



HAL
open science

Microplastics controlling approaches: removal reaction pathways, kinetics, and toxicity evaluation of the products

Shahnaz Ghasemi, Ali Parastesh, Hossein Ramezani, Mohsen Padervand, Elmuez A Dawi, Tayebah Hamzehlouyan, Abdelkader Labidi, Sima Hajiahmadi, Michela Signoretto, Eric Lichtfouse, et al.

► To cite this version:

Shahnaz Ghasemi, Ali Parastesh, Hossein Ramezani, Mohsen Padervand, Elmuez A Dawi, et al.. Microplastics controlling approaches: removal reaction pathways, kinetics, and toxicity evaluation of the products. Nadeem A. Khan; Lakhveer Singh. Microplastic Pollutants in Biotic Systems: Environmental Impact and Remediation Techniques., 1482 (9), American Chemical Society, pp.213 - 237, 2024, 9780841296800. <10.1021/bk-2024-1482.ch009>. <hal-04873520>

HAL Id: hal-04873520

<https://hal.science/hal-04873520v1>

Submitted on 8 Jan 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC0 1.0 - Universal - International License

Microplastics controlling approaches: removal reaction pathways, kinetics, and toxicity evaluation of the products

In Microplastic Pollutants in Biotic Systems: Environmental Impact and Remediation Techniques. ACS Symposium Series 1482, eISBN 9780841296800. Chapter 9, pp 213-237. <https://doi.org/10.1021/bk-2024-1482.ch009>

Shahnaz Ghasemi,^{1,*} Ali Parastesh,² Hossein Ramezani,² Mohsen Padervand,^{3,4,5,6,*} Elmuez A. Dawi,⁷ Tayebah Hamzehlouyan,² Abdelkader Labidi,⁸ Sima Hajiahmadi,⁹ Michela Signoretto,⁶ Eric Lichtfouse,¹⁰ and Chuanyi Wang^{4,5,*}

¹Sharif Energy, Water and Environment Institute, Sharif University of Technology, Azadi Avenue, Tehran, P.O. Box, 11365-8639 Tehran, Iran

²Chemical and Petroleum Engineering Department, Sharif University of Technology, Tehran, Iran

³Department of Chemistry, Faculty of Science, University of Maragheh, P.O. Box 55181-83111, Maragheh, Iran

⁴Guangzhou Institute of Industrial Intelligence, Guangzhou 511400, China

⁵Guangdong Engineering and Technology Research Center for Environmental Purification and Functional Materials, Guangzhou 511400, China

⁶CATMAT Lab, Department of Molecular Sciences and Nanosystems Ca' Foscari University Venice and INSTM Consortium, RU of Venice, Via Torino 155, 30172 Venezia Mestre, Italy

⁷College of Humanities and Sciences, Department of Mathematics and Sciences, Ajman University, P.O. Box 346, United Arab Emirates

⁸School of Environmental Science and Engineering, Shaanxi University of Science and Technology, Xi'an 710021, China

⁹Western Caspian University, Baku, Azerbaijan

¹⁰State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi, 710049 P.R. China

*Email: padervand@maragheh.ac.ir.

*Email: sh.ghasemi@sharif.edu.

*Email: wangchuanyi@sust.edu.cn.

The widespread existence of microplastics and their potential negative impacts on ecosystems and human health make them one of the most prevalent global environmental challenges today. Microplastics are either formed by the fragmentation of large plastics or are purposefully manufactured for specific applications. Several studies have revealed that microplastics pose severe risks to both marine life and humans among which the undesirable effects on the human food chain are serious and inevitable. To control the level of such pollution in the environment, systematic regulatory measures, public awareness, and advanced

removal technologies should be simultaneously considered. After a short introduction to the basic global concerns, this chapter discusses the mechanism of formation and environmental distribution of microplastics alongside their potential threats to natural life. Additionally, it evaluates a variety of removal techniques for adsorbing and/or degrading microplastics in terms of kinetics, removal reaction pathways, and toxicity assessment of byproducts, while considering their physical, chemical, and biological properties. It also delves into recent advancements in this field, provides insights into the current state of knowledge, and points out areas that need more research.

1. Introduction

The invention of plastic in 1907 (1) was a major turning point in history after the Industrial Revolution. For the first time, humans could manufacture material with no roots in nature. The affordable plastics as the raw ingredient meant a plethora of affordable tools, kitchen appliances, and other possible products to become accessible to the public- for this reason, plastic was called the material of a thousand uses. This accessibility helped a more equitable distribution of wealth and caused economic growth.

However, it was only in recent years that researchers found the potential threat of this synthetic material (2), the pollution of nature with microplastics the building blocks of plastics. This contamination poses significant environmental risks and raises concerns regarding its impact on ecosystems and human health.

In particular, the discovery of nanoplastics (less than 1 μm) and microplastics (MPs) with particle sizes between 1 μm to 5mm is of major concern. These MPs come from the decomposition of larger plastics used in the production of goods such as textiles and personal care items. The existence of these particles has been studied and confirmed in marine, atmospheric, and soil environments which highlights the destructive role human activities could have on nature (3).

It is, therefore, essential for the environment and ecosystem health to develop and study efficient methods for MP removal and degradation. The current methods for this purpose are categorized into three sections; physical, chemical, and biological techniques. The first methods rely on the isolation of the MPs from the contamination source using filters and/or membranes. The chemical method, meanwhile, takes advantage of certain chemical reactions to degrade these microplastics into less harmful materials. Lastly, biological MP degradation uses living organism and their natural capabilities to degrade and break down plastic particles. Each of these methods could be employed depending on the level of the pollution, the source of contamination, and the type of MP. Undoubtedly all these removal approaches have their advantage and disadvantages which will be explored in the upcoming sections.

2. Definition

The term “Microplastic” was first used in an article titled “Plastic and Other Artifacts on South African Beaches: Temporal Trends in Abundance and Composition” in 1990 (4). This definition was refined in 2009 when Arthur et al. (5) suggested microplastics have an upper limit size of 5 nanometers. In the next two years, Cole et al. (6) introduced another dimension to the microplastics definition, besides their size, which was the source of the plastic fragments. They divided

microplastics into primary sources and the secondary sources. The former are the plastics that were originally made in microscopic sizes while the latter are the ones that are degraded from larger pieces of plastics. One globally accepted definition of microplastic is proposed by the Aspects of Marine Environmental Production (GESAMP) which describes microplastics as plastic particles with sizes smaller than 5 millimeters (7). Table 1 illustrates the properties of typical microplastic monomers in the environment.

Table 1. Polymeric microplastics and their monomers, chemical formula, and density^a

<i>Polymer name</i>	<i>Monomer name</i>	<i>Chemical formula</i>	<i>Density (g.cm⁻³)</i>
Low-density polyethylene (LDPE)	Ethene	C ₂ H ₄	0.91–0.92
High-density polyethylene (HDPE)	Ethene	C ₂ H ₄	0.93–0.97
Polyethylene terephthalate (PET)	Ethylene terephthalate	C ₁₀ H ₈ O ₄	1.37–1.38
Polypropylene (PP)	Propylene	C ₃ H ₆	0.89–0.92
Polystyrene (PS)	Styrene	C ₈ H ₈	0.28–1.04
Polyvinyl chloride (PVC)	Vinyl chloride	C ₂ H ₃ Cl	1.10–1.47

^a Adapted with permission from reference (8). Copyright 2024 Springer Nature.

3. Mechanism of Formation and the Source of MPs

The primary factor in microplastic pollution is human activities. This role can be seen in the widespread use of microplastics in all aspects of our lives from industries such as building and construction to everyday household tasks such as washing cloth. However, a significant portion of the microplastic contamination is rooted in raw plastic production, the textile industry, and laundromats (9, 10). On top of these, water and sewage treatment plants are also another contributing group releasing microplastic into the environment and spoiling the ecosystem (11).

As discussed, microplastics either originate from primary sources or secondary sources. Industries usually produce primary microplastics in two main forms. The first form is the small pieces of polymers used as additives mostly in personal care items such as toothpaste or facial cleanser creams. The second form is macroscopic fiber polymers resulting from abrasion and washing of textiles. Additionally, oil and explosive industries are two other contributors to the creation of primary microplastics (11).

On the other hand, secondary microplastics are created by the degradation of larger pieces of plastics through chemical, physical, and biological processes into smaller particles (10). The vast complexity of microplastic sources raises the need for a more accurate and thorough database indicating the role each source of pollution plays in the overall contamination level of microplastics (12). Nevertheless, as a consensus, it is believed that the main source of microplastic pollution is the secondary sources as larger plastics make their way into the environment one way or another (13).

Figure 1 depicts the main sources of microplastic pollution released into the environment gathered by the International Union for Conservation of Nature (IUCN) in 2017.

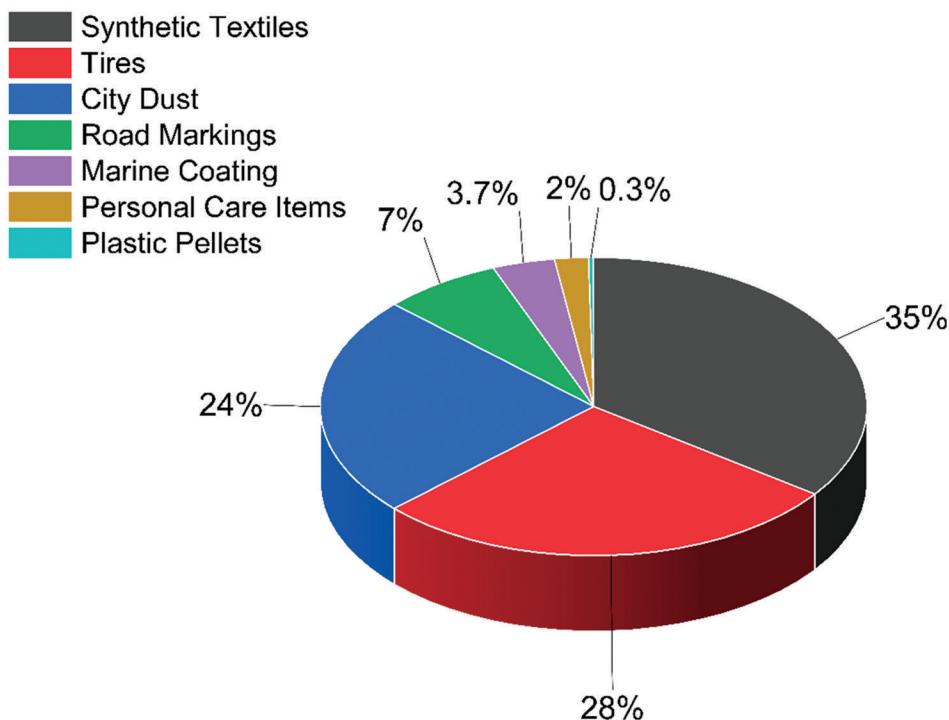


Figure 1. Main sources of microplastics (Data from IUCN, 2017).

These secondary forms of microplastics are degraded and fragmented before entering the environment. This process can be divided into two separate pathways; abiotic degradation and biotic degradation. In the first path, the degradation and fragmentation are caused by UV irradiation, heat, chemical, or mechanical stress. The biotic path, however, includes biodegradation and biodisintegration of plastics. While biodegradation is caused by enzymes, hydrolysis, or chain scission, biodisintegration is simply a result of fragmentation (14).

4. Distribution in the Environment

The small size and the low-weight nature of microplastics means that they can be easily carried away and enter a different part of the environment depending on the source of the contamination. For instance, water and wind erosion are two means that can transport microplastics from residential areas, landfills, and roads to the environment (15). Direct ingestion and inhalation are also two other means of microplastic contamination which adversely affects living creatures' well-being. Indirect ingestion is also another way of getting contaminated by MP which is caused by the MP-infected food chain and ecosystems (oceans, lakes, food, salt, and water) (16, 17). This contamination will not just infest the human or animal body but it will circle back to the environment through defecation. Nevertheless, the extent of this contamination requires in-depth and reliable quantitative studies to understand the amount of MP released to the environment as well as the temporal and spatial scales of it (18).

Regarding MP transportation in soil, there are various influencing factors; namely soil and wind erosion, infiltration, runoff, and animal migration (19). An example of this transportation is earthworms that could easily ingest microplastics and displace these particles in the soil.

Microplastics could also be released from the soil (to the water sources) via the flow through the holes created by animals' movement (20). Holes created via physical processes such as planting and root deterioration could also cause groundwater MP contamination (21). These are just a few examples of the many ways through which Earth's resources and environment have been contaminated with microplastics and for this reason, even the remote and uninhabited regions of our planet are reported to be infected with these tiny toxic plastic particles (22).

5. Hazards on the Biotic Systems

5.1. Plants

Microplastics are toxic to both aquatic and terrestrial ecosystems. This toxicity can majorly affect soil and plants' health as MPs can diffuse into water and soil resources. There has been much research studying the negative effects of microplastic contamination on the soil and plants' ecosystem. There are two major paths that plants are affected by MP particles; direct way and indirect way. The first path causes major issues for the plant's natural life cycle as the minuscule particles can block seed probes, interfere with nutrient uptake through roots, and constrain aggregation (23). On the other hand, MP particles also cause issues for plants in indirect ways. For instance, the physicochemical properties of the soil such as pH, porosity, and bulk density would alter if contaminated by microplastics. It is worth noting that the effects of MPs on each soil property should be studied separately as it can be misleading to draw an overall conclusion. For example, while the MP particles could cause lower pH and therefore more bioavailable heavy metals, they could help respiration in the soil. Another indirect effect of MP contamination is the decline in the soil's microbes and organisms population (24).

Depending on the microplastic size, shape, and concentration, plants' roots and leaves absorb the particles and this causes major interference with the plant's normal growth cycle. The size of particles profoundly affects the level of toxicity as the smaller the size means a higher danger to the plant's life. This is particularly true for nanoscale particles as they can penetrate the biological membranes of the plant (18).

5.2. Animals

The effects of MP contamination on animals' health can be seen in three different ways. First, particles can attach to the surface of small animals causing them damage and hindering their movement. Then, larger animals can directly or indirectly ingest these particles which depending on the level of toxicity can result in a damaged digestive system and interference with the metabolism. Lastly, as MPs have a very low degradation rate, they can accumulate inside the animal's tissues causing a long-term danger to its well-being. This also threatens animals higher on the food chain ladder (predators) as they also would be in danger if they consume the contaminated animal (25).

A common biological model for studying the toxicity of MPs on animal life is the fish population. Experiments indicate that microplastics can disrupt nutrient absorption in fish by accumulating in their intestines. The MP accumulation hinders the fish's immune system, lowers their reproduction rate, and could also lead to organ failure. Nevertheless, as these experiments were conducted in a controlled laboratory environment, they may not necessarily reflect the actual consequences of the microplastic contamination on the fish population. But they can give a rough picture of what effect can microplastic have on aquatic ecosystems. According to reports, in an environment polluted with heavy metal and fabric softeners MPs could have even more severe negative effects on the fish population's health (26, 27).

5.3. Human

As the head of the food chain, humans are more vulnerable to the contamination caused by microplastics. Ingesting, inhalation, and direct skin contact with microplastics can seriously affect people's health. Accordingly, microplastics act as a stimulus for the inflammatory response in humans. These toxic particles also affect the cellular system, tissues, and organs in the human body (28–30). Moreover, an average of 20 microplastic particles (50-500 micrometers), mostly PP and PET, have been identified in every 10 grams of human feces, highlighting the extent of MP pollution and drawing global attention (22). Additionally, according to recent reports our drinking water, both tap and bottled water, is also contaminated by microplastics with a concentration of 0.01 to 100 million particles per one square meter of water, depending on the type and the source of the water (31). As the last concern, there is a big concern about the potential of MNPs (micro/nano-plastics) to induce cancer in human organs and tissues in the long term. Subsequent exposure to these small particles is associated with the development of some adverse signs including, bioaccumulation, oxidative stress, genetic damage, inflammation, fibrosis, or long-term toxicity, indicating the progressive growth of carcinogenesis in human body. DNA damage has been also detected for the healthy human cells treated with MNPs periodically, which remarks the urgent care of such pollution in the human communities.

5.4. Aquatic and Soil Microorganisms

Microorganisms have a vital role in soil health; they participate in the geochemical substance cycle, enhance pollution degradation, and help the soil to adapt to the changes in the environment (32). Microplastics could heavily impact these microorganisms and thereby the soil's health. This impact usually is seen as a decline in the bacteria and fungi population in an ecosystem. The MPs effect, however, may vary depending on the type of pollution. For instance, polyester and polyacrylic presence in the soil causes a decline in the activity and diversity of microbial communities, while fibrous PP and membranous PE do the opposite. Nevertheless, there is a lack of a wholesome understanding regarding the role of MP pollution in the soil and the effects it can have on the microorganism communities. This has led researchers to continue studying this field to better understand the interaction of the soil biota with plastic particles (33).

Microplastics also affect the microorganisms in the aquatic environment. These particles can act as microorganism carriers by offering an ecological niche for microbial communities' colonization through biofilm colonization which is called *plastisphere*. These carried organisms are associated with antibiotic-resistant genes, pathogenic islands, and diverse metabolic pathways. The plastic particles could also change the function and the structure of the microorganism's communities. For instance, they can change the metabolism of carbon in these communities and the food webs which is considered to have unknown effects on the animals higher on the food chain (larger organisms) (34, 35).

6. Removal Technologies

6.1. Physical Methods

6.1.1. Adsorption

Adsorption is one of the most effective techniques for microplastic removal especially in the solution phase. This method is a surface phenomenon in which particles are adsorbed on the surface of the adsorbent via Van Der Waals interactions. Therefore, the adsorbents with high adsorption capacity such as activated carbons (36), Metal-Organic Frameworks, zeolites, and hydrogels should be utilized for effective MP removal (37). The adsorption capability and the regeneration rate of the adsorbent depend on various factors such as the nature of the adsorption sites and the strength of the adsorbent material.

Even though surface adsorption of the MPs is the objective of this method, certain materials used as adsorbents can also provide other removal pathways simultaneous to the adsorption. For instance, studies show that MOFs with catalytic properties could play a role in microplastic removal through both adsorption and oxidation pathways. Additionally, Aerogels and hydrogels possess active sites that potentially could initiate degradation pathways such as hydrolysis or oxidation. These pathways alongside the adsorption of MPs to the surface of the adsorbent result in effective particle degradation (37).

Kinetics

The degradation of microplastic through this approach can be explained in various steps. First is the adsorption of particles on the surface which is defined as the rate at which the MPs are captured and held on the surface of the adsorbents. This is followed by the degradation of particles through certain chemical, physical, or biological pathways. In this process there are various influencing factors; environmental factors such as temperature and pH and material-specific properties such as specific surface area and porosity. In a study titled “Removal of microplastics from aqueous solutions by magnetic carbon nanotubes” Tang et al. investigated the reaction kinetics for the removal of microplastic through adsorption using magnetic carbon nanotubes as adsorbent material. They fitted the gathered data with different kinetics models and found out that the reaction can be described by both pseudo-first-order and pseudo-second-order kinetics models (38).

Product Toxicity Assessment

A crucial factor in assessing the overall performance of a removal technique is the toxicity of the products and the potential threats the method itself poses. For instance, MOFs might release metal ions during the degradation process, and these metallic ions have severe toxic effects on the health of ecosystems. On the other hand, toxic byproducts generated through the removal process itself are another worrying source of contamination. As an example, carbon-based adsorbents were used for the efficient degradation of polyethylene (PE) particles and it was found that the intermediates produced during this process are even more toxic than the initial contaminant. Therefore, when suggesting an adsorption approach for MP removal it is essential to have a thorough evaluation of the overall contamination level before and after treatment (39).

6.1.2. Membrane Filtration

A recently developed advanced method for microplastic removal filtration with membranes. This process involves the contaminated water moving across membranes with different pore sizes which act as filters and trap the particles. The size of pores is chosen based on the type and size of the microplastic particles. The reasons for the increasing attention toward this method for MP removal are its easy operation, low energy consumption, scalability, and stability. It is worth noting that membrane filtration itself includes nanofiltration, ultrafiltration, microfiltration, and reverse osmosis (40). An overall schematic of membrane filtration for water treatment and MP separation is given in Figure 2.

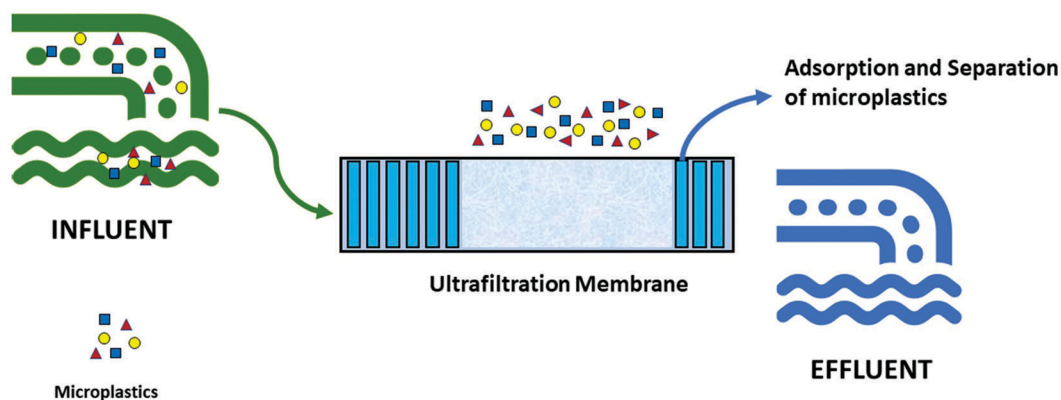


Figure 2. A schematic of an ultrafiltration membrane (41). Copyright the authors. Licensed under CC BY 4.0 DEED: <https://creativecommons.org/licenses/by/4.0/deed.en>.

There are also other membrane-based techniques for MP removal known as Membrane Bioreactors and Dynamic Membrane methods. For effective removal efficiency, certain approaches are suggested such as using membranes with varying pore sizes. Another approach is using external pressure to increase the operation's overall removal. The deciding factors in the MP removal via membranes are the permeability and pore size of membranes, their durability, as well as the type and concentration of the particles (42).

When used in conjunction with other removal methods membrane filtration can have up to 99.9% efficiency. An example of this conjunction is the combined membrane bioreactor (MBR) with the wastewater treatment process (WWTP) for MP degradation. The comparison was done between MBR and an activated sludge approach and the result indicated the membrane method had a higher efficiency for particle separation, comparatively (43).

However, this method is not without fault, and usually, the membrane faces fouling which is a result of MP accumulation inside the pores, and the presence of bacteria. Clogging is a direct result of this problem which in turn causes a decline in the ability of the membrane for MP removal. To avoid this problem, a pre-treatment stage before the membrane filters was suggested. Usually, disinfectants and/or coagulants are the best candidates for this job and lower the chance of fouling. A successful example of these pre-treatment systems is done by UV and chlorine oxidation which decreased the fouling rate of the membrane by roughly fifty percent (44).

6.1.3. Coagulation, Flocculation, and Sedimentation (CFS)

One of the most widely used physical methods for MP removal is the combination of coagulation, flocculation, and sedimentation, or CFS in short. Fundamentally this process uses the density difference of solids and liquids to separate these two phases which results in the sedimentation of the particles. First coagulant agents are in the liquid phase which results in the destabilization of MPs. Then, the resulting solution is mixed at a low rate over a long period, a process known as flocculation. During this process the particles stick together and form flocs which are aggregates of plastic particles. The formation of these flocs is heavily controlled by the properties of the liquid phase such as pH and ionic strength (45).

The sedimentation part, which is controlled by the MP's density, is the settlement of particles with the gravitational force. This part is particularly useful for particles with irregular shapes as these particles can easily stick together and form high-density flocks that easily settle. The CFS process is mainly controlled by the particle's properties such as their shape, size, and surface features (45). Similar to membrane filtration, this method is also used in conjunction with other removal methods to achieve maximum removal efficiencies. Table 2 summarizes the main advantages and disadvantages of CFS and membrane filtration methods for MP removal.

Table 2. Advantages and disadvantages of MP removal with membrane filtration and CFS methods^a

<i>Method</i>	<i>Advantages</i>	<i>Disadvantages</i>
Membrane filtration	-Facile and cheap operation -High efficiency -Stable outcome	-Fouling -The pretreatment process
CFS	-Simple operation -Versatility towards MP particle size	-Need for chemicals -Only studied at smaller scales

^a Data from reference (45).

6.2. Degradation Techniques

6.2.1. AOPs

Another possible MP degradation method is a chemical treatment that uses certain materials or chemical processes to break down plastic particles into less harmful components. This method can be used as the only treatment procedure or be combined with other methods such as physical and biological to reach high efficiencies. Among the degradation or chemical methods, advanced oxidation processes, or AOPs in short, is a promising approach that uses reactive oxygen species (ROS) such as hydroxyl and superoxide radicals to degrade plastic particles. These reactive species are the result of the catalyst reaction with oxidizing agents like ozone (O₃) or hydrogen peroxide (H₂O₂) (46).

Decomposition Pathways

In this method, the reactive radicals stick to the plastic particles and break certain chemical bonds producing reactive intermediates. Then the radicals cause further oxidation that breaks down the MP to small fragments or even produce other products (46).

The chemical degradation of MPs is affected by factors such as particle type, operation conditions, and specific treatment techniques. For instance, in research done by Venkataramana et al., they showed that the MP degradation rate increases as the photocatalyst (TiO_2) concentration and UV light intensity are set to higher values. In the meantime, this rate falls if the particle concentration is higher than the initial concentration (47).

Advantages and Disadvantages

AOPs could offer various positive points for MP degradation. First, they break down toxic plastic particles into smaller less harmful byproducts that can break down naturally (48). On top of that, certain AOPs such as photocatalytic treatment have low energy consumption and can reduce the overall environmental impact of these treatment methods (49). Then there is the versatility of this method meaning that it could be used for treating water, air, and soil MP pollution (50). On the other hand, this method like any other treatment method has its problems. The first issue is the reactive oxygen species which despite their positive role in MP degradation, could have harmful effects on aquatic ecosystems (51). The use of chemicals means there are negative environmental impacts (greenhouse gas emissions and chemical pollution) that accompany this method (52). The final downside is that environmental factors such as pH and temperature limit the applicability of AOPs to different environments (53). It is therefore necessary to evaluate the positive sides and negative sides of this method thoroughly before deciding to employ AOPs for MP degradation in a specific environment.

6.2.2. Photocatalytic Treatment

Photocatalysis is an AOP method that has recently gained attention due to its ability to effectively degrade microplastics. This process uses semiconductors, mostly metal oxides such as TiO_2 , known as photocatalysts to generate reactive radicals. These materials can generate ROS when irradiated with UV and/or visible light. However, the efficiency of this process for MP degradation depends on several factors such as the photocatalyst choice, temperature, light source, and exposure time (54).

Decomposition Pathway

Photocatalysts have a distinct activation energy known as a band gap. This gap's energy value is the difference in the electro-potential levels of the conduction band (CB) and valence band (VB). The exact amount of this value is material-specific and describes the amount of energy needed for the photocatalyst to be activated and create electrons which in turn generates ROS. These reactive species then participate in the oxidation and reduction reaction that results in the MP degradation. In reality, if the irradiated light has enough energy to overcome this barrier, electrons become excited and travel from VB to CB and leave holes behind. These electrons and holes join forces with other ROS and cause the MP to break down into small fragments (55). A schematic of this process can be seen in Figure 3 (56).

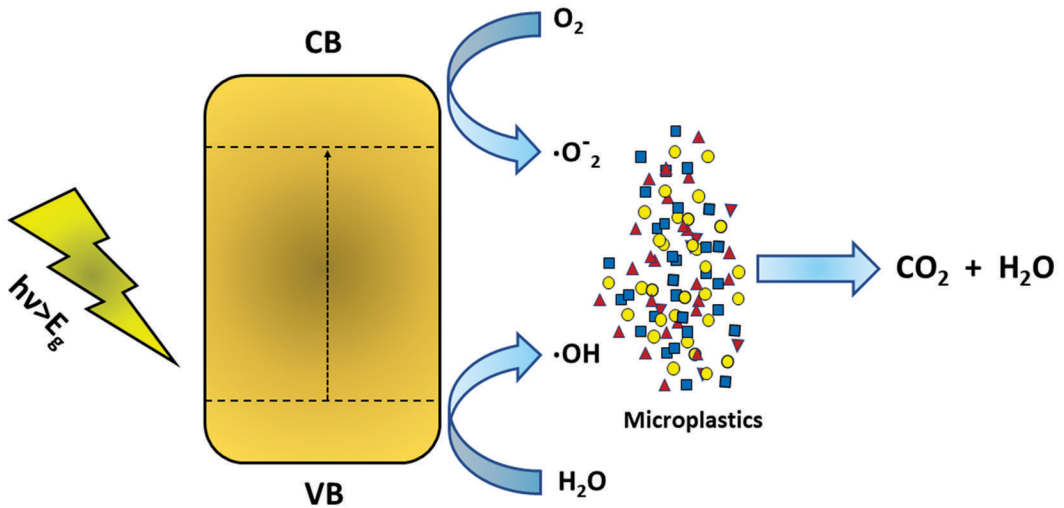


Figure 3. Photocatalytic plastic removal. Reproduced with permission from reference (56). Copyright 2024 Elsevier.

Kinetics of the Reactions

One of the reasons why photocatalysis has not caught on despite its many benefits is the long reaction time it has to degrade the MPs after irradiation compared to other methods. The length of the reaction depends first on the photocatalyst itself, then the environmental operation conditions, and by changing these two variables we can achieve faster degradation (54). The below reactions are the pathways through which the ROS are generated that in turn degrade the particles.



An example of the kinetics study of photocatalytic plastic removal is the study done by Tofa et al. that used rod-shaped ZnO to evaluate the photocatalytic removal of low-density polyethylene. They found that there is a direct correlation between catalyst concentration and the length of light irradiation. Additionally, they fitted the experimental data with kinetic models and proposed a pseudo-first-order model for the LDPE removal reaction (57).

Toxicity of the Products to the Environment

Photocatalytic plastic degradation could result in toxic byproduct generation and this problem depends on the semiconductor type and nature as well as the MP type and size. An example of this is the formation of toxic carbonyl compounds during polyethylene degradation using polypyrrole/TiO₂ as photocatalyst (58). These toxic materials were also found in another study that used nanorod ZnO for propylene removal (59). The MP degradation products could become a source of contamination so it is necessary to have a thorough evaluation of contamination level before and after photocatalytic treatment (58, 59).

Advantages and Disadvantages

This treatment method, similar to other techniques, has merits turning attention toward it. First is the high degradation efficiency of photocatalytic MP removal which can reach a very high removal rate. On top of that, this process is considered to be an economically affordable method compared to other treatments (60). It is also an environmentally-friendly procedure without the need for any toxic chemicals which perfectly aligns with sustainable practices (61). Also, this method is highly versatile as it can treat both solutions and air and it is capable of treating bacteria, dyes, plastics, CO₂, and various other pollutants that are resistant to other methods.

But photocatalysis is not without its shortcomings especially when considering that light source is a necessary part of this treatment. So, a limitation arises that only surface MPs can be removed and the particles buried in sediments will not be affected by this method (62). Another problem is catalyst deactivation over time decreases the overall efficiency in the long run (63). Lastly, the toxic byproducts are another downside of this method highlighting the need for careful consideration before implementing it in treatment systems (64).

Figure 4 compares four methods we have discussed thus far in seven distinct categories. It is evident that except for the method costs, photocatalysis is the superior technique with higher efficiencies, high flexibility, and safety compared to the other three methods.

6.2.3. Thermal Treatment

Another chemical method for microplastic removal in thermal processes such as pyrolysis, gasification, and direct combustion (66).

Decomposition Pathways

When subjected to thermal treatment MP particles undergo processes like thermal cracking, pyrolysis, and gasification. This high-temperature exposure and the resulting thermal cracking cause chains in the polymer (plastic) to break down forming smaller fragments. Meanwhile, when particles undergo pyrolysis the plastics degrade to volatile compounds, gases, and char (65).

The main appeal of this method is the ability to produce energy from plastic while reducing contamination levels. This is due to the high calorific value of plastic which can generate hydrocarbon gases such as methane, which is a form of renewable energy, when thermally treated (67). However, it is important to note that this method is best combined with other physical techniques to reach a high overall removal rate.

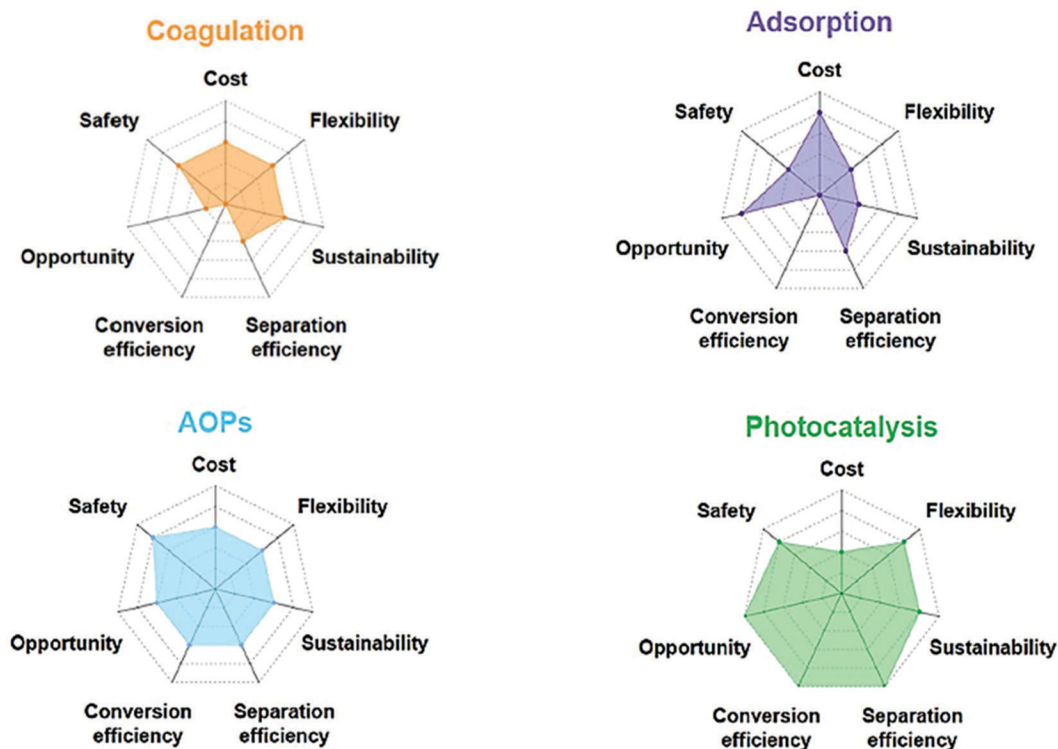


Figure 4. A comparative schematic of the strategies including coagulation, adsorption, AOPs, and photocatalysis towards MP removal (65). Copyright the authors. Licensed under CC BY 4.0 DEED: <https://creativecommons.org/licenses/by/4.0/deed.en>

Kinetics of the Reactions

The kinetics of thermal MP treatment is the rate at which particles degrade under the influence of heat. The study of this kinetics is necessary to understand the degradation pathways that microplastic particles take under high temperatures experienced during processes such as pyrolysis. Additionally, this study can give insight into the kinetics parameters involved in this process which in turn helps to design highly efficient removal systems (68).

An example of these studies is the work done by Chen et al. where they applied the Independent Parallel Reaction (IPR) model and Particle Swarm Optimization (PSO) algorithm to investigate the kinetics of microplastic pyrolysis. It was found that the activation energy was between 273.89 and 292.9 kJ/mol and these values increased with higher heating rate and lower dispersion degrees. This heating rate dependence on the activation energy shows that this rate could control the microplastic degradation rate as expected.

Toxicity of the Products to the Environment

The thermal treatment of microplastics could generate and release harmful gases such as dioxin and furans. In a work by Wang et al., the efficiency of Mg/Zn-modified magnetic biochar's (pyrolysis catalyst) MP degradation from water was studied. It was found that pyrolysis of MP in the operational conditions generates benzene, toluene, and styrene which are Volatile Organic Compounds (VOCs). Despite this finding of toxic byproducts in the outlet, their concentrations

were within the acceptable exposure level guideline established by the US Environmental Protection Agency (EPA) (69).

Advantages and Disadvantages

The thermal treatment of microplastics, especially through pyrolysis, is a highly efficient degradation technique breaking microplastics down into smaller pieces and even mineralizing them into non-toxic products (68). On top of that, thermal treatments such as gasification have the extra benefit of generating clean energy in the form of syngas or biofuel in general by incineration of plastic waste (70). And this method can reduce the plastic waste volume significantly helping the handling and disposal of plastic waste. These benefits of MP thermal treatment are not limited to the type of plastic and this means they can be a very attractive option for waste management (68).

In the meantime, thermal treatments are not the most environmentally friendly approach as they emit greenhouse gases and generate VOCs among other toxic byproducts. So, to prevent further contamination, the residues and byproducts of these treatments should be carefully handled and stored (68). Another issue of these processes is the high energy consumption which undermines their sustainability goals (70). Also since combustion is involved in these methods, there is always the possibility of incomplete degradation which leads to the formation of toxic compounds (68).

6.2.4. Biological Removal

The degradation of plastics by microorganisms is commonly referred to as biological MP removal. These microorganisms bite, chew, and digest plastic particles through biochemical processes (71, 72). Bacteria, fungi, and algae are the main microorganisms responsible for biological plastic degradation (73).

Algae:

The essential function of various photosynthetic and heterotrophic algae in bioremediation has been well investigated. Through accumulation, adsorption, or metabolism, they can eliminate organic and mineral contaminants from various environments to relatively safe levels (74). On the other hand, compared to other microorganisms, the ability of algae to break down synthetic plastic polymers has not been thoroughly investigated. Nevertheless, various reports have demonstrated the capacity to consume plastics by marine algae. It has been demonstrated that some algae species, including *Anabaena*, *Chlorella*, *Spirogyra*, *Nostoc*, *Oscillatoria*, and *Spirulina*, degrade various kinds of plastic, even in terrestrial habitats. However, since algae, as opposed to bacteria, primarily obtain their carbon from sunlight and ambient carbon dioxide, there is no proof that they metabolize polymers (75, 76).

Fungi:

Fungi and bacteria are most significant in maintaining Earth's vital nutrients and biogeochemical cycles. Because these fungal species can use these synthetic polymers as their main or only source of carbon and energy, their potential to break down different synthetic plastic polymers is emphasized.

Particularly, many fungal strains have been shown to eliminate plastics. The majority of recent research has demonstrated that *Aspergillus* is the most significant group of fungi that can degrade synthetic plastic polymers. It has been indicated that *Aspergillus* species *A. clavatus* and *A. niger*, which were isolated from various terrestrial environments, breakdown polyethylene and polypropylene plastics. Additional fungi that can significantly break down plastic include *Geomyces pannorum*, *Fusarium solani*, *Alternaria solani*, and *Spicaria* spp (77, 78). Moreover, contrary to much research that has concentrated on the potential of pure cultures, various fungal consortiums have additionally been demonstrated to synergistically degrade different plastics, such as polyethylene (79). Similar to many biological processes, these investigations have emphasized the function of fungal enzymes, particularly depolymerase. In addition, these enzymes' diverse properties, which enable them to break down different polymers, are remarkable (80).

Bacteria:

Bacteria are the engine of the Earth's nutrient cycle as they are at the forefront of converting and cycling environmental nutrients. Like other microorganisms, their function in decomposition guarantees the release of carbon and nutrients from various natural and synthetic complex polymers. Due to their essential role in bioremediation, they have been studied and shown to break down various substances such as antibiotics, metallic compounds, oil, and plastic materials. Among bacteria species, *Pseudomonas*, *Escherichia*, and *Bacillus* species have demonstrated a high degree of capability for degrading plastic polymers (78). Bacteria's ability to break down plastics depends on the natural ability to break down long-chain fatty acids (81). Although most research has focused on the biodegradation of pure bacterial cultures, bacteria typically work cooperatively in consortia in nature (82).

Degradation Pathway

Microplastic degradation aims to mineralize particles into CO_2 and H_2O (CH_4 under anaerobic conditions). The first step towards achieving this objective involves breaking the plastics into smaller fragments by depolymerizing them into smaller chains or smaller molecules that may be critical for microbial uptake and growth. Extracellular enzymes and free radicals that microbes produce catalytically cleave the biodegraded plastics.

The premise of enzymatic degradation is microbial colonization on the plastic surface through adhesion or exposure. Afterward, catalytic hydrolysis and cracking occur by combining enzyme and polymer matrix, known as hydrolysis. This hydrolysis catalysis by hydrolase as the bound enzyme. Extracellular enzymes, such as depolymerase and hydrolases, cause hydrolytic breakage of the polymer chain, resulting in tiny oligomers or monomers with which bacteria can integrate. Small oligomers or monomers can also be absorbed in the cell after being metabolized by cell enzymes (83).

The biological degradation process of microplastics can be summarized as follows (84):

- 1) Polymers are initially degraded into smaller particles with shorter chains.
- 2) The degradation of polymers to oligomers, dimers, and their monomers.
- 3) The mineralization of microplastics by microbial communities.

These steps are schematically exhibited in Figure 5 (85) for further attention of the reader.

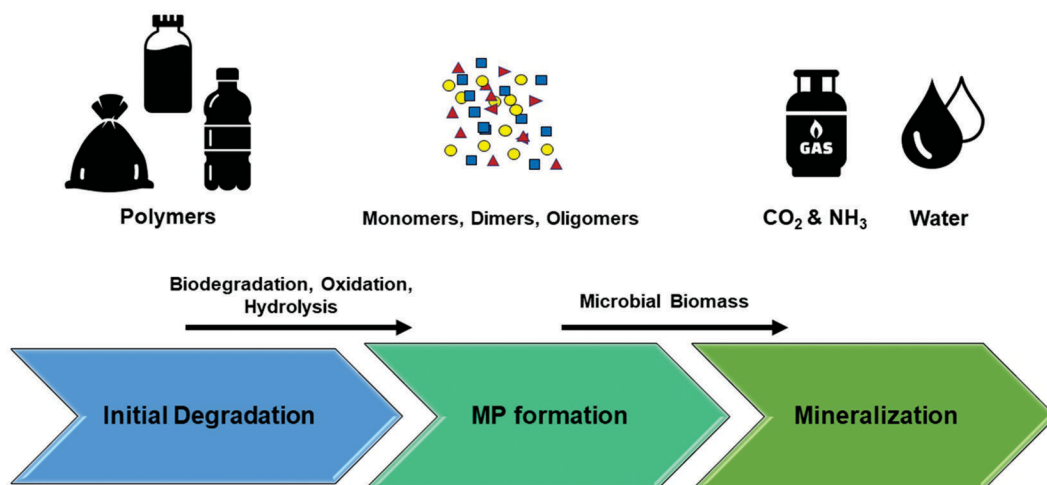


Figure 5. Degradation and biodegradation of polymers. Reproduced with permission from reference (85). Copyright 2024 Elsevier.

Microorganisms have adapted to survive under the harsh conditions brought on by microplastics in the environment. Microorganisms react to this stress in several manners, including accelerated growth, increased metabolic rate, and the creation of new macromolecules for cellular defense. Since these enzymes play a significant role in regulating cellular function, there is a close relationship between enzymatic activity and these stress responses. Enzymes play a role in cellular function, regulation, and degradation of human pollutants, including microplastics (8). Each enzyme shows unique interaction mechanisms during the degradation of microplastics. Typically, the mechanism can be broadly classified into two primary categories.

The surface modification mechanisms by hydrolytic enzymes (Lipase, Carboxylesterase, Cutinase, and Protease) are responsible for modifying the surface of microplastic polymers susceptible to degradation. These enzymes increase the hydrophilicity of microplastic surfaces. They may create specific sensitive links in the polymer side chains or new chemical groups on the polymer chain, increasing the chain cleavage. However, due to their size, it is unlikely that they will be released into the polymer structure; therefore, degradation may occur at the surface level, and the building blocks of microplastics would not be destroyed (85, 86).

In the second mechanism, degrading enzymes secreted by microorganisms can specifically target the polymer structure of microplastics and break them down into their monomers, oligomers, and dimers, which can later be used as a carbon source in the energy production of microorganisms. Many studies have been conducted in the past decade to find these enzymes. It is claimed that several groups of enzymes can degrade polymers into their monomeric forms. Oxidase, Amidase, Laccase, Hydrolase, and Peroxidases are groups of enzymes that play a role in polymer degradation (87, 88).

Kinetics

The kinetics of microplastic biological degradation refers to the rate at which microorganisms remove the microplastic. Microplastic biological degradation kinetics could vary based on the kind of microplastic and the microbial species involved. *Bacillus cereus* and *Bacillus gotthelii*, for example, have been discovered to break a variety of microplastics, including polyethylene, polypropylene, polystyrene, and polyethylene terephthalate, at different rates. Environmental parameters, including temperature, salinity, pH, and nutrition availability, can also impact the kinetics of microplastic

biological degradation. Plastic characteristics may also influence the kinetics of microplastic biological removal. For instance, the molecular weight and chemical structure of plastic can influence its biodegradability (89, 90).

Determination of weight loss of residual, reduction rate, and half-life of residual microplastic particles are three ways to evaluate the plastic polymer degradation pathway and its kinetic, which are shown in the following formulas.

$$\% \text{weight loss} = \left(\frac{W_0 - W}{W_0} \right) \times 100 \quad (1)$$

where W_0 is the initial weight of the microplastics (in grams), and W is the residual weight of the microplastics (in grams).

$$K = -\frac{1}{t} \left(\ln \frac{W}{W_0} \right) \quad (2)$$

where K is the first-order rate constant for the microplastics uptake per day, t is time in days, W is the weight of residual microplastics, and W_0 is the initial weight of microplastics.

Toxicity Assessment of the Products

A necessary step for evaluating the efficiency of this method is to assess the toxicity levels of products. There have been several studies focusing on this subject an example of which is the study by Miloloža et al. In this study, *Pseudomonas putida* was used to degrade polystyrene microplastics and the assessments indicated that the products had less toxicity than PS highlighting the effectiveness of this microorganism in PS particle removal (91).

This finding, on top of many similar research, shows that the byproducts of biological MP degradation are usually less toxic than the original contaminants. Nevertheless, it has to be noted that the toxicity level of byproducts depends on the type of MP, the microorganism involved, and the environmental conditions (45).

Advantages and Disadvantages

Using biological plastic removal is commonly seen as an environmentally-friendly approach. The removal can occur by various biological procedures resulting in much lower contamination levels. On top of that, this method can even be more affordable than alternative chemical or physical removal techniques. So, wastewater treatment plants usually incorporate this technique in their systems to maximize plastic removal. However, biological removal can be relatively slow requiring extended time for efficient MP degradation. Additionally, the long-term effect of plastic removal by microorganisms on human health is not a fully understood subject and it requires more investigation. Certain organisms lack removal versatility and may only be effective for certain MP types which limits their application. Therefore, more investigation is required to find the optimum biological removal method for MPs, understand this method's effect on the ecosystems, and establish environment-specific protocols for applying it (92, 93).

7. Perspective

The removal of microplastics is still being researched in several exciting directions. Future research may concentrate on developing new catalysts and adjusting type-specific parameters of MPs.

Creating new catalysts with higher photocatalytic activity is another pathway forward. To increase the effectiveness and selectivity for MP removal, research proposes looking into modified catalyst materials as well as examining the synergistic effects between various types of catalysts (94).

Further, developing new materials with improved adsorption kinetics and capabilities for effective microplastic removal is another promising research path that may be pursued by enhancing sorbent materials. This may include composite materials, functionalized surfaces, or tailored nanostructures (38). Additionally, investigating cutting-edge thermal degradation methods like plasma treatment or microwave-assisted pyrolysis provides novel approaches to improve the effectiveness and selectivity of MP degradation (68). Finally, incorporating current biotechnological techniques, such as gene editing tools and bioinformatics, may enhance the selectivity and efficiency of microbial degradation processes, providing creative answers to the problems brought on by MP contamination (93). Together, these research directions provide practical approaches to reducing microplastic contamination in various environmental settings.

8. Conclusion

In summary, this chapter discussed the importance of plastic in recent history as well as its problems later discovered. Then, the removal approaches (physical, chemical, and biological) were discussed to lessen the harmful effects of microplastic particles in different environments. Each method was discussed in detail highlighting its benefits, drawbacks, MP degradation pathway, and the kinetics. On top of these, the toxicity of byproducts was also mentioned as a factor to consider when assessing the viability of each technique. Overall, as discussed, each method has its drawbacks limiting its applicability, so it is essential to pursue further research to improve the techniques. Doing this will ensure the degradation methods become more environmentally friendly and follow sustainable development guidelines.

References

1. Baekeland, L. H. *Method of Making Insoluble Products of Phenol and Formaldehyde*. Patent US942699A, 1909.
2. Hamd, W.; Daher, E. A.; Tofa, T. S.; Dutta, J. Recent Advances in Photocatalytic Removal of Microplastics: Mechanisms, Kinetic Degradation, and Reactor Design. *Front. Mar. Sci.* **2022**, *9*; DOI: 10.3389/fmars.2022.885614.
3. Ahmed, R.; Hamid, A. K.; Krebsbach, S. A.; He, J.; Wang, D. Critical Review of Microplastics Removal from the Environment. *Chemosphere* **2022**, *293*, 133557; DOI: 10.1016/j.chemosphere.2022.133557.
4. Alimi, O. S.; Fadare, O. O.; Okoffo, E. D. Microplastics in African Ecosystems: Current Knowledge, Abundance, Associated Contaminants, Techniques, and Research Needs. *Sci. Total Environ.* **2021**, *755* (1), 142422; DOI: 10.1016/j.scitotenv.2020.142422.
5. Arthur, C.; Baker, J. E.; Bamford, H. A. *Proceedings of the International Research Workshop on the Occurrence, Effects, and Fate of Microplastic Marine Debris, September 9-11, 2008*; University of Washington, 2009, Technical memorandum. https://repository.library.noaa.gov/view/noaa/2509/noaa_2509_DS1.pdf
6. Cole, M.; Lindeque, P.; Halsband, C.; Galloway, T. S. Microplastics as Contaminants in the Marine Environment: A Review. *Mar. Pollut. Bull.* **2011**, *62* (12), 2588–2597; DOI: 10.1016/j.marpolbul.2011.09.025.

7. Kershaw, P. J.; Rochman, C. M. Sources, Fate and Effects of Microplastics in the Marine Environment: part 2 of a global assessment. *Reports and Studies-IMO/FAO/Unesco-IOC/WMO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) Eng No. 93*, 2015. <http://www.gesamp.org> (accessed 08-08-2024).
8. Othman, A. R.; Hasan, H. A.; Muhamad, M. H.; Ismail, N. I.; Abdullah, S. R. S. Microbial Degradation of Microplastics by Enzymatic Processes: A Review. *Environ. Chem. Lett.* **2021**, *19* (4), 3057–3073; DOI: 10.1007/s10311-021-01197-9.
9. Wagner, S.; Hüffer, T.; Klöckner, P.; Wehrhahn, M.; Hofmann, T.; Reemtsma, T. Tire Wear Particles in the Aquatic Environment - A Review on Generation, Analysis, Occurrence, Fate and Effects. *Water Res* **2018**, *139*, 83–100; DOI: 10.1016/j.watres.2018.03.051.
10. He, L.; Wu, D.; Rong, H.; Li, M.; Tong, M.; Kim, H. Influence of Nano- and Microplastic Particles on the Transport and Deposition Behaviors of Bacteria in Quartz Sand. *Environ. Sci. Technol.* **2018**, *52* (20), 11555–11563; DOI: 10.1021/acs.est.8b01673.
11. Li, X.; Chen, L.; Ji, Y.; Li, M.; Dong, B.; Qian, G.; Zhou, J.; Dai, X. Effects of Chemical Pretreatments on Microplastic Extraction in Sewage Sludge and Their Physicochemical Characteristics. *Water Res* **2020**, *171*, 115379; DOI: 10.1016/j.watres.2019.115379.
12. Li, Z.; Li, R.; Li, Q.; Zhou, J.; Wang, G. Physiological Response of Cucumber (*Cucumis sativus* L.) Leaves to Polystyrene Nanoplastics Pollution. *Chemosphere* **2020**, *255*, 127041; DOI: 10.1016/j.chemosphere.2020.127041.
13. Kurniawan, S. B.; Abdullah, S. R. S.; Imron, M. F.; Ismail, N. I. Current State of Marine Plastic Pollution and Its Technology for More Eminent Evidence: A Review. *J. Cleaner Prod.* **2021**, *278*, 123537; DOI: 10.1016/j.jclepro.2020.123537.
14. Zhang, K.; Hamidian, A. H.; Tubić, A.; Zhang, Y.; Fang, J. K. H.; Wu, C.; Lam, P. K. S. Understanding Plastic Degradation and Microplastic Formation in the Environment: A Review. *Environ. Pollut.* **2021**, *274*, 116554; DOI: 10.1016/j.envpol.2021.116554.
15. Chen, X.; Xiong, X.; Jiang, X.; Shi, H.; Wu, C. Sinking of Floating Plastic Debris Caused by Biofilm Development in a Freshwater Lake. *Chemosphere* **2019**, *222*, 856–864; DOI: 10.1016/j.chemosphere.2019.02.015.
16. Rezaei, M.; Riksen, M. J. P. M.; Sirjani, E.; Sameni, A.; Geissen, V. Wind Erosion as a Driver for Transport of Light Density Microplastics. *Sci. Total Environ.* **2019**, *669*, 273–281; DOI: 10.1016/j.scitotenv.2019.02.382.
17. Du, C.; Liang, H.; Li, Z.; Gong, J. Pollution Characteristics of Microplastics in Soils in Southeastern Suburbs of Baoding City, China. *Int. J. Environ. Res. Public Health* **2020**, *17* (3), 845; DOI: 10.3390/ijerph17030845.
18. Zhang, S.; Wang, J.; Yan, P.; Hao, X.; Xu, B.; Wang, W.; Aurangzeib, M. Non-biodegradable Microplastics in Soils: A Brief Review and Challenge. *J. Hazard. Mater.* **2021**, *409*, 124525; DOI: 10.1016/j.jhazmat.2020.124525.
19. Zhang, S.; Liu, X.; Hao, X.; Wang, J.; Zhang, Y. Distribution of Low-Density Microplastics in the Mollisol Farmlands of Northeast China. *Sci. Total Environ.* **2020**, *708*, 135091; DOI: 10.1016/j.scitotenv.2019.135091.
20. Yu, M.; Van Der Ploeg, M.; Lwanga, E. H.; Yang, X.; Zhang, S.; Ma, X.; Ritsema, C. J.; Geissen, V. Leaching of Microplastics by Preferential Flow in Earthworm (*Lumbricus terrestris*) Burrows. *Environ. Chem.* **2019**, *16* (1), 31–40; DOI: 10.1071/EN18161.

21. Zhang, S.; Wang, J.; Liu, X.; Qu, F.; Wang, X.; Wang, X.; Li, Y.; Sun, Y. Microplastics in the Environment: A Review of Analytical Methods, Distribution, and Biological Effects. *TrAC Trends Anal. Chem.* **2019**, *111*, 62–72; DOI: 10.1016/j.trac.2018.12.002.
22. Schwabl, P.; Köppel, S.; Königshofer, P.; Bucsecs, T.; Trauner, M.; Reiberger, T.; Liebmann, B. Detection of Various Microplastics in Human Stool: A Prospective Case Series. *Ann. Intern. Med.* **2019**, *171* (7), 453–457; DOI: 10.7326/M19-0618.
23. Li, Z.; Yi, X.; Zhou, H.; Chi, T.; Li, W.; Yang, K. Combined Effect of Polystyrene Microplastics and Dibutyl Phthalate on the Microalgae *Chlorella pyrenoidosa*. *Environ. Pollut.* **2020**, *257*, 113604; DOI: 10.1016/j.envpol.2019.113604.
24. Khalid, N.; Aqeel, M.; Noman, A. Microplastics Could Be a Threat to Plants in Terrestrial Systems Directly or Indirectly. *Environ. Pollut.* **2020**, *267*, 115653; DOI: 10.1016/j.envpol.2020.115653.
25. Chang, X.; Fang, Y.; Wang, Y.; Wang, F.; Shang, L.; Zhong, R. Microplastic Pollution in Soils, Plants, and Animals: A Review of Distributions, Effects and Potential Mechanisms. *Sci. Total Environ.* **2022**, *850*, 157857; DOI: 10.1016/j.scitotenv.2022.157857.
26. Helcoski, R.; Yonkos, L. T.; Sanchez, A.; Baldwin, A. H. Wetland Soil Microplastics Are Negatively Related to Vegetation Cover and Stem Density. *Environ. Pollut.* **2020**, *256*, 113391; DOI: 10.1016/j.envpol.2019.113391.
27. Lusher, A. L.; Mchugh, M.; Thompson, R. C. Occurrence of Microplastics in the Gastrointestinal Tract of Pelagic and Demersal Fish from the English Channel. *Mar. Pollut. Bull.* **2013**, *67* (1-2), 94–99; DOI: 10.1016/j.marpolbul.2012.11.028.
28. Wang, T.; Yu, C.; Chu, Q.; Wang, F.; Lan, T.; Wang, J. Adsorption Behavior and Mechanism of Five Pesticides on Microplastics from Agricultural Polyethylene Films. *Chemosphere* **2020**, *244*, 125491; DOI: 10.1016/j.chemosphere.2019.125491.
29. Huang, W.; Song, B.; Liang, J.; Niu, Q.; Zeng, G.; Shen, M.; Deng, J.; Luo, Y.; Wen, X.; Zhang, Y. Microplastics and Associated Contaminants in the Aquatic Environment: A Review on Their Ecotoxicological Effects, Trophic Transfer, and Potential Impacts to Human Health. *J. Hazard. Mater.* **2021**, *405*, 124187; DOI: 10.1016/j.jhazmat.2020.124187.
30. Ju, P.; Zhang, Y.; Zheng, Y.; Gao, F.; Jiang, F.; Li, J.; Sun, C. Probing the Toxic Interactions Between Polyvinyl Chloride Microplastics and Human Serum Albumin by Multispectroscopic Techniques. *Sci. Total Environ.* **2020**, *734*, 139219; DOI: 10.1016/j.scitotenv.2020.139219.
31. Koelmans, A. A.; Mohamed Nor, N. H. M.; Hermsen, E.; Kooi, M.; Mintenig, S. M.; De France, J. Microplastics in Freshwaters and Drinking Water: Critical Review and Assessment of Data Quality. *Water Res* **2019**, *155*, 410–422; DOI: 10.1016/j.watres.2019.02.054.
32. Ya, H.; Jiang, B.; Xing, Y.; Zhang, T.; Lv, M.; Wang, X. Recent Advances on Ecological Effects of Microplastics on Soil Environment. *Sci. Total Environ.* **2021**, *798*, 149338; DOI: 10.1016/j.scitotenv.2021.149338.
33. Li, Z.; Yang, Y.; Chen, X.; He, Y.; Bolan, N.; Rinklebe, J.; Lam, S. S.; Peng, W.; Sonne, C. A Discussion of Microplastics in Soil and Risks for Ecosystems and Food Chains. *Chemosphere* **2023**, *313*, 137637; DOI: 10.1016/j.chemosphere.2022.137637.
34. Zhang, T.; Jiang, B.; Xing, Y.; Ya, H.; Lv, M.; Wang, X. Current Status of Microplastics Pollution in the Aquatic Environment, Interaction with Other Pollutants, and Effects on Aquatic Organisms. *Environ. Sci. Pollut. Res. Int.* **2022**, *29* (12), 16830–16859; DOI: 10.1007/s11356-022-18504-8.

35. Arias-Andres, M.; Rojas-Jimenez, K.; Grossart, H.-P. Collateral Effects of Microplastic Pollution on Aquatic Microorganisms: An Ecological Perspective. *TrAC Trends Anal. Chem.* **2019**, *112*, 234–240; DOI: 10.1016/j.trac.2018.11.041.
36. Hartmann, N. B.; Rist, S.; Bodin, J.; Jensen, L. H.; Schmidt, S. N.; Mayer, P.; Meibom, A.; Baun, A. Microplastics as Vectors for Environmental Contaminants: Exploring Sorption, Desorption, and Transfer to Biota. *Integr. Environ. Assess. Manag.* **2017**, *13* (3), 488–493; DOI: 10.1002/ieam.1904.
37. Liu, Q.; Khor, S. M. Emerging Adsorption-Based Techniques for Removing Microplastics and Nanoplastics from Actual Water Bodies. *TrAC Trends Anal. Chem.* **2024**, *170*, 117465; DOI: 10.1016/j.trac.2023.117465.
38. Tang, Y.; Zhang, S.; Su, Y.; Wu, D.; Zhao, Y.; Xie, B. Removal of Microplastics from Aqueous Solutions by Magnetic Carbon Nanotubes. *Chem. Eng. J.* **2021**, *406*, 126804; DOI: 10.1016/j.cej.2020.126804.
39. Singh, S.; Kalyanasundaram, M.; Diwan, V. Removal of Microplastics from Wastewater: Available Techniques and Way Forward. *Water Sci. Technol.* **2021**, *84* (12), 3689–3704; DOI: 10.2166/wst.2021.472.
40. Adegoke, K. A.; Adu, F. A.; Oyebamiji, A. K.; Bamisaye, A.; Adigun, R. A.; Olasoji, S. O.; Ogunjinmi, O. E. Microplastics Toxicity, Detection, and Removal from Water/Wastewater. *Mar. Pollut. Bull.* **2023**, *187*, 114546; DOI: 10.1016/j.marpolbul.2022.114546.
41. New, W. X.; Kristanti, R. A.; Manik, H.; Wijayanti, Y.; Adeyemi, D. A. Occurrence of Microplastics in Drinking Water in South East Asia: A Short Review. *Trop. Environ. Biol. Technol.* **2023**, *1* (1), 14–24; DOI: 10.53623/tebt.v1i1.221.
42. Zhang, Y.; Jiang, H.; Bian, K.; Wang, H.; Wang, C. A Critical Review of Control and Removal Strategies for Microplastics from Aquatic Environments. *J. Environ. Chem. Eng.* **2021**, *9* (4), 105463; DOI: 10.1016/j.jece.2021.105463.
43. Prata, J. C.; Silva, A. L. P.; Walker, T. R.; Duarte, A. C.; Rocha-Santos, T. COVID-19 Pandemic Repercussions on the Use and Management of Plastics. *Environ. Sci. Technol.* **2020**, *54* (13), 7760–7765; DOI: 10.1021/acs.est.0c02178.
44. Xing, J.; Wang, H.; Cheng, X.; Tang, X.; Luo, X.; Wang, J.; Wang, T.; Li, G.; Liang, H. Application of Low-Dosage UV/Chlorine Pre-oxidation for Mitigating Ultrafiltration (UF) Membrane Fouling in Natural Surface Water Treatment. *Chemical Engineering Journal* **2018**, *344*, 62–70; DOI: 10.1016/j.cej.2018.03.052.
45. Pandey, B.; Pathak, J.; Singh, P.; Kumar, R.; Kumar, A.; Kaushik, S.; Thakur, T. K. Microplastics in the Ecosystem: An Overview on Detection, Removal, Toxicity Assessment, and Control Release. *Water* **2022**, *15* (1), 51; DOI: 10.3390/w15010051.
46. Miranda Zoppas, F. M.; Sacco, N.; Soffiatti, J.; Devard, A.; Akhter, F.; Marchesini, F. A. Catalytic Approaches for the Removal of Microplastics from Water: Recent Advances and Future Opportunities. *Chem. Eng. J. Adv.* **2023**, *16*, 100529; DOI: 10.1016/j.cej.2023.100529.
47. Venkataramana, C.; Botsa, S. M.; Shyamala, P.; Muralikrishna, R. Photocatalytic Degradation of Polyethylene Plastics by NiAl₂O₄ Spinels-Synthesis and Characterization. *Chemosphere* **2021**, *265*, 129021; DOI: 10.1016/j.chemosphere.2020.129021.

48. Kumar, R.; Sharma, P.; Manna, C.; Jain, M. Abundance, Interaction, Ingestion, Ecological Concerns, and Mitigation Policies of Microplastic Pollution in Riverine Ecosystem: A Review. *Sci. Total Environ.* **2021**, *782*, 146695; DOI: 10.1016/j.scitotenv.2021.146695.
49. Kamalian, P.; Khorasani, S. N.; Abdolmaleki, A.; Karevan, M.; Khalili, S.; Shirani, M.; Neisiany, R. E. Toward the Development of Polyethylene Photocatalytic Degradation. *J. Polym. Eng.* **2020**, *40* (2), 181–191; DOI: 10.1515/polyeng-2019-0230.
50. Tsiota, P.; Karkanorachaki, K.; Syranidou, E.; Franchini, M.; Kalogerakis, N. Microbial Degradation of HDPE Secondary Microplastics: Preliminary Results. In *Proceedings of the International Conference on Microplastic Pollution in the Mediterranean Sea*; Springer: 2018; pp 181–188. DOI: 10.1007/978-3-319-71279-6_24.
51. Huang, D.; Tao, J.; Cheng, M.; Deng, R.; Chen, S.; Yin, L.; Li, R. Microplastics and Nanoplastics in the Environment: Macroscopic Transport and Effects on Creatures. *J. Hazard. Mater.* **2021**, *407*, 124399; DOI: 10.1016/j.jhazmat.2020.124399.
52. Liu, F.; Xu, Y.; Zhang, B.; Liu, Y.; Zhang, H. Heterogeneous Degradation of Organic Contaminant by Peroxydisulfate Catalyzed by Activated Carbon Cloth. *Chemosphere* **2020**, *238*, 124611; DOI: 10.1016/j.chemosphere.2019.124611.
53. Lin, J.; Yan, D.; Fu, J.; Chen, Y.; Ou, H. Ultraviolet-C and Vacuum Ultraviolet Inducing Surface Degradation of Microplastics. *Water Res.* **2020**, *186*, 116360; DOI: 10.1016/j.watres.2020.116360.
54. Ebrahimbabaie, P.; Yousefi, K.; Pichtel, J. Photocatalytic and Biological Technologies for Elimination of Microplastics in Water: Current Status. *Sci. Total Environ.* **2022**, *806* (2), 150603; DOI: 10.1016/j.scitotenv.2021.150603.
55. Ibhaddon, A. O.; Fitzpatrick, P. Heterogeneous Photocatalysis: Recent Advances and Applications. *Catalysts* **2013**, *3* (1), 189–218; DOI: 10.3390/catal3010189.
56. Nabi, I.; Bacha, A.-U.-R.; Ahmad, F.; Zhang, L. Application of Titanium Dioxide for the Photocatalytic Degradation of Macro- and Micro-plastics: A Review. *J. Environ. Chem. Eng.* **2021**, *9* (5), 105964; DOI: 10.1016/j.jece.2021.105964.
57. Tofa, T. S.; Kunjali, K. L.; Paul, S.; Dutta, J. Visible Light Photocatalytic Degradation of Microplastic Residues with Zinc Oxide Nanorods. *Environ. Chem. Lett.* **2019**, *17* (3), 1341–1346; DOI: 10.1007/s10311-019-00859-z.
58. Li, S.; Xu, S.; He, L.; Xu, F.; Wang, Y.; Zhang, L. Photocatalytic Degradation of Polyethylene Plastic with Polypyrrole/TiO₂ Nanocomposite as Photocatalyst. *Polym. Plast. Technol. Eng.* **2010**, *49* (4), 400–406; DOI: 10.1080/03602550903532166.
59. Xaba, B. S.; Mahomed, A. S.; Friedrich, H. B. The Effect of CO₂ and H₂ Adsorption Strength and Capacity on the Performance of Ga and Zr Modified Cu-Zn Catalysts for CO₂ Hydrogenation to Methanol. *J. Environ. Chem. Eng.* **2021**, *9* (1), 104834; DOI: 10.1016/j.jece.2020.104834.
60. Rezania, S.; Park, J.; Md Din, M. F.; Mat Taib, S.; Talaiekhosani, A.; Kumar Yadav, K.; Kamyab, H. Microplastics Pollution in Different Aquatic Environments and Biota: A Review of Recent Studies. *Mar. Pollut. Bull.* **2018**, *133*, 191–208; DOI: 10.1016/j.marpolbul.2018.05.022.
61. Li, J.; Yang, D.; Li, L.; Jabeen, K.; Shi, H. Microplastics in Commercial Bivalves from China. *Environ. Pollut.* **2015**, *207*, 190–195; DOI: 10.1016/j.envpol.2015.09.018.

62. Alimi, O. S.; Farner Budariz, J.; Hernandez, L. M.; Tufenkji, N. Microplastics and Nanoplastics in Aquatic Environments: Aggregation, Deposition, and Enhanced Contaminant Transport. *Environ. Sci. Technol.* **2018**, *52* (4), 1704–1724; DOI: 10.1021/acs.est.7b05559.
63. Ariza-Tarazona, M. C.; Villarreal-Chiu, J. F.; Barbieri, V.; Siligardi, C.; Cedillo-González, E. I. New Strategy for Microplastic Degradation: Green Photocatalysis Using a Protein-Based Porous N-TiO₂ Semiconductor. *Ceram. Int.* **2019**, *45* (7), 9618–9624; DOI: 10.1016/j.ceramint.2018.10.208.
64. Ali, S. S.; Qazi, I. A.; Arshad, M.; Khan, Z.; Voice, T. C.; Mehmood, C. T. Photocatalytic Degradation of Low Density Polyethylene (LDPE) Films Using Titania Nanotubes. *Environ. Nanotechnol. Monit. Manag.* **2016**, *5*, 44–53; DOI: 10.1016/j.enmm.2016.01.001.
65. Chen, J.; Wu, J.; Sherrell, P. C.; Chen, J.; Wang, H.; Zhang, W.-X.; Yang, J. How to Build a Microplastics-Free Environment: Strategies for Microplastics Degradation and Plastics Recycling. *Adv. Sci. (Weinh)* **2022**, *9* (6), e2103764; DOI: 10.1002/advs.202103764.
66. Dümichen, E.; Eisentraut, P.; Bannick, C. G.; Barthel, A.-K.; Senz, R.; Braun, U. Fast Identification of Microplastics in Complex Environmental Samples by a Thermal Degradation Method. *Chemosphere* **2017**, *174*, 572–584; DOI: 10.1016/j.chemosphere.2017.02.010.
67. Hu, K.; Tian, W.; Yang, Y.; Nie, G.; Zhou, P.; Wang, Y.; Duan, X.; Wang, S. Microplastics Remediation in Aqueous Systems: Strategies and Technologies. *Water Res* **2021**, *198*, 117144; DOI: 10.1016/j.watres.2021.117144.
68. Chen, W.-H.; Sun, S.-C.; Ocreto, J. B.; Nguyen, T.-B.; Lam, S. S.; Park, Y.-K.; Dong, C.-D. Thermodegradation Characterization of Microplastics: Dispersion Effect and Pyrolysis Kinetics by Artificial Intelligence. *Chem. Eng. J.* **2023**, *457*, 141285; DOI: 10.1016/j.cej.2023.141285.
69. Wang, J.; Sun, C.; Huang, Q.-X.; Chi, Y.; Yan, J.-H. Adsorption and Thermal Degradation of Microplastics from Aqueous Solutions by Mg/Zn Modified Magnetic Biochars. *J. Hazard. Mater.* **2021**, *419*, 126486; DOI: 10.1016/j.jhazmat.2021.126486.
70. Uheida, A.; Mejía, H. G.; Abdel-Rehim, M.; Hamd, W.; Dutta, J. Visible Light Photocatalytic Degradation of Polypropylene Microplastics in a Continuous Water Flow System. *J. Hazard. Mater.* **2021**, *406*, 124299; DOI: 10.1016/j.jhazmat.2020.124299.
71. Porter, A.; Smith, K. E.; Lewis, C. The Sea Urchin *Paracentrotus lividus* as a Bioeroder of Plastic. *Sci. Total Environ.* **2019**, *693*, 133621; DOI: 10.1016/j.scitotenv.2019.133621.
72. Danso, D.; Chow, J.; Streit, W. R. Plastics: Environmental and Biotechnological Perspectives on Microbial Degradation. *Appl. Environ. Microbiol.* **2019**, *85* (19), e01095–e01019; DOI: 10.1128/AEM.01095-19.
73. Crawford, C. B.; Quinn, B. *Microplastic Pollutants*; Elsevier: 2016.
74. Hwang, J.-H.; Sadmani, A.; Lee, S.-J.; Kim, K.-T.; Lee, W. H. Microalgae: An Eco-friendly Tool for the Treatment of Wastewaters for Environmental Safety. *Bioremediation of Industrial Waste for Environmental Safety, II: Biological Agents and Methods for Industrial Waste Management*; Springer: 2019; pp 283–304; DOI: 10.1007/978-981-13-3426-9_12
75. Sarmah, P.; Rout, J. Algal Colonization on Polythene Carry Bags in a Domestic Solid Waste Dumping Site of Silchar Town in Assam. *Phykos* **2018**, *48* (67), e77.
76. Dineshbabu, G.; Uma, V. S.; Mathimani, T.; Prabakaran, D.; Uma, L. Elevated CO₂ Impact on Growth and Lipid of Marine Cyanobacterium *Phormidium Valderianum* BDU 20041-Towards Microalgal Carbon Sequestration. *Biocatal. Agric. Biotechnol.* **2020**, *25*, 101606; DOI: 10.1016/j.bcab.2020.101606.

77. Zhang, J.; Gao, D.; Li, Q.; Zhao, Y.; Li, L.; Lin, H.; Bi, Q.; Zhao, Y. Biodegradation of Polyethylene Microplastic Particles by the Fungus *Aspergillus flavus* from the Guts of Wax Moth *Galleria mellonella*. *Sci. Total Environ.* **2020**, *704*, 135931; DOI: 10.1016/j.scitotenv.2019.135931.
78. Amobonye, A.; Bhagwat, P.; Singh, S.; Pillai, S. Plastic Biodegradation: Frontline Microbes and Their Enzymes. *Sci. Total Environ.* **2021**, *759*, 143536; DOI: 10.1016/j.scitotenv.2020.143536.
79. Sowmya, H.; Ramalingappa, B.; Nayanashree, G.; Thippeswamy, B.; Krishnappa, M. Polyethylene Degradation by Fungal Consortium. *Int. J. Environ. Res.* **2015**, *9* (3), 823–830; DOI: 10.22059/ijer.2015.969.
80. Rodrigues da Luz, J.; Soares da Silva, M.; Ferreira Dos Santos, L.; Kasuya, M. In *Plastics Polymers Degradation by Fungi*; Blumenber, M., Shaaban, M., Elgaml, A., Eds.; IntechOpen: 2019, p 70336. DOI: 10.5772/intechopen.88608.
81. Wilkes, R. A.; Aristilde, L. Degradation and Metabolism of Synthetic Plastics and Associated Products by *Pseudomonas* sp.: Capabilities and Challenges. *J. Appl. Microbiol.* **2017**, *123* (3), 582–593; DOI: 10.1111/jam.13472.
82. Shah, A. A.; Hasan, F.; Akhter, J. I.; Hameed, A.; Ahmed, S. Degradation of Polyurethane by Novel Bacterial Consortium Isolated from Soil. *Ann. Microbiol.* **2008**, *58* (3), 381–386; DOI: 10.1007/BF03175532.
83. Cai, Z.; Li, M.; Zhu, Z.; Wang, X.; Huang, Y.; Li, T.; Gong, H.; Yan, M. Biological Degradation of Plastics and Microplastics: A Recent Perspective on Associated Mechanisms and Influencing Factors. *Microorganisms* **2023**, *11* (7), 1661; DOI: 10.3390/microorganisms11071661.
84. Espinoza, R. M. B.; *Microplastics in wastewater treatment systems and receiving waters*; 2019, University of Glasgow, DOI: 10.5525/gla.thesis.76781.
85. Miri, S.; Saini, R.; Davoodi, S. M.; Pulicharla, R.; Brar, S. K.; Magdouli, S. Biodegradation of Microplastics: Better Late Than Never. *Chemosphere* **2022**, *286* (1), 131670; DOI: 10.1016/j.chemosphere.2021.131670.
86. Kawai, F.; Kawabata, T.; Oda, M. Current Knowledge on Enzymatic PET Degradation and Its Possible Application to Waste Stream Management and Other Fields. *Appl. Microbiol. Biotechnol.* **2019**, *103* (11), 4253–4268; DOI: 10.1007/s00253-019-09717-y.
87. Álvarez-Barragán, J.; Domínguez-Malfavón, L.; Vargas-Suárez, M.; González-Hernández, R.; Aguilar-Osorio, G.; Loza-Tavera, H. Biodegradative Activities of Selected Environmental Fungi on a Polyester Polyurethane Varnish and Polyether Polyurethane Foams. *Appl. Environ. Microbiol.* **2016**, *82* (17), 5225–5235; DOI: 10.1128/AEM.01344-16.
88. Gómez-Méndez, L. D.; Moreno-Bayona, D. A.; Poutou-Piñales, R. A.; Salcedo-Reyes, J. C.; Pedroza-Rodríguez, A. M.; Vargas, A.; Bogoya, J. M. Biodeterioration of Plasma Pretreated LDPE Sheets by *Pleurotus ostreatus*. *PLOS ONE* **2018**, *13* (9), e0203786; DOI: 10.1371/journal.pone.0203786.
89. Auta, H. S.; Emenike, C. U.; Fauziah, S. H. Screening of *Bacillus* Strains Isolated from Mangrove Ecosystems in Peninsular Malaysia for Microplastic Degradation. *Environ. Pollut.* **2017**, *231* (2), 1552–1559; DOI: 10.1016/j.envpol.2017.09.043.

90. Auta, H. S.; Emenike, C. U.; Jayanthi, B.; Fauziah, S. H. Growth Kinetics and Biodeterioration of Polypropylene Microplastics by *Bacillus* sp. and *Rhodococcus* sp. Isolated from Mangrove Sediment. *Mar. Pollut. Bull.* **2018**, *127*, 15–21; DOI: 10.1016/j.marpolbul.2017.11.036.
91. Miloloža, M.; Bule, K.; Prevarić, V.; Cvetnić, M.; Ukić, Š.; Bolanča, T.; Kučić Grgić, D. Assessment of the Influence of Size and Concentration on the Ecotoxicity of Microplastics to Microalgae *Scenedesmus* sp., Bacterium *Pseudomonas putida* and Yeast *Saccharomyces cerevisiae*. *Polymers* **2022**, *14* (6), 1246; DOI: 10.3390/polym14061246.
92. Padervand, M.; Lichtfouse, E.; Robert, D.; Wang, C. Removal of Microplastics from the Environment. A Review. *Environ. Chem. Lett.* **2020**, *18* (3), 807–828; DOI: 10.1007/s10311-020-00983-1.
93. Anand, U.; Dey, S.; Bontempi, E.; Ducoli, S.; Vethaak, A. D.; Dey, A.; Federici, S. Biotechnological Methods to Remove Microplastics: A Review. *Environ. Chem. Lett.* **2023**, *21* (3), 1787–1810; DOI: 10.1007/s10311-022-01552-4.
94. He, J.; Han, L.; Wang, F.; Ma, C.; Cai, Y.; Ma, W.; Xu, E. G.; Xing, B.; Yang, Z. Photocatalytic Strategy to Mitigate Microplastic Pollution in Aquatic Environments: Promising Catalysts, Efficiencies, Mechanisms, and Ecological Risks. *Crit. Rev. Environ. Sci. Technol.* **2023**, *53* (4), 504–526; DOI: 10.1080/10643389.2022.2072658.