunction NH2-MIL-88B(Fe)/MoS2 via enhanced electron-transfer. Sep. Purif. Technol. 302, 122138 https://doi.org/10.1016/j.seppur.2022. 122138.

Feng, S., Lu, H., Yao, T., 2023. Effects of multiple environmental factors and land use patterns on microplastic distribution in the topsoil of the Qinghai and Sichuan provinces of China. J. Environ. Chem. Eng. 11, 109657 https://doi.org/10.1016/j.jece.2023.109657.

Free, C.M., Jensen, O.P., Mason, S.A., Eriksen, M., Williamson, N.J., Boldgiv, B., 2014. High-levels of microplastic pollution in a large, remote, mountain lake. Mar. Pollut. Bull. 85, 156–163. https://doi.org/10.1016/j.marpolbul.2014.06.001.

Frias, J.P.G.L., Nash, R., 2019. Microplastics: finding a consensus on the definition. Mar. Pollut. Bull. 138, 145–147. https://doi.org/10.1016/j.marpolbul.2018.11.022.

Gao, F., Li, J., Hu, J., Li, X., Sun, C., 2020. Occurrence of microplastics carried on Ulva prolifera from the Yellow Sea, China. Case Studies in Chemical and Environmental Engineering 2, 100054. https://doi.org/10.1016/j.cscee.2020.100054.

Garcia-Vazquez, E., Garcia-Ael, C., Ardura, A., Rodriguez, N., Dopico, E., 2023. Towards a plastic-less planet. Gender and individual responsibility predict the effect of imagery nudges about marine (micro)plastic pollution on R-behavior intentions. Marine Pollution Bulletin 193, 115157. doi:https://doi.org/10.1016/j.marpolbul.2023.115157.

Ge, J., Wang, M., Liu, P., Zhang, Z., Peng, J., Guo, X., 2023. A systematic review on the aging of microplastics and the effects of typical factors in various environmental media. TrAC Trends Anal. Chem. 162, 117025 https://doi.org/10.1016/j.trac.2023.117025.

General Secretariat Council of the European Union, 2014. NOTE 16163/14 Elimination of micro-plastics in products - an urgent need - Information from the Belgian, Dutch, Austrian and Swedish delegations, supported by the Luxembourg delegation.

General Secretariat Council of the European Union, 2023. NOTE 10736/13, Micro-plastic litter: a growing environmental problem - Information from the Netherlands delegation.

GESAMP, 2015. "Sources, fate and effects of microplastics in the marine environment: a global assessment". In: Kershaw, P.J. (Ed.), (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. GESAMP. No. 90, 96 p.

Geyer, R., 2020. A brief history of plastics. In: Streit-Bianchi, M., Cimadevila, M., Trettnak, W. (Eds.), Mare Plasticum-The Plastic Sea: Combatting Plastic Pollution Through Science and Art. Springer International Publishing, Cham, pp. 31–47. https://doi.org/10.1007/978-3-030-38945-1_2.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3, e1700782 https://doi.org/10.1126/sciadv.1700782.

Gigault, J., Halle, A. ter, Baudrimont, M., Pascal, P.-Y., Gauffre, F., Phi, T.-L., El Hadri, H., Grassl, B., Reynaud, S., 2018. Current opinion: what is a nanoplastic? Environ. Pollut. 235, 1030–1034. https://doi.org/10.1016/j.envpol.2018.01.024.

Giraldo, L.J.Q., Cruz, L.J., García, J.A., Alcaraz, A., González, E., Osorio, J.A., 2019. Incidence of mercerization treatment in the mechanical properties of bamboo fibre bundles "Guadua Angustifolia Kunth" from colombian origin. DYNA 86, 156–163. https://doi.org/10.15446/dyna.v86n210.71782.

Government of Canada, P.W. and G.S.C., 2017. Canada Gazette–Index [WWW Document]. URL https://canadagazette.gc.ca/rp-pr/p2/2017/2017-06-14/html/index-eng.html (accessed 6.30.23).

Grbić, J., Helm, P., Athey, S., Rochman, C.M., 2020. Microplastics entering northwestern Lake Ontario are diverse and linked to urban sources. Water Res. 174, 115623 https://doi.org/10.1016/j.watres. 2020.115623.

Greco, R., Baxauli-Marin, L., Temerov, F., Daboczi, M., Eslava, S., Niu, Y., Zakharov, A., Zhang, M., Li, T., Cao, W., 2023. Activation of 2D cobalt hydroxide with 0D cobalt oxide decoration for microplastics degradation and hydrogen evolution. Chem. Eng. J. 471, 144569 https://doi.org/10.1016/j.cej.2023.144569.

Grelaud, M., Ziveri, P., 2020. The generation of marine litter in Mediterranean island beaches as an effect of tourism and its mitigation. Sci. Rep. 10, 20326 https://doi.org/10.1038/s41598-020-77225-5.

Guo, X., Chen, C., Wang, J., 2019. Sorption of sulfamethoxazole onto six types of microplastics. Chemosphere 228, 300–308. https://doi.org/10.1016/j.chemosphere.2019.04.155.

Guo, J.-J., Huang, X.-P., Xiang, L., Wang, Y.-Z., Li, Y.-W., Li, H., Cai, Q.-Y., Mo, C.-H., Wong, M.-H., 2020. Source, migration and toxicology of microplastics in soil. Environ. Int. 137 (105), 263. https://doi.org/10.1016/j.envint.2019.105263.

Haber, F., Weiss, J., Pope, W.J., 1934. The catalytic decomposition of hydrogen peroxide by iron salts. Proceedings of the Royal Society of London. Series A-Mathematical and Physical Sciences 147, 332–351. https://doi.org/10.1098/rspa.1934.0221.

Habib, S., Iruthayam, A., Abd Shukor, M.Y., Alias, S.A., Smykla, J., Yasid, N.A., 2020. Biodeteriora- tion of untreated polypropylene microplastic particles by Antarctic Bacteria. Polymers 12, 2616. https://doi.org/10.3390/polym12112616.

Hamidian, A.H., Ozumchelouei, E.J., Feizi, F., Wu, C., Zhang, Y., Yang, M., 2021. A review on the characteristics of microplastics in wastewater treatment plants: a source for toxic chemicals. J. Clean. Prod. 295, 126480 https://doi.org/10.1016/j.jclepro.2021.126480.

Hanif, M.A., Ibrahim, N., Dahalan, F.A., Md Ali, U.F., Hasan, M., Jalil, A.A., 2022. Microplastics and nanoplastics: recent literature studies and patents on their removal from aqueous environment. Sci. Total Environ. 810, 152115 https://doi.org/10.1016/j.scitotenv.2021.152115.

Hartmann, N.B., Hüffer, T., Thompson, R.C., Hassellöv, M., Verschoor, A., Daugaard, A. E., Rist, S., Karlsson, T., Brennholt, N., Cole, M., Herrling, M.P., Hess, M.C., Ivleva, N. P., Lusher, A.L., Wagner, M., 2019. Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. Environ. Sci. Technol. 53, 1039–1047. https://doi.org/10.1021/acs.est.8b05 297.

He, P., Chen, L., Shao, L., Zhang, H., Lü, F., 2019. Municipal solid waste (MSW) landfill: a source of microplastics?-evidence of microplastics in landfill leachate. Water Res. 159, 38–45. https://doi.org/10.1016/j.watres.2019.04.060.

He, D., Zhang, Y., Gao, W., 2021. Micro(nano)plastic contaminations from soils to plants: human food risks. Curr. Opin. Food Sci. 41, 116–121. https://doi.org/10.1016/j.cofs.2021.04.001.

He, J., Han, L., Ma, W., Chen, L., Ma, C., Xu, C., Yang, Z., 2023a. Efficient photodegradation of polystyrene microplastics integrated with hydrogen evolution: uncovering degradation pathways. iScience 26. https://doi.org/10.1016/j.isci.2023.106833.

He, Y., Rehman, A.U., Xu, M., Not, C.A., Ng, A.M.C., Djurišić, A.B., 2023b. Photocatalytic degradation of different types of microplastics by TiOx/ZnO tetrapod photocatalysts. Heliyon 9. https://doi.org/10.1016/j. heliyon.2023.e22562.

Horton, A.A., Dixon, S.J., 2018. Microplastics: an introduction to environmental transport processes. WIREs Water 5, e1268. https://doi.org/10.1002/wat2.1268.

Horton, A.A., Walton, A., Spurgeon, D.J., Lahive, E., Svendsen, C., 2017. Microplastics in freshwater and terrestrial environments: evaluating the current understanding to identify the knowledge gaps and future research priorities. Sci. Total Environ. 586, 127–141. https://doi.org/10.1016/j.scitotenv. 2017.01.190.

Hsieh, L., He, L., Zhang, M., Lv, W., Yang, K., Tong, M., 2022. Addition of biochar as thin preamble layer into sand filtration columns could improve the microplastics removal from water. Water Res. 221, 118783 https://doi.org/10.1016/j.watres.2022.118783.

Hu, K., Zhou, P., Yang, Y., Hall, T., Nie, G., Yao, Y., Duan, X., Wang, S., 2022. Degradation of microplastics by a thermal Fenton reaction. ACS EST Eng. 2, 110–120. https://doi.org/10.1021/acsestengg. 1c00323.

Hu, Y., Zhou, L., Zhu, J., Gao, J., 2023. Efficient removal of polyamide particles from wastewater by electrocoagulation. Journal of Water Process Engineering 51, 103417. https://doi.org/10.1016/j.jwpe.2022. 103417.

Huang, Y., Liu, Q., Jia, W., Yan, C., Wang, J., 2020. Agricultural plastic mulching as a source of microplastics in the terrestrial environment. Environ. Pollut. 260, 114096 https://doi.org/10.1016/j. envpol.2020.114096.

Huang, Z., Bu, J., Wang, H., 2022. Application of two modified kaolin materials in removing micro-plastics from water. J Mater Cycles Waste Manag 24, 1460–1475. https://doi.org/10.1007/s10163-022-01393-x.

Hurley, R.R., Nizzetto, L., 2018. Fate and occurrence of micro(nano)plastics in soils: knowledge gaps and possible risks. Current Opinion in Environmental Science & Health, Micro and Nanoplastics Edited by Dr. Teresa A.P. Rocha-Santos 1, 6–11. https://doi.org/10.1016/j.coesh.2017.10.006.

Imhof, H.K., Ivleva, N.P., Schmid, J., Niessner, R., Laforsch, C., 2013. Contamination of beach sediments of a subalpine lake with microplastic particles. Curr. Biol. 23, R867–R868. https://doi.org/10.1016/j.cub.2013.09.001.

International Organization for Standardization, ISO, 2013. ISO 472:2013 Plastics — Vocabulary.

Isobe, A., Uchiyama-Matsumoto, K., Uchida, K., Tokai, T., 2017. Microplastics in the Southern Ocean. Mar. Pollut. Bull. 114, 623–626. https://doi.org/10.1016/j.marpolbul.2016.09.037.

Iyare, P.U., Ouki, S.K., Bond, T., 2020. Microplastics removal in wastewater treatment plants: a critical review. Environ. Sci.: Water Res. Technol. 6, 2664–2675. https://doi.org/10.1039/D0EW00397B.

Jayan, N., Skariyachan, S., Sebastian, D., 2023. The escalated potential of the novel isolate Bacillus cereus NJD1 for effective biodegradation of LDPE films without pre-treatment. J. Hazard. Mater. 455, 131623 https://doi.org/10.1016/j.jhazmat.2023.131623.

Jia, W., Karapetrova, A., Zhang, M., Xu, L., Li, K., Huang, M., Wang, J., Huang, Y., 2022. Automated identification and quantification of invisible microplastics in agricultural soils. Sci. Total Environ. 844, 156853 https://doi.org/10.1016/j.scitotenv.2022.156853.

Jiang, H., Zhang, Y., Bian, K., Wang, C., Xie, X., Wang, H., Zhao, H., 2022. Is it possible to efficiently and sustainably remove microplastics from sediments using froth flotation? Chem. Eng. J. 448, 137692 https://doi.org/10.1016/j.cej.2022.137692.

Journal officiel "Lois et Décrets", 2017. Décret n° 2017-291 du 6 mars 2017 relatif aux conditions de mise en œuvre de l'interdiction de mise sur le marché des produits cosmétiques rincés à usage d'exfoliation ou de nettoyage comportant des particules plastiques solides et des bâtonnets ouatés à usage domestique dont la tige est en plastique.

Julienne, F., Lagarde, F., Bardeau, J.-F., Delorme, N., 2022. Thin polyethylene (LDPE) films with controlled crystalline morphology for studying plastic weathering and microplastic generation. Polym. Degrad. Stab. 195, 109791 https://doi.org/10.1016/j.polymdegradstab. 2021.109791.

Kang, J., Zhou, L., Duan, X., Sun, H., Ao, Z., Wang, S., 2019. Degradation of cosmetic microplastics via functionalized carbon nanosprings. Matter 1, 745–758. https://doi.org/10.1016/j.matt.2019.06.004.

Kang, M.-G., Kwak, M.-J., Kim, Y., 2023. Polystyrene microplastics biodegradation by gut bacterial Enterobacter hormaechei from mealworms under anaerobic conditions: anaerobic oxidation and depolymerization. J. Hazard. Mater. 459, 132045 https://doi.org/10.1016/j.jhazmat.2023.132045.

Kanhai, L.D.K., Gardfeldt, K., Krumpen, T., Thompson, R.C., O'Connor, I., 2020. Microplastics in sea ice and seawater beneath ice floes from the Arctic Ocean. Sci. Rep. 10, 5004. https://doi.org/10.1038/s41598-020-61948-6.

KEMI Swedish Chemicals Agency, 2023. Plastic microbeads in cosmetic products [WWW document]. URL https://www.kemi.se/en/rules-and-regulations/rules-applicable-in-sweden-only/certain-swedish-restrictions-and-bans/plastic-microbeads-in-cosmetic-products (accessed 6.30.23).

Khan, Aziz, Jie, Z., Wang, J., Nepal, J., Ullah, N., Zhao, Z.-Y., Wang, P.-Y., Ahmad, W., Khan, Adnan, Wang, W., Li, M.-Y., Zhang, W., Elsheikh, M.S., Xiong, Y.-C., 2023. Ecological risks of microplastics contamination with green solutions and future perspectives. Sci. Total Environ. 899, 165688 https://doi.org/10.1016/j.scitotenv.2023.165688.

Kim, H., Lee, J.-Y., 2020. Emerging concerns about microplastic pollution on groundwater in South Korea. Sustainability 12, 5275. https://doi.org/10.3390/su12135275.

Kiss, T., Fórián, S., Szatmári, G., Sipos, G., 2021. Spatial distribution of microplastics in the fluvial sediments of a transboundary river – a case study of the Tisza River in Central Europe. Sci. Total Environ. 785, 147306 https://doi.org/10.1016/j.scitotenv.2021.147306.

Koelmans, A.A., Mohamed Nor, N.H., Hermsen, E., Kooi, M., Mintenig, S.M., De France, J., 2019. Microplastics in freshwaters and drinking water: critical review and assessment of data quality. Water Res. 155, 410–422. https://doi.org/10.1016/j.watres.2019.02.054.

Kothawale, S.S., Kumar, L., Singh, S.P., 2023. Role of organisms and their enzymes in the biodegradation of microplastics and nanoplastics: a review. Environ. Res. 232, 116281 https://doi.org/10.1016/j.envres.2023.116281.

Kutralam-Muniasamy, G., Shruti, V.C., Pérez-Guevara, F., Roy, P.D., 2023. Microplastic diagnostics in humans: "the 3Ps" Progress, problems, and prospects. Sci. Total Environ. 856, 159164 https://doi.org/10.1016/j.scitotenv.2022.159164.

Kwak, J.I., An, Y.-J., 2021. Microplastic digestion generates fragmented nanoplastics in soils and damages earthworm spermatogenesis and coelomocyte viability. J. Hazard. Mater. 402, 124034 https://doi.org/10.1016/j.jhazmat.2020.124034.

Lagarde, F., Olivier, O., Zanella, M., Daniel, P., Hiard, S., Caruso, A., 2016. Microplastic interactions with freshwater microalgae: hetero-aggregation and changes in plastic density appear strongly dependent on polymer type. Environ. Pollut. 215, 331–339. https://doi.org/10.1016/j.envpol.2016.05.006.

Lapointe, M., Farner, J.M., Hernandez, L.M., Tufenkji, N., 2020. Understanding and improving microplastic removal during water treatment: impact of coagulation and flocculation. Environ. Sci. Technol. 54, 8719–8727. https://doi.org/10.1021/acs.est.0c00712.

Lechthaler, S., Waldschläger, K., Stauch, G., Schüttrumpf, H., 2020. The way of macroplastic through the environment. Environments 7, 73. https://doi.org/10.3390/environments7100073.

Lee, J., Lee, J.S., Jang, Y.C., Hong, S.Y., Shim, W.J., Song, Y.K., Hong, S.H., Jang, M., Han, G.M., Kang, D., Hong, S., 2015. Distribution and size relationships of plastic marine debris on beaches in South Korea. Arch. Environ. Contam. Toxicol. 69, 288–298. https://doi.org/10.1007/s00244-015-0208-x.

Lee, J., Wang, J., Oh, Y., Jeong, S., 2023. Highly efficient microplastics removal from water using in-situ ferrate coagulation: performance evaluation by micro-Fourier-transformed infrared spectroscopy and coagulation mechanism. Chem. Eng. J. 451, 138556 https://doi.org/10.1016/j.cej.2022.138 556.

Lehmann, M., Häusl, F.P., Gekle, S., 2023. Modeling of vertical microplastic transport by rising bubbles. Microplastics and Nanoplastics 3, 4. https://doi.org/10.1186/s43591-023-00053-7.

Leifheit, E.F., Kissener, H.L., Faltin, E., Ryo, M., Rillig, M.C., 2022. Tire abrasion particles negatively affect plant growth even at low concentrations and alter soil biogeochemical cycling. Soil Ecol. Lett. 4, 409–415. https://doi.org/10.1007/s42832-021-0114-2.

Li, Y., Zhang, H., Tang, C., 2020. A review of possible pathways of marine microplastics transport in the ocean. Anthropocene Coasts 3, 6–13. https://doi.org/10.1139/anc-2018-0030.

Li, Z., Xu, B., Zhang, Runhua, Wang, F., Li, L., Wang, K., Zhang, Runqin, Jing, X., Liu, Y., Chen, P., 2023a. Effects of land use on soil microplastic distribution adjacent to Danjiangkou reservoir. China. Chemosphere 338, 139389. https://doi.org/10.1016/j.chemosphere.2023.139389.

Li, S., Yang, Y., Yang, S., Zheng, H., Zheng, Y., M, J., Nagarajan, D., Varjani, S., Chang, J.-S., 2023b. Recent advances in biodegradation of emerging contaminants - microplastics (MPs): feasibility, mechanism, and future prospects. Chemosphere 331, 138776. doi:https://doi.org/10.1016/j.chemosphere.2023.138776.

Lian, J., Liu, W., Meng, L., Wu, J., Zeb, A., Cheng, L., Lian, Y., Sun, H., 2021. Effects of microplastics derived from polymer-coated fertilizer on maize growth, rhizosphere, and soil properties. J. Clean. Prod. 318, 128571 https://doi.org/10.1016/j.jclepro.2021.128571.

Liao, J., Chen, Q., 2021. Biodegradable plastics in the air and soil environment: low degradation rate and high microplastics formation. J. Hazard. Mater. 418, 126329 https://doi.org/10.1016/j.jhazmat. 2021.126329.

Liao, Z., Ji, X., Ma, Y., Lv, B., Huang, W., Zhu, X., Fang, M., Wang, Q., Wang, X., Dahlgren, R., Shang, X., 2021. Airborne microplastics in indoor and outdoor environments of a coastal city in eastern China. J. Hazard. Mater. 417, 126007 https://doi.org/10.1016/j.jhazmat.2021.126007.

Library of the Congress, n.d. China: Single-use Plastic Straw and Bag Ban Takes Effect [WWW Document]. Library of Congress, Washington, D.C. 20540 USA. URL https://www.loc.gov/item/global-legal-monitor/2021-03-23/china-single-use-plastic-straw-and-bag-ban-takes-effect/(accessed 6.30. 23).

Liu, X., Xu, J., Zhao, Y., Shi, H., Huang, C.-H., 2019. Hydrophobic sorption behaviors of 17β-estradiol on environmental microplastics. Chemosphere 226, 726–735. https://doi.org/10.1016/j.chemosphere.2019.03. 162.

Liu, K., Wang, X., Fang, T., Xu, P., Zhu, L., Li, D., 2019a. Source and potential risk assessment of suspended atmospheric microplastics in Shanghai. Sci. Total Environ. 675, 462–471. https://doi.org/10.1016/j.scitotenv.2019.04.110.

Liu, K., Wu, T., Wang, X., Song, Z., Zong, C., Wei, N., Li, D., 2019b. Consistent transport of terrestrial microplastics to the ocean through atmosphere. Environ. Sci. Technol. 53, 10612–10619. https://doi.org/10.1021/acs.est.9b03427.

Liu, S., Jin, R., Zhang, J., Zhao, Y., Shen, M., Wang, Y., 2023a. Are algae a promising ecofriendly approach to micro/nanoplastic remediation? Sci. Total Environ. 904, 166779 https://doi.org/10.1016/j.scitotenv.2023.166779.

Liu, H., Zhang, X., Ji, B., Qiang, Z., Karanfil, T., Liu, C., 2023b. UV aging of microplastic polymers promotes their chemical transformation and byproduct formation upon chlorination. Sci. Total Environ. 858, 159842 https://doi.org/10.1016/j.scitotenv.2022.159842.

Llorente-García, B.E., Hernández-López, J.M., Zaldívar-Cadena, A.A., Siligardi, C., Cedillo-González, E.I., 2020. First insights into photocatalytic degradation of HDPE and LDPE microplastics by a mesoporous N–TiO2 coating: effect of size and shape of microplastics. Coatings 10, 658. https://doi.org/10.3390/coatings10070658.

Long, M., Paul-Pont, I., Hégaret, H., Moriceau, B., Lambert, C., Huvet, A., Soudant, P., 2017. Interactions between polystyrene microplastics and marine phytoplankton lead to species-specific hetero-aggregation. Environ. Pollut. 228, 454–463. https://doi.org/10.1016/j.envpol.2017.05.047.

Lu, S., Liu, L., Yang, Q., Demissie, H., Jiao, R., An, G., Wang, D., 2021. Removal characteristics and mechanism of microplastics and tetracycline composite pollutants by coagulation process. Sci. Total Environ. 786, 147508 https://doi.org/10.1016/j.scitotenv.2021.147508.

Ma, B., Xue, W., Hu, C., Liu, H., Qu, J., Li, L., 2019. Characteristics of microplastic removal via coagulation and ultrafiltration during drinking water treatment. Chem. Eng. J. 359, 159–167. https://doi.org/10.1016/j.cej.2018.11.155.

Magni, S., Binelli, A., Pittura, L., Avio, C.G., Della Torre, C., Parenti, C.C., Gorbi, S., Regoli, F., 2019. The fate of microplastics in an Italian wastewater treatment plant. Sci. Total Environ. 652, 602–610. https://doi.org/10.1016/j.scitotenv.2018.10.269.

Magnusson, K., Norén, F., 2014. Screening of Microplastic Particles in and Down-stream a Waste-water Treatment Plant.

Malchiodi, B., Cedillo-González, E.I., Siligardi, C., Pozzi, P., 2022. A practical valorization approach for mitigating textile fibrous microplastics in the environment: collection of textile-processing waste microfibers and direct reuse in green thermal-insulating and mechanical-performing composite construction materials. Microplastics 1, 393–405. https://doi.org/10.3390/microplastics1030029.

Mani, T., Hauk, A., Walter, U., Burkhardt-Holm, P., 2015. Microplastics profile along the Rhine River. Sci. Rep. 5, 17988 https://doi.org/10.1038/srep17988.

Metzler, D., Simbeck, S., 2022. Global concern increases microplastics regulation [WWW document]. Haley Aldrich. URL https://www.haleyaldrich.com/resources/articles/microplastics-global-buzz-and-concern-spur-increased-regulation/ (accessed 6.30.23).

Miao, M., Liu, J., Dou, Y., Hao, H., Cheng, X., Zhang, M., Li, Y., 2022. Effects of microplastics on DBPs formation under the chlorination of natural organic matters. Chemosphere 296, 134067. https://doi.org/10.1016/j.chemosphere.2022.134067.

Ministério da Integração e do Desenvolvimento Regional, 2023. Água no mundo [WWW document]. Água no mundo - Agência Nacional de Águas e Saneamento Básico (ANA). URL https://www.gov.br/ana/pt-br/acesso-a-informacao/acoes-e-programas/cooperacao-internacional/agua-no-mundo/agua-no-mundo (accessed 6.29.23).

Mitrano, D.M., Bigalke, M., Booth, A.M., Carteny, C.C., Coffin, S., Egger, M., Gondikas, A., Hüffer, T., Koelmans, A.A., Lahive, E., Mattsson, K., Reynaud, S., Wagner, S., 2023. Training the next generation of plastics pollution researchers: tools, skills and career perspectives in an interdisciplinary and transdisciplinary field. Microplastics and Nanoplastics 3, 24. https://doi.org/10.1186/s43591-023-00072-4.

Montazer, Z., Habibi Najafi, M.B., Levin, D.B., 2019. Microbial degradation of low-density polyethylene and synthesis of polyhydroxyalkanoate polymers. Can. J. Microbiol. 65, 224–234. https://doi.org/10.1139/cjm-2018-0335.

Mossman, S., 2017. Early plastics: perspectives 1850-1950. In: Ferrum: Nachrichten Aus Der Eisenbibliothek. Stiftung der Georg Fischer AG.

Moyses, D.N., Teixeira, D.A., Waldow, V.A., Freire, D.M.G., Castro, A.M., 2021. Fungal and enzymatic bio-depolymerization of waste post-consumer poly(ethylene terephthalate) (PET) bottles using Penicillium species. 3 Biotech 11, 435. https://doi.org/10.1007/s13205-021-02988-1.

Mwanza, B.G., 2021. Introduction to recycling. In: Parameswaranpillai, J., Mavinkere Rangappa, S., Gulihonnehalli Rajkumar, A., Siengchin, S. (Eds.), Recent Developments in Plastic Recycling, Composites Science and Technology. Springer, Singapore, pp. 1–13. https://doi.org/10.1007/978-981-16-3627-1_1.

Nabi, I., Bacha, A.-U.-R., Li, K., Cheng, H., Wang, T., Liu, Y., Ajmal, S., Yang, Y., Feng, Y., Zhang, L., 2020. Complete photocatalytic mineralization of microplastic on TiO2 nanoparticle film. iScience 23. https://doi.org/10.1016/j.isci.2020.101326.

Nanthini Devi, K., Raju, P., Santhanam, P., Dinesh Kumar, S., Krishnaveni, N., Roopavathy, J., Perumal, P., 2021. Biodegradation of low-density polyethylene and polypropylene by microbes isolated from Vaigai River, Madurai, India. Arch. Microbiol. 203, 6253–6265. https://doi.org/10.1007/s00203-021-02592-0.

Napper, I.E., Thompson, R.C., 2016. Release of synthetic microplastic plastic fibres from domestic washing machines: effects of fabric type and washing conditions. Mar. Pollut. Bull. 112, 39–45. https://doi.org/10.1016/j.marpolbul.2016.09.025.

Neelavannan, K., Sen, I.S., Lone, A.M., Gopinath, K., 2022. Microplastics in the high-altitude Himalayas: assessment of microplastic contamination in freshwater lake sediments, northwest Himalaya (India). Chemosphere 290, 133354. https://doi.org/10.1016/j.chemosphere.2021.133354.

New Zeland Legislation, 2017. Waste Minimisation (Microbeads) Regulations 2017 (LI 2017/291) Contents–New Zealand Legislation.

Nguyen, L.H., Nguyen, B.-S., Le, D.-T., Alomar, T.S., AlMasoud, N., Ghotekar, S., Oza, R., Raizada, P., Singh, P., Nguyen, V.-H., 2023. A concept for the biotechnological minimizing of emerging plastics, micro- and nano-plastics pollutants from the environment: a review. Environ. Res. 216, 114342 https://doi.org/10.1016/j.envres.2022.114342.

Nohara, N.M.L., Filho, H.J.I., Alcântara, M.A.K. de, Oliveira, G.C.K. de, Junior, F.V., Nohara, E.L., Oliveira, K.A. de, Oliveira, M.F. de, 2022. Binary mixtures of ZnO/TiO2 for solar heterogeneous photocatalysis of non-purgeable organic carbon in landfill leachate. Research, Society and Development 11. https://doi.org/10.33448/rsd-v11i6.24570 (e48411624570–e48411624570).

Nohara, N.M.L., Filho, H.J.I., Siqueira, A.F., Aguiar, L.G. de, Oliveira, G.C.K. de, Nohara, E.L., Alcântara, M.A.K. de, Napoleão, D.A. dos S., 2023. Study of the effectiveness of a ZnO-TiO$_2$ formulation in the degradation of humic substances in mature leachate by solar photocatalysis Brazil. Rev. Ambient. Água 18, e2932. doi:https://doi.org/10.4136/ambi-agua.2932.

O'Brien, A.M., Lins, T.F., Yang, Y., Frederickson, M.E., Sinton, D., Rochman, C.M., 2022. Micro-plastics shift impacts of climate change on a plant-microbe mutualism: temperature, CO2, and tire wear particles. Environ. Res. 203, 111727 https://doi.org/10.1016/j.envres.2021.111727.

Oliani, P., Cedillo-González, E.I., 2021. Il Diario di Pelucco. Lo Spunk, il giornale delle bambine e dei bambini IV, 16.

Oliani, P., Cedillo-González, E.I., 2022a. Pelucco: Il Viaggio Della Microplastica, 1^{o}. ed. Amazon KDP. ISBN-13 979-8366393447 ↱ : .

Oliani, P., Cedillo-González, E.I., 2022b. Pelucco, the microplastic journey: a book that teaches children the wonders of plastic and the environmental impacts of microplastic pollution. In: Presented at the 7th International Marine Debris Conference, Busan, South Korea.

Oliani, P., Cedillo-González, E.I., 2022c. The Microplastics Journey: Teaching to the Youngest Minds the Wonders of Plastic and the Environmental Impact of Microplastic Pollution Through a Story for Children. Presented at the MICRO 2022 Online Atlas Edition, Lanzarore, Spain. https://doi.org/10.5281/zenodo.7216636.

Oliveira, A.C., Dantas Neto, A.A., Moura, M.C.P.A., Castro Dantas, T.N., 2023. Use of surfactant-modified adsorbents in the removal of microplastics from wastewater. J. Environ. Chem. Eng. 11, 110827 https://doi.org/10.1016/j.jece.2023.110827.

Omnexus, 2023. Density of plastics material: technical properties table [WWW document]. URL https://omnexus.specialchem.com/polymer-properties/properties/density (accessed 6.29.23).

Ortega, D.E., Cortés-Arriagada, D., 2023. Atmospheric microplastics and nanoplastics as vectors of primary air pollutants - a theoretical study on the polyethylene terephthalate (PET) case. Environ. Pollut. 318, 120860 https://doi.org/10.1016/j.envpol.2022.120860.

Ortiz, D., Munoz, M., Nieto-Sandoval, J., Romera-Castillo, C., de Pedro, Z.M., Casas, J.A., 2022. Insights into the degradation of microplastics by Fenton oxidation: from surface modification to mineralization. Chemosphere 309, 136809. https://doi.org/10.1016/j.chemosphere.2022.136809.

Panno, S.V., Kelly, W.R., Scott, J., Zheng, W., McNeish, R.E., Holm, N., Hoellein, T.J., Baranski, E.L., 2019. Microplastic contamination in karst groundwater systems. Groundwater 57, 189–196. https://doi.org/10.1111/gwat.12862.

Park, S.Y., Kim, C.G., 2019. Biodegradation of micro-polyethylene particles by bacterial colonization of a mixed microbial consortium isolated from a landfill site. Chemosphere 222, 527–533. https://doi.org/10.1016/j.chemosphere.2019.01.159.

Park, J.W., Lee, S.J., Hwang, D.Y., Seo, S., 2021. Removal of microplastics via tannic acid-mediated coagulation and in vitro impact assessment. RSC Adv. 11, 3556–3566. https://doi.org/10.1039/D0RA09645H.

Peller, J., Nevers, M.B., Byappanahalli, M., Nelson, C., Ganesh Babu, B., Evans, M.A., Kostelnik, E., Keller, M., Johnston, J., Shidler, S., 2021. Sequestration of microfibers and other microplastics by green algae, Cladophora, in the US Great Lakes. Environ. Pollut. 276, 116695 https://doi.org/10.1016/j. envpol.2021.116695.

Peng, B.-Y., Chen, Z., Chen, J., Yu, H., Zhou, X., Criddle, C.S., Wu, W.-M., Zhang, Y., 2020. Biodegradation of polyvinyl chloride (PVC) in Tenebrio molitor (Coleoptera: Tenebrionidae) larvae. Environ. Int. 145, 106106 https://doi.org/10.1016/j.envint.2020.106106.

Peng, G., Xiang, M., Wang, W., Su, Z., Liu, H., Mao, Y., Chen, Y., Zhang, P., 2022. Engineering 3D graphene-like carbon-assembled layered double oxide for efficient microplastic removal in a wide pH range. J. Hazard. Mater. 433, 128672 https://doi.org/10.1016/j.jhazmat.2022.128672.

Peng, B.-Y., Sun, Y., Li, P., Yu, S., Xu, Y., Chen, J., Zhou, X., Wu, W.-M., Zhang, Y., 2023. Bio- degradation of polyvinyl chloride, polystyrene, and polylactic acid microplastics in Tenebrio molitor larvae: physiological responses. J. Environ. Manag. 345, 118818 https://doi.org/10.1016/j. jenvman.2023.118818.

Periyasamy, A.P., 2021. Evaluation of microfiber release from jeans: the impact of different washing conditions. Environ. Sci. Pollut. Res. 28, 58570–58582. https://doi.org/10.1007/s11356-021-14761-1.

Piazza, V., Uheida, A., Gambardella, C., Garaventa, F., Faimali, M., Dutta, J., 2022. Ecosafety screening of photo-Fenton process for the degradation of microplastics in water. Front. Mar. Sci. 8.

Pramanik, B.K., Pramanik, S.K., Monira, S., 2021. Understanding the fragmentation of microplastics into nano-plastics and removal of nano/microplastics from wastewater using membrane, air flotation and nano-ferrofluid processes. Chemosphere 282, 131053. https://doi.org/10.1016/j.chemosphere.2021.131053.

Prata, J.C., Castro, J.L., Costa, J.P. da, Duarte, A.C., Cerqueira, M., Rocha-Santos, T., 2020. An easy method for processing and identification of natural and synthetic microfibers and microplastics in indoor and outdoor air. Methods X 7. doi:https://doi.org/10.1016/j.mex.2019.11.032.

Prüst, M., Meijer, J., Westerink, R.H.S., 2020. The plastic brain: neurotoxicity of micro- and nano-plastics. Part. Fibre Toxicol. 17, 24. https://doi.org/10.1186/s12989-020-00358-y.

Puckowski, A., Cwięk, W., Mioduszewska, K., Stepnowski, P., Białk-Bielińska, A., 2021. Sorption of pharmaceuticals on the surface of microplastics. Chemosphere 263, 127976. https://doi.org/10.1016/j.chemo- sphere.2020.127976.

Qi, H., Li, H., Meng, X., Peng, L., Zheng, H., Wang, L., Wang, W., Chen, K., Zhang, J., Zhang, H., Cai, M., 2022. Fate of microplastics in deep-sea sediments and its influencing factors: evidence from the eastern Indian Ocean. Sci. Total Environ. 828, 154266 https://doi.org/10.1016/j.scitotenv. 2022.154266.

Qin, J., Dou, Y., Wu, F., Yao, Y., Andersen, H.R., Hélix-Nielsen, C., Lim, S.Y., Zhang, W., 2022. In-situ formation of Ag2O in metal-organic framework for light-driven upcycling of microplastics coupled with hydrogen production. Appl. Catal. B Environ. 319, 121940 https://doi.org/10.1016/j.apcatb. 2022.121940.

Qiu, Y., Zhou, S., Qin, W., Zhang, C., Lv, C., Zou, M., 2023. Effects of land use on the distribution of soil microplastics in the Lihe River watershed, China. Chemosphere 324, 138292. https://doi.org/10.1016/j. chemosphere.2023.138292.

quill-letter-l11195-epa-microplastic-actions-version-3-05-12-2023-09-36-am, n.d.

Raab, P., Bogner, F.X., 2020. Microplastics in the environment: raising awareness in primary education. Am. Biol. Teach. 82, 478–487. https://doi.org/10.1525/abt.2020.82.7.478.

Ragusa, A., Svelato, A., Santacroce, C., Catalano, P., Notarstefano, V., Carnevali, O., Papa, F., Rongioletti, M.C.A., Baiocco, F., Draghi, S., D'Amore, E., Rinaldo, D., Matta, M., Giorgini, E., 2021. Plasticenta: first evidence of microplastics in human placenta. Environ. Int. 146, 106274 https://doi.org/10.1016/j.envint.2020.106274.

Ragusa, A., Notarstefano, V., Svelato, A., Belloni, A., Gioacchini, G., Blondeel, C., Zucchelli, E., De Luca, C., D'Avino, S., Gulotta, A., Carnevali, O., Giorgini, E., 2022. Raman microspectroscopy detection and characterisation of microplastics in human breastmilk. Polymers 14, 2700. https://doi.org/10.3390/polym14132700.

Rasmussen, S.C., 2018. Revisiting the early history of synthetic polymers: critiques and new insights. Ambix 65, 356–372. https://doi.org/10.1080/00026980.2018.1512775.

Ray, S.S., Lee, H.K., Huyen, D.T.T., Chen, S.-S., Kwon, Y.-N., 2022. Microplastics waste in environment: a perspective on recycling issues from PPE kits and face masks during the COVID-19 pandemic. Environ. Technol. Innov. 26, 102290 https://doi.org/10.1016/j.eti.2022.102290.

Rehm, R., Zeyer, T., Schmidt, A., Fiener, P., 2021. Soil erosion as transport pathway of microplastic from agriculture soils to aquatic ecosystems. Sci. Total Environ. 795, 148774 https://doi.org/10.1016/j.scitotenv.2021.148774.

Ren, S., Xu, X., Zhu, Z.-S., Yang, Y., Tian, W., Hu, K., Zhong, S., Yi, J., Duan, X., Wang, S., 2024. Catalytic transformation of microplastics to functional carbon for catalytic peroxymonosulfate activation: conversion mechanism and defect of scavenging. Appl. Catal. B Environ. 342, 123410 https://doi.org/10.1016/j.apcatb.2023.123410.

Rethink Plastic Alliance, 2023. Open Letter From Microplastic-free Brands.

Ricardo, I.A., Alberto, E.A., Silva Júnior, A.H., Macuvele, D.L.P., Padoin, N., Soares, C., Gracher Riella, H., Starling, M.C.V.M., Trovó, A.G., 2021. A critical review on microplastics, interaction with organic and inorganic pollutants, impacts and effectiveness of advanced oxidation processes applied for their removal from aqueous matrices. Chem. Eng. J. 424, 130282 https://doi.org/10.1016/j.cej.2021.130282.

Rojas-Guerrero, C.A., Villanueva-Rodríguez, M., Guzmán-Mar, J.L., Hernández-Ramírez, A., Cedillo-González, E.I., Longoria Rodríguez, F.E., Hinojosa-Reyes, L., 2023. Solar photocatalytic degradation of polyethylene terephthalate nanoplastics: evaluation of the applicability of the TiO2/MIL-100(Fe) composite material. J. Environ. Chem. Eng. 11, 110415 https://doi.org/10.1016/j.jece. 2023.110415.

Rolsky, C., Kelkar, V., Driver, E., Halden, R.U., 2020. Municipal sewage sludge as a source of microplastics in the environment. Current Opinion in Environmental Science & Health, Environmental Pollution: Biosolids 14, 16–22. https://doi.org/10.1016/j.coesh.2019.12.001.

Royer, S.-J., Ferrón, S., Wilson, S.T., Karl, D.M., 2018. Production of methane and ethylene from plastic in the environment. PLoS One 13, e0200574. https://doi.org/10.1371/journal.pone.0200574.

Sanchez, W., Bender, C., Porcher, J.-M., 2014. Wild gudgeons (Gobio gobio) from French rivers are contaminated by microplastics: preliminary study and first evidence. Environ. Res. 128, 98–100. https://doi.org/10.1016/j.envres.2013.11.004.

SAPEA, Science Advice for Policy by European Academies, 2019. A Scientific Perspective on Microplastics in Nature and Society (No. version 2019.1.1). SAPEA, Berlin.

Sembiring, E., Fajar, M., Handajani, M., 2021. Performance of rapid sand filter – single media to remove microplastics. Water Supply 21, 2273–2284. https://doi.org/10.2166/ws.2021.060.

Senathirajah, K., Kandaiah, R., Panneerselvan, L., Sathish, C.I., Palanisami, T., 2023. Fate and transformation of microplastics due to electrocoagulation treatment: impacts of polymer type and shape. Environ. Pollut. 334, 122159 https://doi.org/10.1016/j.envpol.2023.122159.

Sharma, S., Basu, S., Shetti, N.P., Nadagouda, M.N., Aminabhavi, T.M., 2021. Microplastics in the environment: occurrence, perils, and eradication. Chem. Eng. J. 408, 127317 https://doi.org/10.1016/j.cej.2020.127317.

Sharma, S., Sharma, V., Chatterjee, S., 2023. Contribution of plastic and microplastic to global climate change and their conjoining impacts on the environment - a review. Sci. Total Environ. 875, 162627 https://doi.org/10.1016/j.scitotenv.2023.162627.

Shekhar, A.R., Kumar, A., Syamsai, R., Cai, X., Pol, V.G., 2022. Is the plastic pandemic a greater threat to humankind than COVID-19? ACS Sustain. Chem. Eng. 10, 3150–3154. https://doi.org/10.1021/acssuschemeng.1c08468.

Shen, M., Zhang, Y., Almatrafi, E., Hu, T., Zhou, C., Song, B., Zeng, Z., Zeng, G., 2022. Efficient removal of microplastics from wastewater by an electrocoagulation process. Chem. Eng. J. 428, 131161 https://doi.org/10.1016/j.cej.2021.131161.

Simon, M., Vianello, A., Vollertsen, J., 2019. Removal of >10 μm microplastic particles from treated wastewater by a disc filter. Water 11, 1935. https://doi.org/10.3390/w11091935.

Sipe, J.M., Bossa, N., Berger, W., von Windheim, N., Gall, K., Wiesner, M.R., 2022. From bottle to microplastics: can we estimate how our plastic products are breaking down? Sci. Total Environ. 814, 152460 https://doi.org/10.1016/j.scitotenv.2021.152460.

So, W.K., Chan, K., Not, C., 2018. Abundance of plastic microbeads in Hong Kong coastal water. Mar. Pollut. Bull. 133, 500–505. https://doi.org/10.1016/j.marpolbul.2018.05.066.

Song, B., Hall, P., 2020. Densification of biomass and waste plastic blends as a solid fuel: hazards, advantages, and perspectives. Frontiers in Energy Research 8.

Song, X., Wu, X., Song, X., Shi, C., Zhang, Z., 2021. Sorption and desorption of petroleum hydrocarbons on biodegradable and nondegradable microplastics. Chemosphere 273, 128553. https://doi.org/10.1016/j.chemosphere.2020.128553.

Song, X., Zhuang, W., Cui, H., Liu, M., Gao, T., Li, A., Gao, Z., 2022. Interactions of microplastics with organic, inorganic and bio-pollutants and the ecotoxicological effects on terrestrial and aquatic organisms. Sci. Total Environ. 838, 156068 https://doi.org/10.1016/j.scitotenv.2022.156068.

Spina, F., Tummino, M.L., Poli, A., Prigione, V., Ilieva, V., Cocconcelli, P., Puglisi, E., Bracco, P., Zanetti, M., Varese, G.C., 2021. Low density polyethylene degradation by filamentous fungi. Environ. Pollut. 274, 116548 https://doi.org/10.1016/j.envpol.2021.116548.

STATE WATER RESOURCES CONTROL BOARD RESOLUTION NO. 2022-0032, n.d.

Strady, E., Kieu-Le, T.-C., Gasperi, J., Tassin, B., 2020. Temporal dynamic of anthropogenic fibers in a tropical river-estuarine system. Environ. Pollut. 259, 113897 https://doi.org/10.1016/j.envpol.2019.113 897.

Su, L., Xiong, X., Zhang, Y., Wu, C., Xu, X., Sun, C., Shi, H., 2022. Global transportation of plastics and microplastics: a critical review of pathways and influences. Sci. Total Environ. 831, 154884 https://doi.org/10.1016/j.scitotenv.2022.154884.

Sun, C., Wang, Z., Chen, L., Li, F., 2020. Fabrication of robust and compressive chitin and graphene oxide sponges for removal of microplastics with different functional groups. Chem. Eng. J. 393, 124796 https://doi.org/10.1016/j.cej.2020.124796.

Swart, B., Pihlajamäki, A., John Chew, Y.M., Wenk, J., 2022. Microbubble-microplastic interactions in batch air flotation. Chem. Eng. J. 449, 137866 https://doi.org/10.1016/j.cej.2022.137866.

Ta, A.T., Babel, S., 2023. Occurrence and spatial distribution of microplastic contaminated with heavy metals in a tropical river: effect of land use and population density. Mar. Pollut. Bull. 191, 114919 https://doi.org/10.1016/j.marpolbul.2023.114919.

Tanis-Kanbur, M.B., Tamilselvam, N.R., Lai, H.Y., Chew, J.W., 2022. Impact of particle shape and surface group on membrane fouling. Membranes 12, 403. https://doi.org/10.3390/membranes12040403.

Tareen, A., Saeed, S., Iqbal, A., Batool, R., Jamil, N., 2022. Biodeterioration of microplastics: a promising step towards plastics waste management. Polymers 14, 2275. https://doi.org/10.3390/polym1411 2275.

The State Council, The People's Republic of China, 2020. China reveals plan to cut plastic use by 2025 [WWW Document]. URL http://english.www.gov.cn/statecouncil/ministries/202001/19/content_WS5e243ea1c6d0db64b784ccd1.html (accessed 6.30.23).

Tofa, T.S., Kunjali, K.L., Paul, S., Dutta, J., 2019a. Visible light photocatalytic degradation of microplastic residues with zinc oxide nanorods. Environ. Chem. Lett. 17, 1341–1346. https://doi.org/10.1007/s 10311-019-00859-z.

Tofa, T.S., Ye, F., Kunjali, K.L., Dutta, J., 2019b. Enhanced visible light photodegradation of microplastic fragments with Plasmonic platinum/zinc oxide nanorod photocatalysts. Catalysts 9, 819. https://doi.org/10.3390/catal9100819.

Torres, F.G., Dioses-Salinas, D.C., Pizarro-Ortega, C.I., De-la-Torre, G.E., 2021. Sorption of chemical contaminants on degradable and non-degradable microplastics: recent progress and research trends. Sci. Total Environ. 757, 143875 https://doi.org/10.1016/j.scitotenv.2020.143875.

Uekert, T., Kasap, H., Reisner, E., 2019. Photoreforming of nonrecyclable plastic waste over a carbon nitride/nickel phosphide catalyst. J. Am. Chem. Soc. 141, 15201–15210. https://doi.org/10.1021/jacs. 9b06872.

Uheida, A., Mejía, H.G., Abdel-Rehim, M., Hamd, W., Dutta, J., 2021. Visible light photocatalytic degradation of polypropylene microplastics in a continuous water flow system. J. Hazard. Mater. 406, 124299 https://doi.org/10.1016/j.jhazmat.2020.124299.

UK Department for Environment, Food & Rural Affairs, The Rt Hon Michael Gove, 2018. World leading microbeads ban comes into force [WWW document]. GOV.UK. URL https://www.gov.uk/government/news/world-leading-microbeads-ban-comes-into-force (accessed 6.30.23).

United Nations Environment Assembly of the United Nations Environment Programme, 2022. Resolution adopted by the United Nations Environment Assembly on 2 March 2022.

United Nations Environment Assembly of the United Nations Environment Programme, 2023. Turning Off the Tap. How the World Can End Plastic Pollution and Create a Circular Economy. Nairobi.

United Nations Environment Programme (UNEP), 2018. Plastic planet: how tiny plastic particles are polluting our soil [WWW document]. UNEP. URL http://www.unep.org/news-and-stories/story/plastic-planet-how-tiny-plastic-particles-are-polluting-our-soil (accessed 6.29.23).

United Nations Environment Programme (UNEP), 2023. Everything you need to know About plastic pollution [WWW document]. UNEP-Everything you need to know about plastic pollution. URL http://www.unep.org/news-and-stories/story/everything-you-need-know-about-plastic-pollution (accessed 6.29.23).

United States of America 114th Congress, 2015. PUBLIC LAW 114–114—DEC. 28, 2015.

Uogintė, I., Pleskytė, S., Skapas, M., Stanionytė, S., Lujanienė, G., 2023. Degradation and optimization of microplastic in aqueous solutions with graphene oxide-based nanomaterials. Int. J. Environ. Sci. Technol. 20, 9693–9706. https://doi.org/10.1007/s13762-022-04657-z.

Upadhyay, R., Singh, S., Kaur, G., 2022. Sorption of pharmaceuticals over microplastics' surfaces: interaction mechanisms and governing factors. Environ. Monit. Assess. 194, 803. https://doi.org/10.1007/s10661-022-10475-0.

Van Cauwenberghe, L., Janssen, C.R., 2014. Microplastics in bivalves cultured for human consumption. Environ. Pollut. 193, 65–70. https://doi.org/10.1016/j.envpol.2014.06.010.

Vethaak, A.D., Legler, J., 2021. Microplastics and human health. Science 371, 672–674. https://doi.org/10.1126/science.abe5041.

Vital-Grappin, A.D., Ariza-Tarazona, M.C., Luna-Hernández, V.M., Villarreal-Chiu, J.F., Hernández-López, J.M., Siligardi, C., Cedillo-González, E.I., 2021. The role of the reactive species involved in the photocatalytic degradation of HDPE microplastics using C,N-TiO2 powders. Polymers 13, 999. https://doi.org/10.3390/polym13070999.

Volkheimer, G., 1975. Hematogenous dissemination of ingested polyvinyl chloride particles. Ann. N. Y. Acad. Sci. 246, 164–171. https://doi.org/10.1111/j.1749-6632.1975.tb51092.x.

Wan, Y., Chen, X., Liu, Q., Hu, H., Wu, C., Xue, Q., 2022a. Informal landfill contributes to the pollution of microplastics in the surrounding environment. Environ. Pollut. 293, 118586 https://doi.org/10.1016/j. envpol.2021.118586.

Wan, H., Wang, J., Sheng, X., Yan, J., Zhang, W., Xu, Y., 2022b. Removal of polystyrene microplastics from aqueous solution using the metal–organic framework material of ZIF-67. Toxics 10, 70. https://doi.org/10.3390/toxics10020070.

Wang, T., Yu, C., Chu, Q., Wang, F., Lan, T., Wang, J., 2020. Adsorption behavior and mechanism of five pesticides on microplastics from agricultural polyethylene films. Chemosphere 244, 125491. https://doi.org/10.1016/j.chemosphere.2019.125491.

Wang, L.-C., Lin, J.C.-T., Dong, C.-D., Chen, C.-W., Liu, T.-K., 2021a. The sorption of persistent organic pollutants in microplastics from the coastal environment. J. Hazard. Mater. 420, 126658 https://doi.org/10.1016/j.jhazmat.2021.126658.

Wang, J., Sun, C., Huang, Q.-X., Chi, Y., Yan, J.-H., 2021b. Adsorption and thermal degradation of microplastics from aqueous solutions by Mg/Zn modified magnetic biochars. J. Hazard. Mater. 419, 126486 https://doi.org/10.1016/j.jhazmat.2021.126486.

Wang, C., Zhao, J., Xing, B., 2021c. Environmental source, fate, and toxicity of microplastics. J. Hazard. Mater. 407, 124357 https://doi.org/10.1016/j.jhazmat.2020.124357.

Wang, W., Zhang, J., Qiu, Z., Cui, Z., Li, N., Li, X., Wang, Y., Zhang, H., Zhao, C., 2022. Effects of polyethylene microplastics on cell membranes: a combined study of experiments and molecular dynamics simulations. J. Hazard. Mater. 429, 128323 https://doi.org/10.1016/j.jhazmat.2022. 128323.

Wang, C., Liang, S., Bai, L., Gu, X., Jin, X., Ok, Y.S., Gu, C., 2023. Photoaging of typical micro-plastics as affected by air humidity: mechanistic insights into the important role of water molecules. Environ. Sci. Technol. 57, 5967–5977. https://doi.org/10.1021/acs.est.2c08571.

Wesch, C., Elert, A.M., Wörner, M., Braun, U., Klein, R., Paulus, M., 2017. Assuring quality in microplastic monitoring: about the value of clean-air devices as essentials for verified data. Sci. Rep. 7, 5424. https://doi.org/10.1038/s41598-017-05838-4.

Williams, J.O., Osahon, N.T., 2021. Assessment of microplastic degrading potential of fungal isolates from an estuary in Rivers State, Nigeria. SAJRM 11–19. https://doi.org/10.9734/sajrm/2021/v9i230204.

Willis, B., Fytianos, G., 2022. Towards microplastic reduction within institutions. Water Air Soil Pollut. 233, 337. https://doi.org/10.1007/s11270-022-05790-8.

Wright, S.L., Kelly, F.J., 2017. Plastic and human health: a micro issue? Environ. Sci. Technol. 51, 6634–6647. https://doi.org/10.1021/acs.est.7b00423.

Wright, S.L., Rowe, D., Thompson, R.C., Galloway, T.S., 2013. Microplastic ingestion decreases energy reserves in marine worms. Curr. Biol. 23, R1031–R1033. https://doi.org/10.1016/j.cub.2013.10.068.

Wu, P., Cai, Z., Jin, H., Tang, Y., 2019. Adsorption mechanisms of five bisphenol analogues on PVC microplastics. Sci. Total Environ. 650, 671–678. https://doi.org/10.1016/j.scitotenv.2018.09.049.

Wu, X., Zhao, X., Chen, R., Liu, P., Liang, W., Wang, J., Teng, M., Wang, X., Gao, S., 2022. Waste-water treatment plants act as essential sources of microplastic formation in aquatic environments: a critical review. Water Res. 221, 118825 https://doi.org/10.1016/j.watres.2022.118825.

Xia, Y., Xiang, X.-M., Dong, K.-Y., Gong, Y.-Y., Li, Z.-J., 2020. Surfactant stealth effect of micro- plastics in traditional coagulation process observed via 3-D fluorescence imaging. Sci. Total Environ. 729, 138783 https://doi.org/10.1016/j.scitotenv.2020.138783.

Xu, B., Liu, F., Cryder, Z., Huang, D., Lu, Zhijiang, He, Y., Wang, H., Lu, Zhenmei, Brookes, P.C., Tang, C., Gan, J., Xu, J., 2020. Microplastics in the soil environment: occurrence, risks, interactions and fate – a review. Crit. Rev. Environ. Sci. Technol. 50, 2175–2222. https://doi.org/10.1080/10643389.2019.1694822.

Xu, J.-L., Lin, X., Wang, J.J., Gowen, A.A., 2022. A review of potential human health impacts of micro- and nanoplastics exposure. Sci. Total Environ. 851, 158111 https://doi.org/10.1016/j. scitotenv.2022.158111.

Xue, J., Peldszus, S., Van Dyke, M.I., Huck, P.M., 2021. Removal of polystyrene microplastic spheres by alum-based coagulation-flocculation-sedimentation (CFS) treatment of surface waters. Chem. Eng. J. 422, 130023 https://doi.org/10.1016/j.cej.2021.130023.

Xue, W., Maung, G.Y.T., Otiti, J., Tabucanon, A.S., 2023. Land use-based characterization and source apportionment of microplastics in urban storm runoffs in a tropical region. Environ. Pollut. 329, 121698 https://doi.org/10.1016/j.envpol.2023.121698.

Ya, H., Jiang, B., Xing, Y., Zhang, T., Lv, M., Wang, X., 2021. Recent advances on ecological effects of microplastics on soil environment. Sci. Total Environ. 798, 149338 https://doi.org/10.1016/j. scitotenv.2021.149338.

Yang, X., Zhang, Z., Zhang, J., 2023. Study of soil microplastic pollution and influencing factors based on environmental fragility theory. Sci. Total Environ. 899, 165435 https://doi.org/10.1016/j. scitotenv.2023.165435.

Yao, J., Peng, Z., Chen, W., Lin, Q., Cheng, M., Li, H., Yang, Y., Yang, H.Y., 2023. Surface characteristics of polystyrene microplastics mainly determine their coagulation performances. Mar. Pollut. Bull. 186, 114347 https://doi.org/10.1016/j.marpolbul.2022.114347.

Ye, S., Pei, D., 2023. Relationships between microplastic pollution and land use in the Chongqing section of the Yangtze River. Front. Ecol. Evol. 11.

Yee, M.S.-L., Hii, L.-W., Looi, C.K., Lim, W.-M., Wong, S.-F., Kok, Y.-Y., Tan, B.-K., Wong, C.-Y., Leong, C.-O., 2021. Impact of microplastics and nanoplastics on human health. Nanomaterials 11, 496. https://doi.org/10.3390/nano11020496.

Yong, C.Q.Y., Valiyaveettil, S., Tang, B.L., 2020. Toxicity of microplastics and Nanoplastics in mammalian systems. Int. J. Environ. Res. Public Health 17, 1509. https://doi.org/10.3390/ijerph17051509.

Yousef, S., Eimontas, J., Zakarauskas, K., Striūgas, N., Mohamed, A., 2021. A new strategy for using lint-microfibers generated from clothes dryer as a sustainable source of renewable energy. Sci. Total Environ. 762, 143107 https://doi.org/10.1016/j.scitotenv.2020.143107.

Yuan, J., Ma, J., Sun, Y., Zhou, T., Zhao, Y., Yu, F., 2020. Microbial degradation and other environmental aspects of microplastics/plastics. Sci. Total Environ. 715, 136968 https://doi.org/10.1016/j.scitotenv.2020.136968.

Yuan, J., Cao, J., Yu, F., Ma, J., 2022a. Microbial degradation of polystyrene microplastics by a novel isolated bacterium in aquatic ecosystem. Sustain. Chem. Pharm. 30, 100873 https://doi.org/10.1016/j.scp.2022.100873.

Yuan, F., Li, X., Yu, W., Du, J., Wang, D., Yang, X., Zhou, C., Wang, J., Yuan, H., 2022b. A high-efficiency mini-hydrocyclone for microplastic separation from water via air flotation. Journal of Water Process Engineering 49, 103084. https://doi.org/10.1016/j.jwpe.2022.103084.

Yurtsever, M., 2019a. Glitters as a source of primary microplastics: an approach to environmental responsibility and ethics. J. Agric. Environ. Ethics 32, 459–478. https://doi.org/10.1007/s10806-019-09785-0.

Yurtsever, M., 2019b. Tiny, shiny, and colorful microplastics: are regular glitters a significant source of microplastics? Mar. Pollut. Bull. 146, 678–682. https://doi.org/10.1016/j.marpolbul.2019.07.009.

Zaken, M. van B., 2023. Non-paper: call for ambitious EU measures to reduce and prevent microplastics pollution - publication-The Netherlands at International Organisations [WWW document]. URL https://www.permanentrepresentations.nl/documents/publications/2023/05/02/non-paper—call-for-ambitious-eu-measures-to-reduce-and-prevent-microplastics-pollution (accessed 6.30.23).

Zha, F., Dai, J., Han, Y., Liu, P., Wang, M., Liu, H., Guo, X., 2023. Release of millions of micro (nano)plastic fragments from photooxidation of disposable plastic boxes. Sci. Total Environ. 858, 160044 https://doi.org/10.1016/j.scitotenv.2022.160044.

Zhang, Y., Gao, T., Kang, S., Sillanpää, M., 2019. Importance of atmospheric transport for microplastics deposited in remote areas. Environ. Pollut. 254, 112953 https://doi.org/10.1016/j. envpol.2019.07.121.

Zhang, J., Gao, D., Li, Q., Zhao, Yixuan, Li, L., Lin, H., Bi, Q., Zhao, Yucheng, 2020a. Biodegradation of polyethylene microplastic particles by the fungus Aspergillus flavus from the guts of wax moth Galleria mellonella. Sci. Total Environ. 704, 135931 https://doi.org/10.1016/j.scitotenv.2019. 135931.

Zhang, Y., Kang, S., Allen, S., Allen, D., Gao, T., Sillanpää, M., 2020b. Atmospheric microplastics: a review on current status and perspectives. Earth Sci. Rev. 203, 103118 https://doi.org/10.1016/j. earscirev.2020.103118.

Zhang, Yingshuang, Jiang, H., Bian, K., Wang, H., Wang, C., 2021. Is froth flotation a potential scheme for microplastics removal? Analysis on flotation kinetics and surface characteristics. Sci. Total Environ. 792, 148345 https://doi.org/10.1016/j.scitotenv.2021.148345.

Zhang, Y., Zhao, J., Liu, Z., Tian, S., Lu, J., Mu, R., Yuan, H., 2021a. Coagulation removal of microplastics from wastewater by magnetic magnesium hydroxide and PAM. Journal of Water Process Engineering 43, 102250. https://doi.org/10.1016/j.jwpe.2021.102250.

Zhang, Y., Zhou, G., Yue, J., Xing, X., Yang, Z., Wang, X., Wang, Q., Zhang, J., 2021b. Enhanced removal of polyethylene terephthalate microplastics through polyaluminum chloride coagulation with three typical coagulant aids. Sci. Total Environ. 800, 149589 https://doi.org/10.1016/j.scitotenv. 2021.149589.

Zhang, Y., Jiang, H., Bian, K., Wang, H., Wang, C., 2022a. Flotation separation of hazardous polyvinyl chloride towards source control of microplastics based on selective hydrophilization of plasticizer-doping surfaces. J. Hazard. Mater. 423, 127095 https://doi.org/10.1016/j.jhazmat.2021.127095.

Zhang, X., Li, H.-N., Zhu, C.-Y., Huang, X.-J., Greiner, A., Xu, Z.-K., 2022b. Biomimetic gill-inspired membranes with direct-through micropores for water remediation by efficiently removing microplastic particles. Chem. Eng. J. 434, 134758 https://doi.org/10.1016/j.cej.2022.134758.

Zhang, Y.-L., Wang, W.-L., Lee, M.-Y., Yang, Z.-W., Wu, Q.-Y., Huang, N., Hu, H.-Y., 2022c. Promotive effects of vacuum-UV/UV (185/254 nm) light on elimination of recalcitrant trace organic contaminants by UV-AOPs during wastewater treatment and reclamation: a review. Sci. Total Environ. 818, 151776 https://doi.org/10.1016/j.scitotenv.2021.151776.

Zhang, A., Hou, Y., Wang, Y., Wang, Q., Shan, X., Liu, J., 2023a. Highly efficient low-temperature biodegradation of polyethylene microplastics by using cold-active laccase cell-surface display system. Bioresour. Technol. 382, 129164 https://doi.org/10.1016/j.biortech.2023.129164.

Zhang, M., Zheng, Y., Li, J., Liu, K., Wang, H., Gu, H., Zhang, Z., Guo, X., 2023b. Distribution characteristics of microplastics in soil of Loess Plateau in Northwest China and their relationship with land use type. Sci. Total Environ. 868, 161674 https://doi.org/10.1016/j.scitotenv.2023.161674.

Zhao, H., Huang, X., Wang, L., Zhao, X., Yan, F., Yang, Y., Li, G., Gao, P., Ji, P., 2022. Removal of polystyrene nanoplastics from aqueous solutions using a novel magnetic material: adsorbability, mechanism, and reusability. Chem. Eng. J. 430, 133122 https://doi.org/10.1016/j.cej.2021.13 3122.

Zheng, B., Li, B., Wan, H., Lin, X., Cai, Y., 2022. Coral-inspired environmental durability aerogels for micron-size plastic particles removal in the aquatic environment. J. Hazard. Mater. 431, 128611 https://doi.org/10.1016/j.jhazmat.2022.128611.

Zhong, Y., Zhang, B., Zhu, Z., Wang, G., Mei, X., Fang, Y., Lu, W., 2023. Photocatalytic-driven self-degradation of polyester microplastics under solar light. J. Polym. Environ. 31, 2415–2423. https://doi.org/10.1007/s10924-023-02763-8.

Zhong, Y., Zhuo, L., Lu, W., 2024. Analysis of photocatalytic degradation of polyamide microplastics in metal salt solution by high resolution mass spectrometry. J. Environ. Sci. 139, 473–482. https://doi.org/10.1016/j.jes.2023.06.018.

Zhou, Q., Zhang, H., Fu, C., Zhou, Y., Dai, Z., Li, Y., Tu, C., Luo, Y., 2018. The distribution and morphology of microplastics in coastal soils adjacent to the Bohai Sea and the Yellow Sea. Geoderma 322, 201–208. https://doi.org/10.1016/j.geoderma.2018.02.015.

Zhou, H., Mayorga-Martinez, C.C., Pumera, M., 2021a. Microplastic removal and degradation by mussel-inspired adhesive magnetic/enzymatic microrobots. Small Methods 5, 2100230. https://doi.org/10.1002/smtd.202100230.

Zhou, G., Wang, Q., Li, J., Li, Q., Xu, H., Ye, Q., Wang, Y., Shu, S., Zhang, J., 2021b. Removal of polystyrene and polyethylene microplastics using PAC and FeCl3 coagulation: performance and mechanism. Sci. Total Environ. 752, 141837 https://doi.org/10.1016/j.scitotenv.2020.141837.

Zhou, D., Luo, H., Zhang, F., Wu, J., Yang, J., Wang, H., 2022. Efficient photocatalytic degradation of the persistent PET fiber-based microplastics over Pt nanoparticles decorated N-doped TiO2 nanoflowers. Adv. Fiber Mater. 4, 1094–1107. https://doi.org/10.1007/s42765-022-00149-4.

Zhu, F., Zhu, C., Wang, C., Gu, C., 2019. Occurrence and ecological impacts of microplastics in soil systems: a review. Bull. Environ. Contam. Toxicol. 102, 741–749. https://doi.org/10.1007/s00128-019-02623-z.

Zhu, L., Zhu, J., Zuo, R., Xu, Q., Qian, Y., An, L., 2023. Identification of microplastics in human placenta using laser direct infrared spectroscopy. Sci. Total Environ. 856, 159060 https://doi.org/10.1016/j.scitotenv.2022.159060.