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Microplastic sources, reduction and remediation: current state and future trends

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ABSTRACT

Plastic waste (PW) and microplastics (MPs) pollution represent one of the main ecological challenges and thus attract society's increasing attention. The exponential growth of plastics' presence and its small (1 µm – 5 mm) particles (MPs) in the environment and inhabiting species is a consequence of linear economy employment. The circular economy has been proposed as the promising route to using plastics more sustainably, and its implementation in the plastic management system is imposed to reduce MPs release. As MPs are emitted in all phases of the plastic life cycle, actions at all levels of the value chain are necessary. Prioritizing the entire plastic value chain also became the goal of more recent plastic pollution regulations, contrary to the previous ones, primarily prohibiting particular plastic items. The microplastic minimization strategy follows an upside-down pyramid, beginning with prevention, then reducing, reusing, recycling, recovering, and finally disposal, which is the least desired alternative. New technologies development for synthetic polymer production and remediation technologies innovations are another key component of the circular economy model. This study outlines microplastics' primary and secondary sources, summarizes the current methods for MPs elimination from different media along with their benefits and drawbacks, and highlights the importance of circular economy principles employment to minimize the MPs' pollution and their possible environmental repercussions.

Keywords: pollution, circular economy, polymers, treatment.

1. Introduction

Plastic represents an important and integral part of the global economy. On the other side, plastic pollution is a global problem nowadays. Plastic production increased exponentially, and only in 2017, it reached 350 million tons (The New Plastics Economy 2016). Nowadays, it is extremely difficult to find anything that we regularly use or come into contact with, that isn't composed of or contains some sort of plastic. This fast-growing trend represents a serious issue that threatens Goal 14 of the United Nations Sustainable Development - Conserve and sustainably use the oceans, seas and marine resources, and Goal 12 - Ensure sustainable consumption and production patterns requiring immediate solutions (Gong and Xie 2020).

The origin of plastics dates back to 1920 when the first plastic polymer was synthesized (Chia et al. 2022). Thanks to its lightweight, durability, adaptability, and relative chemical inertness, plastic has found application in almost all branches of industry. Despite the resistance that characterizes it, under the influence of various physical, chemical, and biological processes that take place in the environment, plastic can be defragmented to particles of size below 5 mm, the so-called microplastics (MPs). The term "microplastics" has been in use for the last 19 years (Thompson et al. 2004). MPs have been found in the most remote parts of the world, in plant and animal species, and even human tissues, and are already considered a ubiquitous environmental pollutant (Osman et al. 2023). Due to their hydrophobic nature, surface morphology, particle size, abundance, and ability to absorb and transport various contaminants (plasticizers, pesticides, and harmful agents) to organisms and their digestive systems, microplastics, and nanoplastics are a major cause for concern (Bhatt et al. 2021). Depending on its origin, there are two MP types - primary and secondary. Primary MPs refer to plastics initially produced in the form of particles, commonly used in cosmetics, construction, and automotive industry, paint and varnish industry, etc., while secondary MPs arise as a result of fragmentation of plastic items under various influences (Gong and Xie 2020).

As the formation of MPs takes place in all stages of the plastics' value chain, starting from its production, through use, to disposal, an effective approach to microplastic pollution solving requires a comprehensive

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approach. The current situation is a consequence of the linear economy model, based on the one-time use of products. Prolonging the life of plastic in the system, maintaining its value, preserving non-renewable virgin feedstocks, and increasing the degree of recycling, are the principles of the circular economy that can enable the reduction of MPs. The foundation of the circular economy is the idea that materials should not flow continuously linearly from production through consumption to end-of-life but rather should loop back into the value chain (World Economic Forum; Ellen McArthur Foundation; McKinsey & Company, 2016). The transition from a linear to a circular economy requires innovation and the design of new, longer-lasting, biodegradable types of polymers, with less harmful substances, with the application of carbon-neutral technologies, i.e. without greenhouse gas emissions. A circular plastics economy strives to preserve plastics at their highest value for as long as possible, while also preventing adverse environmental impacts and benefitting the economy. It includes strategies that mitigate resource loss and environmental harm. An important factor in the transition is the regulation aimed at reducing plastic pollution, which in the early phase was devoted mainly to banning specific products. Today, the focus is on the entire plastic value chain (Syberg et al. 2021). The development of remediation technologies for removing existing pollution is of equal importance as measures to reduce its occurrence. Further research concerning the direct relationship between reduced micro(nano)plastic pollution and increased circularity of plastic products could strengthen the scientific foundation for leading societal initiatives to reduce plastic pollution, including the understanding of the relationship between plastic recycling and micro(nano)plastic production.

The aims of this study are to 1) provide an overview of the MPs sources depending on the generation process and the environment where the pollution occurs, 2) discuss the current state of the plastic management system and the pathways that could lead to MP pollution reduction, and 3) to emphasize the most recent stage in the development of MPs remediation technologies with its advantages and deficiencies.

2. Sources of MPs in the environment

MPs are frequently found in all components of the environment, including soils, freshwaters, estuaries, oceans, coasts, and sediments. However, anthropogenic and environmental influences are the primary factors responsible for MP's distribution and abundance (Sarker et al. 2020). MPs originate from two main sources - primary and secondary, depending on the generation process, which could be further differentiated according to the environment where particles could be found to land-, water- and air-based sources (Figure 1).

Primary MPs refer to particles initially designed and produced in that form, with the aim of use in cosmetics and personal hygiene products - microbeads for scrubs and skin cleansers, gels, toothpaste, etc., in detergents, insecticides, and industry - plastic microparticles are used as an abrasive in the automotive and aviation industry, as industrial raw materials, as an intermediate product in the production of plastic items, microfibers for the production of synthetic textiles, in the paint industry, etc. (Gong and Xie 2020). These particles are usually comprised of polyolefin polymers exhibiting high lipophilicity that enables them to adsorb harmful substances from nearby environments onto their surface (Hasan Anik et al. 2021). The number of primary microplastic particles of different sizes, shapes, and colors found in facial scrubs is between 1000 and 19,000 per milliliter (Napper et al. 2015). The release of primary MPs can occur due to improper disposal or industrial spills, but the most significant way of getting into the environment is the use of products that contain primary MPs in their formulations. Primary MPs are released during every washing cycle of synthetic fabric, widely used today.

Fragmentation, i.e. reduction of material from macro to micro size, resulting from various processes occurring in the environment is categorized as a secondary source of MPs in the environment (Othman et al. 2021). Exposure to certain chemicals and sunlight heath, changes in medium pH, biological activities and physical tension produce natural processes, or so-called environmental cracks. Specific chemicals originating either from microbial activity or another waste and sunlight could initiate chemo-photodegradation (Kurniawan et al. 2021). The abrasion of plastic items could be caused by physical tension from ocean waves, while the periodical exposure to water and air may influence higher plastic fragmentation. Large plastic items could be also eroded due to biological processes such as biofouling, microbial attachment, and animal attachment. Secondary MPs could be formed from every piece of plastic waste, thus, every discarded plastic item that ends up in the environment is a potential source of MPs. The substantial source of secondary MPs is also mechanical stress during plastic items utilization or weathering.

Recent studies attempted to assess defragmentation rates of plastic litter leading to the formation of secondary MPs. For instance, a degradation rate of 1-5% was proposed to evaluate the secondary MPs' quantity generated in the Norwegian sea (Galafassi, Nizzetto, and Volta 2019).

Particles' density, size, and shape determine further transport through atmospheric, aquatic, and terrestrial ecosystems, thus forming a complex and dynamic cycle of MPs in the environment (Chen, Feng, and Wang 2020).

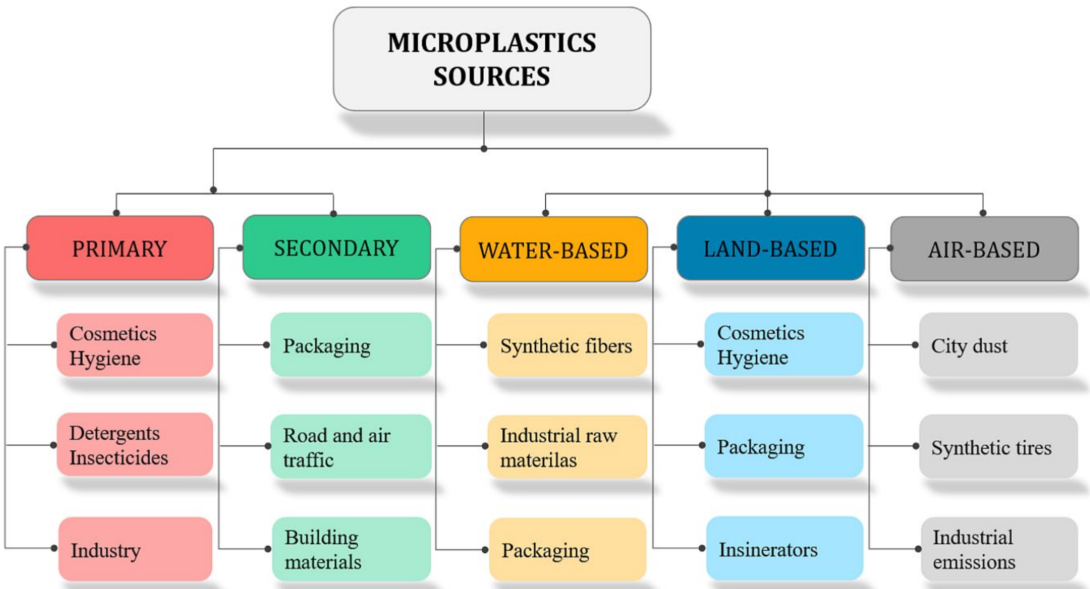

Fig. 1. MPs sources in the environment

Synthetic fibers, industrial raw materials, personal hygiene products, and inappropriate disposal of plastic waste constitute one of the main sources of MPs in freshwater systems (Li, Busquets, and Campos 2020). Contrary to rivers, stagnant water bodies, such as lakes, can accumulate larger amounts of MPs reaching MPs density of even 20.264 particles km−2 (Free et al. 2014). Primary MPs can reach freshwater surfaces through industrial drainage systems and household systems, while the sources of secondary MPs are diverse, and to the greatest extent they originate from improper waste management. Seas' and oceans' pollution with MPs is most often a consequence of coastal tourism, industry, and fishing. It is estimated that the dominant source of MPs in the oceans is secondary MPs, while between 15 and 31% of MPs originate from primary sources (Hasan Anik et al. 2021).

Although the content of MPs in soils has so far been less investigated compared to the aquatic environments, it is considered that land-based sources of pollution are responsible for 80-90% of MPs that end up in water bodies (Osman et al. 2023). Due to the wind and rain, MPs formed on the ground can easily reach rivers and then be further transported to seas and oceans. Plastic bags and bottles, construction materials, clothing, plastic packaging for food and drinks, personal hygiene products, etc. represent the most significant secondary source. Plastic incinerators generate ash containing MPs, thus contributing significantly to soil pollution (Yang et al. 2021). City dust is considered to be a significant carrier of MPs in urban areas, since plastics from polymer-based materials, such as tires, paints, and construction materials, make a significant contribution; detected concentrations range from 210 to 1658 MP items per 10 g of dust (Campanale et al. 2022). The construction sector comprises 20% of the annual production of plastics in Europe (The New Plastics Economy 2016). MPs in agricultural lands originate from wastewater irrigation, the use of compost and sludge left over from wastewater treatment, and the use of plastic products for agricultural production - irrigation systems, boxes, foils, packaging, plastic tanks, mulching foils, greenhouses, etc. (Sanchez-Hernandez 2019). Although they remove 99% of MPs contained in water, wastewater treatment plants release significant amounts of MPs (Galafassi, Nizzetto, and Volta 2019).

Air pollution with MPs occurs as a result of a wide spread of sources. Sources of primary MPs include air pollution from urban dust, wear and tear of synthetic tires, poor landfill management, industrial emissions, plastic recycling process, and waste incineration (Munyaneza et al. 2022).

Knowledge about the MPs' potential source is an essential step and starting point in MPs' effective reduction. Both the primary and secondary sources significantly contribute to the overall pollution, and thus system redesigning requires action in the production process of intentionally generated MPs, followed by changes in activities causing MPs' release by plastic fragmentation.

3. Reduction of MPs pollution

Although plastics have become an integral part of the economy and everyday life long ago, the pollution caused by this material is currently one of the key environmental challenges, attracting the increasing interest of society. Despite the numerous initiatives introduced in recent years in search of a solution for this global problem, the amount of plastics that end up discharged into the environment is constantly increasing (Syberg et al. 2021). The New Plastic Economy initiative (World Economic Forum, Ellen MacArthur Foundation and McKinsey & Company 2016) is dedicated to fundamental changes in the management of plastic packaging waste and plastics in general, offering a new approach to transform the flow of plastic materials by applying the concept of a circular economy. Since MPs are generated at all stages of the plastic life cycle, even during production, reducing the production of plastic waste in general may reduce the risk of microplastic contamination. Therefore, effective reduction implies comprehensive action in all phases of the cycle and a focus on the entire value chain of plastic items. The transition from the linear economy model, based on the single use of products, and the redesign of the system that will function on the principles of the circular economy, represents an approach that would allow the prolonging of products and feedstock life, increasing the recycling degree and reducing leakage of plastics into natural systems, and consequently the microplastic pollution and other negative externalities (Figure 2) (Leal Filho et al. 2019).

The aim is to establish an impact not only on the reduction of the release of plastic waste but also on reducing the use of fossil fuels as raw materials and preserving natural capital, bearing in mind forecasts that 20% of total oil production could be used for plastic production in the future (Syberg et al. 2021). One of the solutions is the synthesis of polymers based on greenhouse gases (GHG-greenhouse gases) such as carbon dioxide and methane, or the use of biomass (Bachmann et al. 2021). Company Newlight Technologies INC. has patented AirCarbon technology for the production of polyhydroxyalkanoates (PHAs), a potential substitute for polymers of petrochemical origin, by synthesis from methane, while carbon dioxide can be converted to polyurethane (PUR).

In this sense, future innovations, development, and design of products should strive to use new longer-lasting polymers than the existing disposable ones, with the possibility of reuse and recycling. An example of the application of circular economy technology is the Serbian company White Lemur co (https://www.soma.eco/), which developed Biosporin, a green and biodegradable alternative to expanded polystyrene (PS, styrofoam). This material has all the technical and thermal characteristics of styrofoam and is completely degradable and fireproof. The production process is carbon neutral - it does not emit greenhouse gases and enables the conversion of various forms of agricultural waste into sustainable materials.

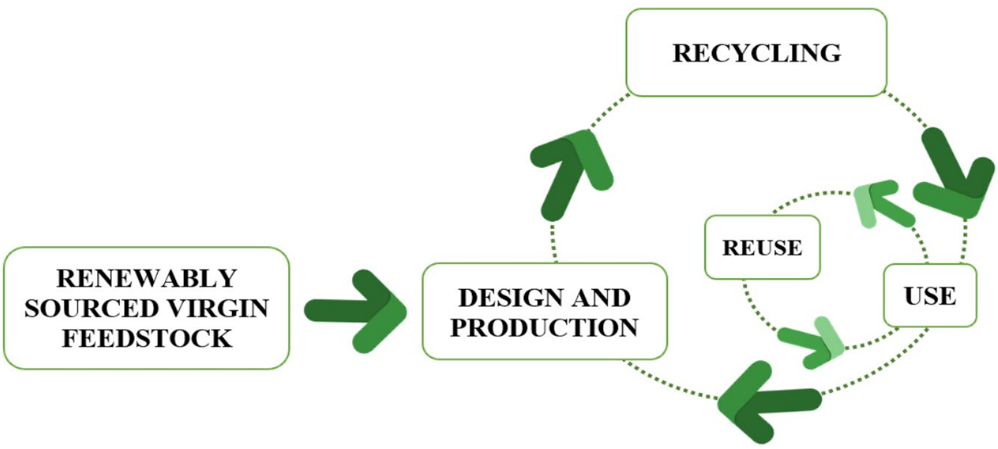

Fig. 2. Principles of circular economy applied to plastics life cycle

Preparation of a proposal for banning the targeted production of MPs (primary MPs) and adding them to the formulations of various product categories, such as plant protection agents, fertilizers, cosmetics, detergents, etc., is in progress (Clausen et al. 2020). An important initiator of changes in product design is regulation that aims to reduce the impact of plastics on the environment through a series of requirements that the product must meet before reaching the market. One such regulation is the EU Directive 2019/904 from June 2019, which also implements extended producer responsibility, or the so-called "Due Diligence", which foresees the responsibility of all participants in the supply chain of a particular product. European Commission Regulation 10/2011 on plastic materials and articles intended to come into contact with food from January 2011 places special emphasis on plastic materials that are in direct contact with food and drink (plastic packaging), whereby only approved substances listed in the document may be used in the production process. The use of single-use products, such as packaging, can lead to abrasion and the release of micro- and nanoplastics. Examples are cups and food containers based on polystyrene (Lambert and Wagner 2016). Plastic products, such as shopping plastic bag and cosmetic products containing microbeads are banned in certain countries (Table 1). The content of (dangerous) additives is also one of the parameters for maintaining the value of plastic within the circular value chain. Plastics contain chemical compounds including phthalates, bisphenol A, and polybrominated diphenyl ethers that, could be harmful if consumed. The European REACH regulation supervises the use of industrial chemicals and thus aims to ensure the production of plastic products following the principles of circularity.

A central component of the transition to a circular economy when it comes to plastics is increasing the recycling rates (European Commission, 2018). In 2018 the first Europe-wide-plastics recycling plan was introduced by European Commission with an aim of making all used plastic packaging recyclable by 2030, and 55% of all packing material. The final result of recycling increase, in an ideal scenario, ensures that materials remain longer in the value chain, reducing the use of feedstocks for production and eliminating pollution. The actual recycling system often results in a loss of material value due to inefficient sorting, and some forms of recycling even lead to an increased release of micro- and nanoplastics (Syberg et al. 2021). Plastics that are recycled at all, are being converted into a product of lower value and application, which also represents its final use since the resulting product cannot be (economically) recycled again. On the other hand, although the use of recycled PET (polyethylene terephthalate) for the production of fabric reduces the exploitation of basic raw materials, and thus ensures feedstock conservation, which is one of the key points of transit toward a circular economy, the fabric produced in this way tends to increase the release of microfibers.

4. MPs remediation technologies

Estimated annual production of the most commnonly used plastics in 2050 will increase by around 30% (Figure 4). Despite wide plastics applications (Figure 4), there is an urgent need to implement and enforce existing legislation as well as improve source control, waste management, and cleaning measures. Strategies related to recycling and consumption/demand of waste plastics established on citizens' behavior changes and enrollment, should also be of great importance for more ambitious recycling and recovery targets (Pico, Alfarhan, and Barcelo 2019). Several cleanup campaigns have been implemented to reduce plastic pollution, such as Clean Up the World (https://www.cleanuptheworld.org) and The Clean Seas Plastic Challenge (https://www.cleanseas.org). Nevertheless, cleaning campaigns turned out to be time-consuming, expensive, and demanding regarding personnel and used equipment. Additionally, these technologies fail to remove plastic debris (MPs and NPs), requiring complementary approaches (Patrício Silva 2021).

Due to the hazardous impacts of MPs, remediation of the existing pollution is of crucial importance, as well as measures of its occurrence reduction. To date, different methods have been used for MPs removal. Depending on the type of treatment, existing remediation technologies can be divided into physical, chemical, and biological, and depending on the medium being treated, the technologies applicable to water and soil treatment differ. Also, there is a division into conventional and innovative strategies. The above-mentioned approaches also differ in terms of the mechanism used, efficiency, and the type of microplastic that can be removed, and all have their advantages and disadvantages (Hasan Anik et al. 2021).

Technologies suitable for the remediation of aquatic ecosystems include coagulation, membrane reactor technology, and adsorption, which can be classified as conventional approaches, while among innovative ones, worth mentioning are electrocoagulation, photocatalytic degradation, magnetic separation, and electrochemical oxidation. Pyrolysis and photocatalytic degradation are considered effective for the treatment of MPs in the surface soil layer. On the other hand, phytoremediation has proven to be a viable option for soil down to the depth of plant roots. Additionally, microbial degradation is a recommended strategy for deeper soil layers (Zhao and Zhang 2023).

4.1. *Physical treatment*

Most of the approaches that can be classified as physical enable the removal of MPs from wastewater with high efficiency (>95%), while membrane bioreactor technology is currently considered the most efficient (Nolte et al. 2017; Lares et al. 2018). It is a reliable method based on nitrifying bacteria and other microorganisms, for treating industrial and municipal wastewater, usually containing different

Table 1. Ban policies in different countries and adoption years

Year	Country	Banned products	Reference
2020	Serbia	Plastic bags for the delivery of goods in sales and services	("Belgrade official gazette" 85/2018 and 74/2019)
2008	China	Total plastic bags ban (less than 25 um)	(Xanthos and Walker 2017)
2016	UK	Cosmetic products containing microbeads	(Rist and Hartmann 2018)
2019	Canada	Personal and natural care products, non-prescription drugs containing microbeads	(Ogunola, Onada, and Falaye 2018)
2020	Italy	Cosmetic products containing microbeads	(Guerranti et al. 2019)
2015	US	Cosmetic products containing microbeads	(FDA, 2015)
2016	France	Light-weight plastic bags in markets	(Eastaugh, 2016)
2009	Australia	Plastic bags (less than 35 um)	(Macintosh et al. 2020)
2002	India	Disposable plastics	(Xanthos and Walker 2017)

Table 2. The most commonly used plastic polymers, their recycling codes, annual production in 2020 and estimates for 2050 (Winiarska, Jutel, and Zemelka-Wiacek 2024, www.statista.com)

The most commonly used plastics	Recycling code	Production in 2020 (million tons)	Estimates for 2050 (million tons)	Applications
PET Polyethylene terephthalate	1	27.5	38.3	Packaging for beverage (water, drinks, beer), containers for food (fruits, fast good, mushrooms), food wrapping foils
HDPE High-Density Polyethylene	2	48.5	72.2	Packaging for cleaning products, cosmetics and beauty items, pipe systems, grocery bags, toys
PVC Polyvinyl Chloride	3	40.3	59.3	Windows frames, medicinal devices, fashion and footwear, automotive interiors and sear covering, cable and wire insulation
LDPE Low-Density Polyethylene	4	69.3	103.2	Plastic bags, foils for food packaging, various containers, molded laboratory equipment, computer component parts
PP Polypropylene	5	75.4	107.2	Pipes and insulation, machinery, automotive industry, batteries, packaging films, agricultural mulch
PS Polystyrene	6	26.5	37.2	Construction industry, foam packaging for shipping, food containers, cups, medical products, automotive parts

contaminants in varying concentrations (Osman et al. 2023). This approach implies a combination of membrane filtration, coagulation, micro and ultrafiltration, and biological processes, and thus enables the removal of pollutants of various concentrations with high-quality effluent. PE was found to be the most abundant MP type in drinking water. The combination of coagulation and ultrafiltration process in PE removal reached an efficacy of up to 91% (Poerio, Piacentini, and Mazzei 2019). Negative aspects are high costs, the addition of nutrients for microorganisms, and the reduction of the membrane (Osman et al. 2023).

Another widely used conventional technology for removing pollutants from wastewater is adsorption. In general, traditional methods are useful for removing small MP particles. Some materials show significant adsorption efficiency, reaching up to 100% for microplastics and even nanoplastics, such as double-layer hydroxide (Tiwari et al. 2020). So far, the adsorbents used to remove MPs are chitin and graphene oxide, and the combination of zinc oxide and aluminum reached a significant efficiency for micro- and nanoplastics - even 100% at pH 4 (Tiwari et al. 2020). The limiting factor is the selectivity of the adsorbent material towards MPs.

4.2. *Chemical treatment*

Chemical treatments are characterized by lower efficiency. Electrocoagulation considered the most effective method (with about 90% removal achieved), attracted the interest of researchers as an alternative to conventional coagulation methods (Perren, Wojtasik, and Cai 2018). It is sustainable and highly efficient for removing MPs from wastewater, integrating the positive aspects of coagulation and electrochemistry. This method enables the treatment of water of different quality, produces a smaller amount of waste, reduces the duration of operations and necessary costs, and ensures energy efficiency, while the disadvantages are frequent replacement of the anode and cathode passivation (Kim and Park 2021).

Pyrolysis is a thermochemical process of long polymer chains degradation into smaller, simpler molecules under the influence of temperature and pressure, and it has proven to be an environmentally friendly option for the treatment of waste plastics (Yansaneh and Zein 2022). Pyrolysis solid residue (char) after activation have various applications as an adsorbent material for wastewater treatment, heavy metals removal, or fuel source, while gas produced from plastics pyrolysis may be potentially utilized as an ignition source (Saleem et al. 2019). Oils obtained by pyrolysis of PS, PP, and PVC have 40.6, 44, and 40 MJ kg^{-1} of calorific value, while careful optimization of process factors such as temperature, catalyst, and heating rate may lead to up to 95% of the liquid oil yield (Mumtaz et al. 2023).

The biggest disadvantage of pyrolysis is the generation of gases with a greenhouse effect and aromas, which require further treatment to reduce harmful effects. According to recent research, the aforementioned gases can be used to obtain heat or electricity, and pyrolysis can potentially be considered an approach that is in alignment with the principles of the circular economy (Venturelli et al. 2022).

Photodegradation takes place under the influence of UV radiation and leads to the breaking of bonds between polymer chains and the formation of other (non)polymeric molecular species. The disadvantage of this method is the impact on the soil properties, and the secondary pollution occurrence. Cost-effectiveness is the key advantage of applying photodegradation on a larger scale.

4.3. Biological treatment

Biological treatment involves degradation by utilization of microorganisms or uptake by aquatic or terrestrial organisms; it is still in the development phase and currently offers limited efficacy (Kumari et al. 2022).

The application of phytoremediation to remove MPs from the soil is currently in its infancy. Silver birch (*Betula pendula*) is a species under consideration for use in phytoremediation of MPs (Austen et al. 2022). So far, a reduced concentration of phthalates in the soil has been recorded with the application of this technology (Ma et al. 2012). It is an environmentally acceptable approach, which potential to remove MPs has yet to be explored.

Although MPs are a long-term pollutant, it has been found that certain organisms, such as fungi and bacteria, can affect the degradation of MPs. Microbial degradation is an economical and environmentally friendly technology for the remediation of MPs and has attracted attention as a potentially effective option. The biodegradation process of MPs includes three consecutive stages: biodegradation, biofragmentation, and assimilation. *Ideonella sakaiensis* 201-F6 represents an example of the bacterial strain breaking down PET polymers by two-stage decomposition, followed by digestion of decomposition products that lead to the formation of terephthalic acid (TPA) and ethylene glycol (EG), which can later be transformed into carbon dioxide and water (Dhiman et al. 2023). Due to its exceptional activity against PET, the IsPETase, an enzyme responsible for PET decomposition has undergone significant structural modifications as a part of biotechnology method development.

To investigate the biodegradation process of MPs, many bacteria have been isolated from different environmental sources. However, the detailed mechanism of plastic degradation and the enzymes involved in the given process are still insufficiently investigated, which requires further extensive studies before commercial application.

5. Conclusions and future trends

Microplastic pollution is a complex problem that requires concerted action by governments, the private sector, consumers, and civil society. Its sources are omnipresent in the environment, among which the most significant are the production and utilization of primary MPs in cosmetics and industry and improper waste management as one of the dominant secondary sources. As the impact of MPs on the environment grows, there is an increasing demand to find and develop sustainable solutions to prevent harmful effects and reduce the presence of this pollutant. The transition from a linear to a circular economy would ensure action in all phases of the plastic value chain, from production to disposal of used products. The priorities are the transition to renewable sources of raw materials, the development of new non-hazardous, biodegradable formulations of polymers as green alternatives, as well as increasing the recyclability of materials. Although the positive impacts of current remediation strategies are recognized, due to the complexity of factors closely associated with MPs ubiquity, none of them offer a solution suitable for all environmental circumstances and matrices. The improvement of existing and the development of new, economical, and efficient technologies for the remediation of MPs from different media is necessary to remediate the already present pollution.

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