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Detection and degradation of microplastics in the environment: a review

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Microplastics (MPs) are a growing environmental concern due to their persistence in the environment and potential negative impacts on human health and the ecosystem. Their widespread presence across terrestrial, aquatic, and atmospheric compartments has prompted an urgent need for improved detection techniques and effective degradation strategies. This review provides an integrated overview of recent advancements in the identification and removal of MPs, with a focus on both analytical and remediation technologies. Progress in spectroscopic, thermal, and imaging-based methods has enabled more precise detection, quantification, and characterization of MPs, particularly at the nano-scale. Simultaneously, a variety of degradation strategies have been developed to mitigate the environmental burden of MPs. These are broadly categorized into physical, chemical, and biological approaches. Physical methods include mechanical removal and thermal processes such as pyrolysis and thermal oxidation. Chemical degradation involves advanced oxidation processes (AOPs) and photocatalysis using semiconductors like titanium dioxide (TiO_2) to accelerate polymer breakdown under light exposure. Among biological approaches, enzymatic and microbial degradation have shown promising results. Enzymes such as PETase, MHETase, cutinases, lipases, and cellulases catalyze the hydrolysis of ester and amide bonds in synthetic polymers, offering selective and environmentally benign pathways for microplastic decomposition. The review further explores the implications of microplastic accumulation, including bioaccumulation and oxidative stress in organisms, and discusses the limitations and challenges of current technologies. Emphasis is placed on integrating detection with degradation strategies to achieve sustainable, scalable, and interdisciplinary solutions. By highlighting the latest scientific advancements, this review aims to guide future research directions and support the development of effective policy and management frameworks for mitigating microplastic pollution.

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Environmental significance

Microplastic pollution has emerged as a critical environmental challenge, with pervasive distribution across terrestrial, freshwater, and marine ecosystems. These microscopic plastic fragments originate from various anthropogenic sources, including industrial processes, synthetic textiles, and the degradation of larger plastic debris. Due to their persistence, bioaccumulative potential, and capacity to adsorb hazardous contaminants, microplastics pose a substantial risk to ecological integrity and human health. Their ingestion by aquatic organisms can lead to trophic transfer, bioamplification, and physiological disruptions, further exacerbating ecosystem imbalances. Consequently, the development of efficient detection methods and sustainable degradation strategies is imperative to mitigate their environmental impact. This review critically evaluates recent advancements in microplastic detection techniques, including spectroscopic, chromatographic, and imaging-based approaches, alongside emerging degradation strategies such as bioremediation, photodegradation, and advanced oxidation processes. Understanding these mechanisms is essential for formulating effective policies and technological interventions aimed at reducing microplastic contamination and preserving environmental sustainability.

1. Introduction

Microplastics, minute plastic particles measuring less than 5 mm, have emerged as a pervasive and intricate environmental concern, representing a global challenge that transcends geographical boundaries and ecosystems.[1] Originating from the fragmentation of larger plastic items, industrial processes, and the breakdown of synthetic materials, these microscopic pollutants have infiltrated terrestrial, freshwater, and marine

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environments, raising critical questions about their occurrence, fate, and overarching environmental impacts.[2,3] But marine habitats, encompassing shorelines, open oceans, and deep seas, are primary areas of focus for microplastics (MPs) research. Currently, over 96% of studies on MPs are related to marine systems. It is estimated that around 4.8 to 12.7 million tons of plastic waste are dumped into the ocean each year from terrestrial sources.[4] Collectively 98% of primary MPs stems from land-based activities and only 2% are come from activities directly related to the ocean. Rivers play a significant role in conveying microplastics from inland areas to the oceans.[5] The ubiquity of microplastics underscores their resilience and the complex pathways through which they enter ecosystems.[6] Their presence has been documented in diverse environmental matrices, including soils, sediments, and aquatic systems, necessitating a comprehensive review to synthesize the current state of knowledge and address critical gaps in understanding.[7,8] Microplastics can trace their origins to a myriad of sources, from the wear and tear of car tyres to the disintegration of plastic packaging and the breakdown of synthetic fibers from textiles.[9–11]

Globally, in the present era, the excessive use of plastic materials and their disposal is a threat for the environment. Following their introduction into the environment, plastic waste endures a gradual degradation process, yielding numerous smaller plastic particles *via* interplay of physical, chemical, and biological mechanisms.[12] This microplastic pollution is increasingly recognized as a significant global environmental concern.[13]

Approximately, 280 million tons of microplastics entering into our environment through different sources and their concentration increases with the passage of time.[14] However, locating the precise source of microplastics detected in the environment is challenging, if not unattainable.[15] Major sources of MPs include domestic sewage, beads, fibers from clothing and personal care products, fertilizer,[16] biosolids,[17,18] vinyl mulch heavily used in agricultural activities,[19,20] illegal waste dumping and littering,[21] dispersion from the landfills, water flooding, irrigation with wastewater, tyre abrasion and transportation of atmospheric particles[22,23] (Fig. 1).

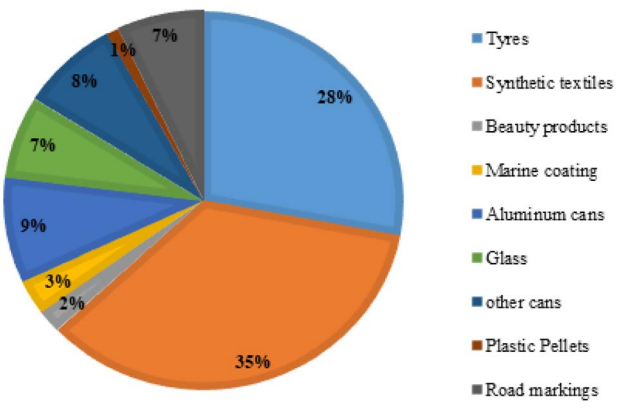

Fig. 1 Sources of microplastics in the environment adapted from ref. 5 and 24.

2. Microplastics

Predominantly microplastics originate from the degradation and fragmentation of larger plastic objects, which occurs through thermal, oxidative, and microbial processes. In fragmentation process, which is carried out through mechanical, chemical and biological processes that convert it into small-size particles.[25,26] Many studies conducted by scientist considered that 'Microplastics' are emerging pollutants based on their size (5 mm).[27,28] Microplastics, the fastest-growing source of aquatic environmental pollution, is becoming a major challenge for the world community. Many of the world scientists working in the area of the environment have reported that less than 10% of plastic products are recyclable and reused again whereas remaining released into the environment to be converted into challenging MPs.[29–31]

According to an estimate, more than 80% of plastic enters into the oceans to make aquatic pollution from land which is freely disposed of on land without any control.[32] In terrestrial ecosystems, the contamination of MPs might be 4–23 folds higher than in the oceans,[16] whereas soil has more capacity to accumulate plastic debris than aquatic ecosystems.[33] Plastic pollution is caused by smaller size particles (1 to <1000 mm) which are unpredictable, persistent and abundantly found in terrestrial, freshwater and marine ecosystems.[34] Generally, it takes decades to centuries to completely degrade in a natural environment due to high stability and durability of plastic materials. As a result, it is crucial to focus on the pollution of MPs in environment as a serious issue (Fig. 2).

Plastic particles of sizes ranging between 1.0 nm to 1.0 μm, 1–5 mm, 5–25 mm and greater than 25 mm, were categorized as nano, micro, meso and macro plastics, respectively. The particulates of microplastics vary in composition, colour, density and dimension, and are classified into various categories. Considering their usage and source, microplastics (MPs) are classified into primary and secondary. Among various types of plastics, the most significant is non-fiber plastics production which includes polypropylene (PP), polyvinylchloride (PVC), polyethylene terephthalate (PET) and polyethylene (PE).[29,35] Microplastic particles are known for having a high capacity of adsorption and desorption of organic pollutants.[36]

Primary microplastics are microscopically formed and present in personal care products such as scrubbers, toothpaste and other cosmetics.[37] These kinds of microplastics are skin care product, and contains various naturally used cosmetics including almonds, walnuts and oatmeal.[38] Small plastic particulates, typically about 0.25 mm in size, are widely utilized in industrial abrasives as shot-blasting agents and beauty products. Microplastic particulates having dimensions like powders and granules are commonly used in a wider variety of applications.[28,39] Microplastic particulates display variable sizes, such as different-sized granules in the same product. Primary microplastics are released directly into the environment from sewage and domestic factories. Plastic pellets from the manufacturing industries, plastic fluff or powder used to produce plastic goods, plastic resin flakes, commercial cleaning

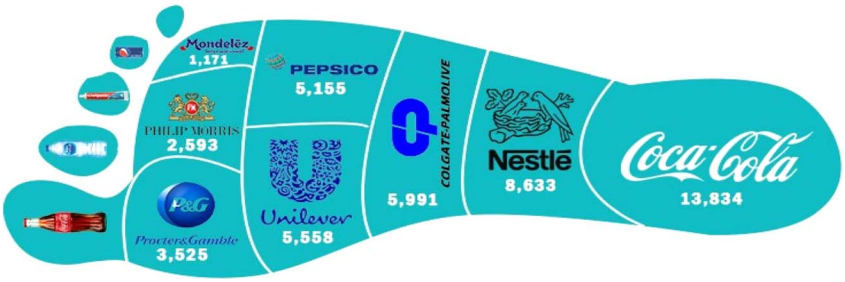

Fig. 2 Footprints of plastic material from 55 countries (2020).

abrasives and scrubbers,[2] together with volatile particulate pollutants including nano SiO_2 and Fe_3O_4 from printing toners and micro-polyester, are the possible origins of primary microplastics.[40]

Microplastic beads are also concluded as constituents in skin-cleansing personal care products, in face and hand scrubs, and for improving the viscosity of toothpaste.[41] Gradual environmental degradation and high demand for plastic materials have become a major threat worldwide. Microplastic beads from skin care products will be carried through the sewage system with wastewater and will not be efficiently eradicated by sewage and therefore concentrate in the ecosystem.[42] Besides the volatile release of primary microplastics, large fragments of plastics can gradually become fragile under the influence of heat and UV and then broken down into smaller particles by mechanical forces such as ocean currents and winds.[43] The majority of microplastics produced in the aquatic environment are caused by the breakdown of larger plastics resulting in secondary microplastics.[44] Degradation of large-sized plastics depends on the amount of UV rays and temperature.[45] The sources of primary and secondary microplastics (MPs) have grown from different pathways of plastic fragmentation as illustrated in Fig. 3.

Along with airborne fragmentation, many other materials disintegrate during use, creating micro-sized particles in the air such as fibers released from clothes during washing.[46] Fabricated clothes comprising microplastics as fibers shed approximately 700 000 fibers from six kg of fabric in one wash.[47] Microplastic pellets which are used as feedstock in industries for plastic products are also a cause of microplastics introduced to the environment. In the therapeutic area of research, microplastics are utilized in pharmaceutical and dental carriers entering the environment by wastewater. The low perceptibility and compact size of primary microplastics make them interesting to isolate from the aquatic environment.[48]

Secondary microplastics are produced from microbial fragmentation of already existing large plastics subsequently into macro-, micro- and nano-sizes, and incremental disintegration by wave abrasion, and UV light. Some other mechanical actions such as intense weathering result in the fragmentation of plastics, thus mounting secondary microplastics in the aqueous system greater than the primary microplastics.[49]

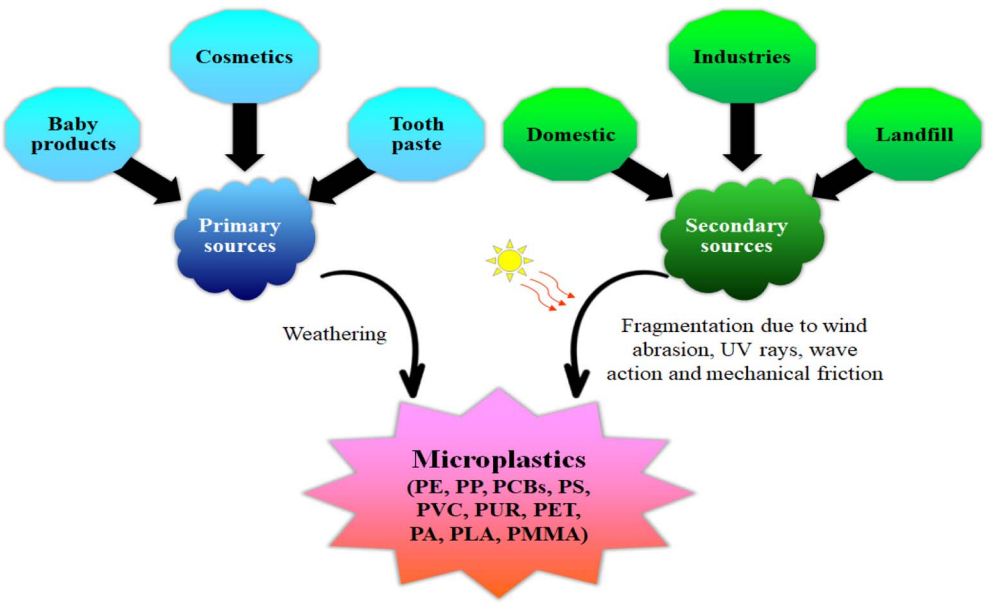

Fig. 3 Types and sources of microplastics.

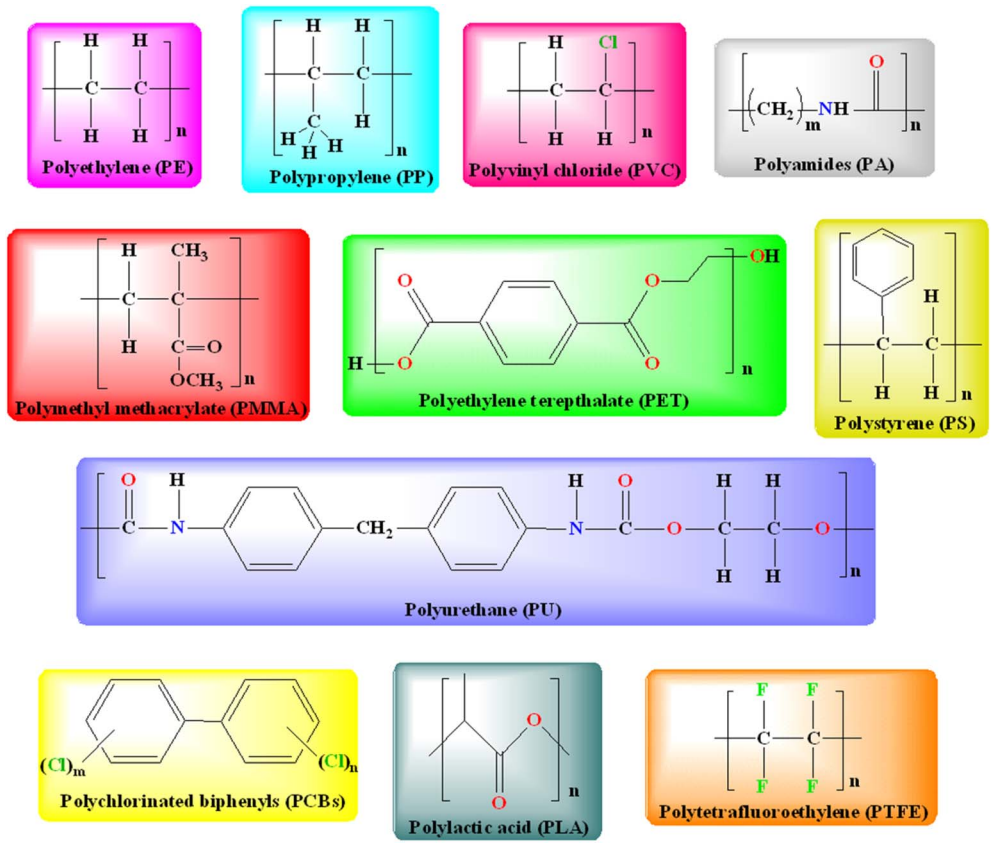

Fig. 4 Structural representation of major compounds of MPs in the environment.

Before settling into the environment because of weathering, like ultraviolet radiation from sunlight, hydrolysis, biodegradation, photo-degradation, wave action and exposure to wind abrasion are the potential paths to produce secondary microplastics.[50] The chemical structure of some major types of plastic found in microplastics (MPs) is illustrated in Fig. 4.

Likewise, the degradation process (Fig. 5), which highlights ways to create secondary microplastics, produced from the slow

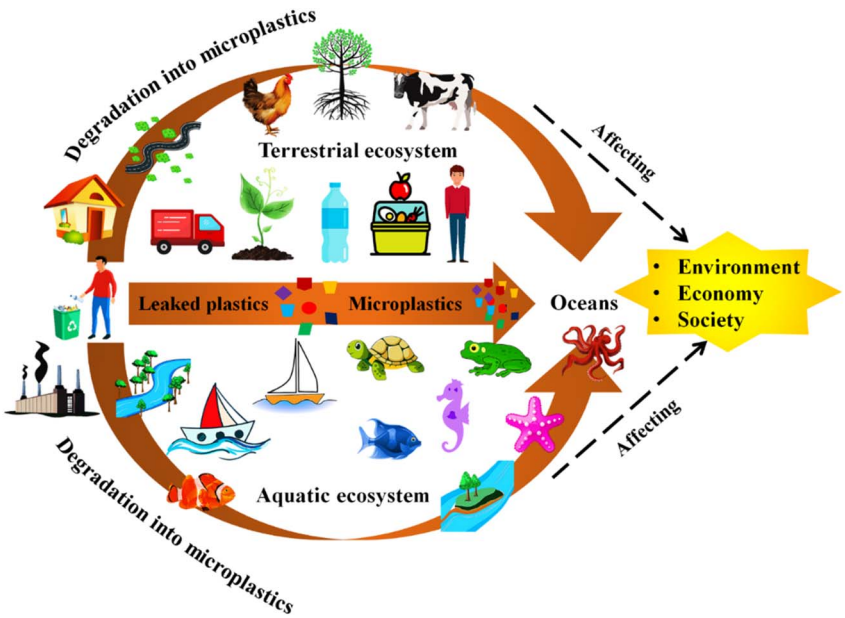

Fig. 5 Schematic sources and transportation routes of waste microplastics.

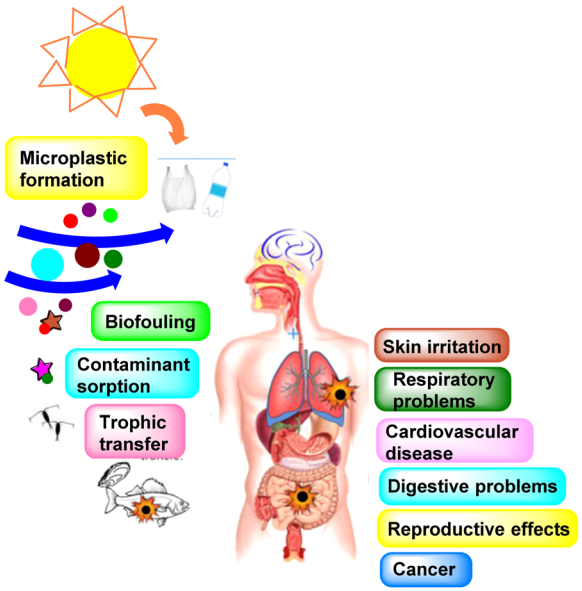

Fig. 6 Effects of microplastics on the human body.

fragmentation of plastics in water, contains three procedures such as bio-deterioration, assimilation and bio-fragmentation presenting emphasized, impactful microplastic generation routes.[51]

Microplastics have the ability to adsorb and concentrate various chemical pollutants from the surrounding environment, including persistent organic pollutants (POPs) and heavy metals. When ingested, these chemical-laden microplastics may release toxins, leading to harmful physiological effects in organisms, disrupting endocrine systems, and causing developmental abnormalities.[52] Microplastics can cause physical harm to organisms at the cellular and tissue levels. Their abrasive nature can lead to internal injuries and inflammation. Behavioral changes, such as altered feeding patterns, reproductive disruptions, and reduced foraging efficiency, have been observed in organisms exposed to microplastics (Fig. 6).[53]

Microplastics are often mistaken for food by marine and terrestrial organisms. Ingestion can lead to physical harm, blockage of digestive tracts, and malnutrition. Bioaccumulation of microplastics can occur as they move up the food chain, potentially reaching concentrations that may have adverse effects on higher trophic levels, including humans.[54] Microplastics can accumulate in soil through various pathways, including the application of plastic mulches, sewage sludge, and the breakdown of plastic debris.[55] Soil-dwelling organisms may be exposed to microplastics, impacting soil health and potentially influencing plant–microbe interactions. The marine environment is particularly vulnerable to microplastic pollution.[56] Floating microplastics can absorb sunlight and affect ocean temperature, potentially disrupting marine ecosystems. Microplastics in the ocean can interact with marine organisms, such as corals, affecting their health and contributing to the overall degradation of marine habitats[57] (Fig. 7).

The environmental persistence of microplastics is a significant concern. These particles are resistant to natural degradation processes, leading to their accumulation in the environment over extended periods. In marine ecosystems, microplastics have been found to interfere with the feeding behavior, growth, and reproductive health of various aquatic organisms.[58,59] Moreover, their ability to adsorb and transport hazardous chemicals, such as persistent organic pollutants and heavy metals, exacerbates their ecological risks.[60,61]

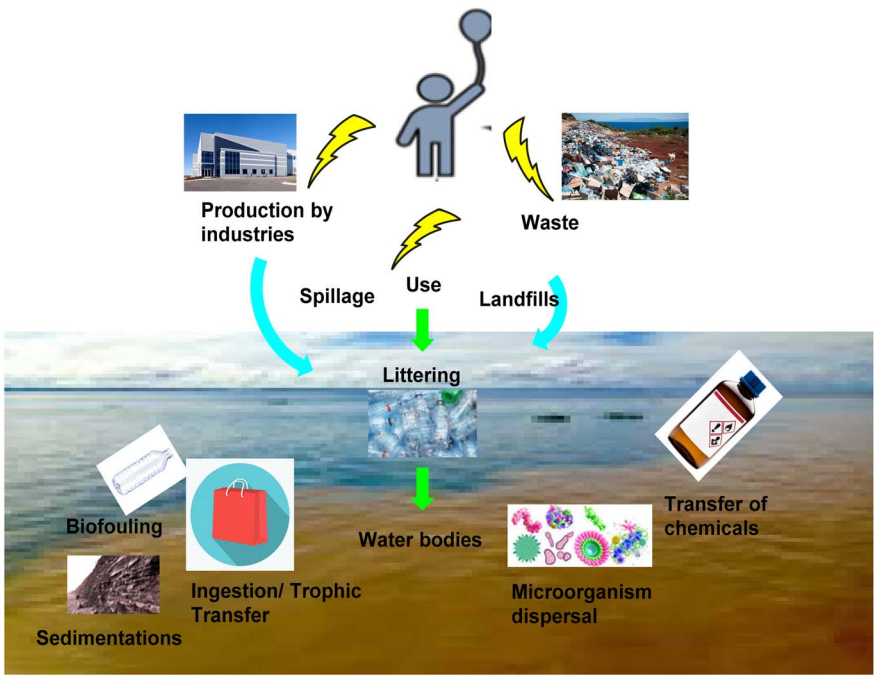

Fig. 7 Effects of microplastics in water and aquatic systems.

Human exposure to microplastics is an emerging area of concern. Studies have reported the presence of microplastics in human tissues, including the liver, kidneys, and even the brain, raising questions about their potential health implications.[62,63] The ingestion and inhalation of microplastics may lead to inflammatory responses, oxidative stress, and other adverse health effects.[11,53]

Despite the growing body of research on microplastics, significant knowledge gaps remain, particularly concerning their sources, transport mechanisms, and long-term effects on both ecosystems and human health. This review provides the latest research on microplastics, focusing on the crucial aspects of detection and degradation. By providing a comprehensive overview of current methodologies and emerging strategies, this review aims to guide future research endeavors and inform the development of effective solutions to mitigate the environmental impact of microplastics.

3. Detection of microplastics in environment

Quick separation and analysis of compositions of microplastics from terrestrial and aquatic systems have become high on the research agenda. By means of visual and combined analytical and visual techniques, a lot of research work was done for the identification and quantification of microplastics. Generally, the identification of MPs can be achieved by using two analytical state-of-the-art techniques: chemical characterization (spectroscopic) following physical characterization (microscopy) for the confirmation of plastics.[64] Four basic stages, including density separation, filtration, sieving, and visual categorization of microplastics, are mandatory prior to identification. These 4 preliminary procedures can easily classify the morphological characteristics (color, size and shape) of large-sized fragments of microplastics.[65]

Additionally, fluorescence as well as density separations offer a simple and sensitive technique to characterize the most frequent fragments of plastic polymers in marine sediments.[66] In addition, multiple techniques were used resulting in a consensus, which may be the best information for detection methods, as demonstrated by the high precision.[67] Therefore, methods that can be used for the identification of these microplastics and their smaller-size plastic particulates are significant for the process of identification, and well-known methods are detailed below.

3.1 Visual detection of MPs

An optical or naked-eye microscope with 10–50× magnification objectives is used for visual identification. Sometimes, software for image analysis such as Olympus and Histolab Stream has been used with the microscope.[68] Visual identification has been used in the majority (almost 79%) to characterize microplastics for the reason that it is feasible and worthwhile to use. But this technique is not suitable for identifying MPs as non-plastic particle particulates like paint chips, fly/coil ash, viscose rayon, keratin and cellulose, which can hamper the method, leading to false positives and this method faces problems in detecting translucent particles and particles below 100 μm in size. Sequentially, for the optimization of methods for the digestion of cigarette filters, cotton clothing fibers and human hair, the staining method (rapid screening of microplastics done by using Nile Red dye) and wet peroxide oxidation (WPO) can be used.[69]

Another specialized technique consists of an advanced digestion step that combines nitric acid (HNO_3) and sodium hydroxide to digest all organic material in 1 hour, with a separate separation step that separates the minerals using sodium iodide (NaI) for reduction of residues in samples if required. With the exception of polyamide, this technique presented a recovery rate of 95% for microplastics and all investigated forms of polymers were obtained with only slight variations in color, size and weight.[70] Also, if the scanning electron microscope (SEM) is included, which envisions the surface characteristic features of the particles, it will be a convenient task for research purposes. By scanning the material surface with an intense beam of electrons, this technique provides high-quality pictures. Additionally, particle discrimination is possible because of finer sample images (>0.5 nm). Still, the SEM fails to determine the composition of polymers.

3.1.1 Stereo/dissecting microscopy. The stereo microscope offers 3-dimensional (3D) scrutiny of the sample by analyzing it from 2 almost different angles in order to get the two images required for stereoscopic vision. The stereomicroscope is suitable and commonly employed to identify those microplastics whose sizes fall in the range of hundreds of microns. Images of a magnified microscope offer a complete structure of the surfaces and morphological details of the microplastics, required to identify the ambiguous plastic particles typology. While various microns-sized plastic particles can be seen using the microscope, but particles less than 100 μm in size with a specific shape or are transparent are challenging to analyze.[71]

It has been reported in the literature that the percentage of plastic particulates which were detected by stereomicroscopy, and then analyzed by different other methods, is around 20 to 70% of the total plastic particles, in the case of transparent plastic particles.[72] Additionally, the stereomicroscope is insufficient to identify natural and synthetic fibers.[73,74] The identification of microplastics using a stereomicroscope depends on their physical form. This is the foremost rapid inspection technique that permits fast characterization of color, size and shape of the plastic particles which will be additionally analyzed by some other approaches. Therefore, there is a requirement to couple the stereomicroscopy with other methods like spectroscopy.

3.1.2 Fluorescence microscopy. Unlike the optical microscope which works by contrasting the image created by the reflecting action of light rays on the microplastics, the fluorescence microscope works by collecting the fluorescent emission rays from the studied microplastics that are targeted by a definite wavelength. Fluorescence microscopy is an advantageous approach, mainly for transparent and white plastics, for the identification of microplastics depending on their distinctive aptitude to emit fluorescence. This approach decreases the

identifying deficiency of microplastics and can decrease the size detection limit of microplastics when combined with imaging. The detection of microplastic in different matrices can also depend on the quantification of fluorescent spheres with microscopy techniques.[75,76]

The restriction in the visual scrutiny of microplastics is exhibited by the chemical additives added in the synthetic procedure that have also impact on the fluorescent properties.[77] For instance, additives can also display fluorescent properties and affect the measurements by fluorescence microscopy.[78] Consequently, it is essential to remove these impurities as much as possible with suitable pretreatment approaches.[79] The rinsing of surfaces with oxidants such as hydrogen peroxide or acids, and digestion by enzymes is generally used.[80] These pretreatment approaches can only eliminate contaminants or surface impurities, but they do not have the ability to decrease the promising inferences from the chemicals confined within the microplastics.

3.1.3 Scanning electron microscopy. Scanning electron microscopy (SEM) is an important microscopic approach used to obtain details of the morphology of microplastics, producing images of high-resolution for their surface condition. In addition, it can also provide information regarding the chemical structure of microplastics, as it can be coupled with a detector for energy-dispersive X-ray spectroscopy (EDS). It is convenient to use scanning electron microscopy in an environmental SEM manner for the characterization of microplastics, as it evades the utilization of nitrogen-like gas in the SEM compartment. Additionally, sputtering carbon or gold on the microplastic surface can also avoid exposure, even if this is valuable for getting high-quality pictures. But, for this, the microplastic will not work for further analysis such as FTIR and EDS.

Conventional SEM is used in many research works to visualize microplastics in various matrices such as sand,[81] sediments,[82] mussels[83] and sewage sludge.[84] Field emission scanning electron microscopy (FE-SEM) is used as an alternative that operates at low voltage and provides high-magnification and high-resolution images of microplastic samples without special treatment for MPs prior to observation. This is a feasible and fast method because the microplastic is not covered with carbon or any metal, but the pieces of microplastic are placed directly on the aluminum stub of the carbon tape.

3.2 Analytical detection of MPs

3.2.1 Raman and FT-IR spectroscopy. Raman spectroscopy is another valuable technique for chemical analysis to identify microplastics in diverse environmental matrices. Conventional Raman is typically used to detect microplastics (>10 μm), whereas micro-Raman (μ-Raman) spectroscopy is used for the analysis of microplastics of size till 1 μm. This type of spectroscopy is the combination of both an optical microscope and a Raman spectroscope that allows one to choose the exact zone of the microplastic for analysis. Plastic particles with dimensions in the range of μm in deep water sediments were grouped into 4 different sites indicating different deep water surroundings at depths in the range of 1100–5000 m.[85]

Along with Raman spectroscopy, FT-IR is extensively practiced for the characterization of microplastics.[86] In each research work, microplastic samples are excited to produce specific vibrations that yield a spectrum within the fingerprint range. This FT-IR spectrum details the nature of the microplastic, which can be detected by comparison with reported standard spectra. Large-sized particles greater than 500 nm can be examined using Attenuated Total Reflectance-Fourier Transform Infrared Spectroscopy (ATR-FTIR), but smaller-sized particles require micro-FTIR (μ-FTIR) which requires concurrent imaging, and recording, and provides definite spectra. This can be achieved in both reflection and ATR mode.

The types of ingested plastic polymers have been identified in sea turtles by definitive ATR-FTIR validation.[87] Attenuated total reflectance (ATR) provides high-resolution FT-IR spectra but requires an infrared-transparent substrate. The lateral resolution is confined to a diffraction limit and microplastics smaller than 20 μm cannot be detected. Micro-FTIR has been generally used in the field of microplastics for their determination and characterization in food, surface water,[88] marine organisms and sediment.[89] This method allows for obtaining infrared signals at a high spatial resolution, also valuable for the analysis of complex microplastics. Micro-FTIR analysis has been performed on MP contamination in surface sediments from 28 positions in Seychelles Bay, classifying eight types of polymers like polyurethane (PU), polymethyl methacrylate (PMMA), polystyrene (PS), polyethylene terephthalate (PET), polyamides (PA), polypropylene (PP), polyethylene (PE) and rayon.[90]

3.2.2 Thermal analysis. In addition to different Raman scattering or infrared absorption properties, plastic polymers also vary in their thermal stability. The analysis of microplastics by thermo-analytical procedures exploits variations in the chemical and physical-chemical features of polymers.[91] The procedure depending on the polymer identification is based on its products of degradation. The advancement of thermal approaches is fundamental to characterize additives and low-solubility microplastics that are not simply dissolved, extracted, or hydrolyzed. The thermal analysis comprises methods such as pyrolysis-gas chromatography-mass spectrometry (py-GC-MS), thermogravimetry (TGA), differential scanning calorimetry (DSC) and combinations of these methods.

DSC is a valuable method to analyze polymeric materials, but it needs to be known as standard materials. Certainly, it is generally practiced to identify primary microplastics like polyethylene (PE) microbeads having well-defined characteristic features.[92] However, the utilization of DSC to analyze plastics like acrylonitrile butadiene (ABS), polycarbonate (PC), polystyrene (PS) and polymethyl methacrylate (PMMA) among others, has restrictions because these plastics have long-ranged melting points. Additionally, the quantitation of the mass of microplastics present in the environment was also described in the literature.[93] Amongst other limitations, DSC outcomes lack particularity when analyzing a combination of microplastics with an overlap of melting peaks or closely spaced melting points.

Table 1 Overview of microplastics detection methods with advantages and limitations

Detection method	Principle	Detected material	Minimum size	Advantages	Limitation	Ref.
Focal plane array-based micro-Fourier-transform infrared spectroscopy	Employs focal plane array detectors to conduct infrared imaging, enabling the identification of microplastics concentrated on membrane filters through their distinct spectral signatures	Microplastics of the polymer polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), polyurethane (PUR), polyethylene terephthalate (PET), other polyesters (PES) and co-polyamide (PAs)	Detection of particles down to 20 μm	High lateral resolution, faster than traditional chemical mapping, and suitable for standard procedures	Requires further automation for fully automated analysis; initial setup may need specialized equipment and expertise	95
Raman spectroscopy	Identify microplastics by detecting molecular vibrations when exposed to laser light, providing a molecular fingerprint	All types of microplastics	Microplastics including those as small as 2–3 μm in plankton	Can identify extremely small microplastics, perform well in wet samples, generate spatial chemical images, complementary to FTIR	Weak signal, fluorescence interference, influenced by color, additives, and attached contaminants. Real-time monitoring is a significant challenge	96 and 97
Stimulated Raman scattering (SRS)	Uses two laser beams to generate a signal when their photon energy difference matches a vibrational state of molecules in the sample	PET = polyethylene terephthalate; PS = polystyrene; PP = polypropylene; PE = polyethylene Nylon		Very fast mapping speeds, significantly reduced signal acquisition time per pixel, suitable for high-throughput screening, non-invasive		98
Pyrolysis-gas chromatography-mass spectrometry (Pyro-GC-MS)	Pyrolyzes single polymer particles under inert conditions, cryo-traps and separates thermal degradation products using a chromatographic column, identifies products *via* mass spectrometry	PE, PP, PET, PS PA		Suitable for single particle analysis, provides chemical identification of polymers, relatively low sample amount required (0.1–0.5 mg)	Time-consuming pre-selection of particles necessary, Prone to contamination during pyrolysis, limited by the sample amount (0.1–0.5 mg)	99
Pyrolysis-gas chromatography-mass spectrometry (Pyro-GC-MS)	Pyrolyzes single polymer particles under inert conditions, cryo-traps and separates thermal degradation products using a chromatographic column, identifies products *via* mass spectrometry	PE, PP, PET, PS PA		Suitable for single particle analysis, provides chemical identification of polymers, relatively low sample amount required (0.1–0.5 mg)	Time-consuming pre-selection of particles necessary, Prone to contamination during pyrolysis, limited by the sample amount (0.1–0.5 mg)	99
Liquid chromatography	Uses solvents and size exclusion chromatography for polymer characterization	All types of microplastics		Analyzes high masses, improves representativeness	Destructive, limited to chemical composition, requires large sample amounts	79
X-ray fluorescence (XRF) spectroscopy	Excitation of sample with X-rays, resulting in emission of characteristic fluorescent X-rays, which are detected and analyzed to determine elemental composition	Beached microplastics (including Br, Cd, Cl, Cr, Cu, Fe, Pb, and Zn)	A few millimeters to a few micrometers	Rapid and non-destructive analysis, capable of characterizing elemental composition of synthetic polymers	Limited spatial resolution, potential interferences from sample matrix	100

Table 1 (*Contd.*)

Detection method	Principle	Detected material	Minimum size	Advantages	Limitation	Ref.
Scanning electron microscopy (SEM) with energy-dispersive X-ray microanalysis	Microscopic imaging of microplastic particles coupled with energy-dispersive X-ray microanalysis to identify inorganic plastic additives (IPAs)	Inorganic plastic additives (IPAs)	Microscopic level	High-resolution imaging of microplastic particles, detection and identification of inorganic plastic additives (IPAs)	Limited to identification of inorganic plastic additives (IPAs), time-consuming analysis process	101
Pressurized fluid extraction	Utilizes solvents at subcritical temperature and pressure conditions to extract microplastics from environmental samples	All types of microplastics	Submicron	Provides a simple analytical method for quantifying common microplastics in a range of environmental samples	Requires optimization of PFE conditions, potential variability in extraction efficiency	102

In TGA, mass loss is determined, while the disintegration of polymer-based materials starts normally by changing the enthalpy. Variations in enthalpy cannot be spotted in thermogravimetric analysis but can be detected through DSC measurements. Consequently, a mixture of two techniques is recommended to analyze microplastics.[94] Various microplastics can be identified, but this detection is not possible for other types of polymers because of their overlapped phase transition signals.

Pyrolysis gas chromatography-mass spectrometry (Py-GC-MS) is one of the analytical techniques that has been effectively applicable to analyze plastic materials. It is perfect for the simultaneous identification as well as quantification of the most commonly found microplastics in complex samples. The semi-quantitative scheming for every single form of existing plastics, mainly for minute concentrations such as parts per billion (ppb) or lower than ppb, signifies the precise identification of the polymeric materials in the animal and environmental microplastics and the external calibration curve (Table 1).

The thermal analysis serves as an alternate technique to spectroscopy to identify some polymers. However, it is a damaging method that prevents the analysis of microplastics with some other resulting approaches. Therefore, it is detrimental to utilize these types of analytical approaches to identify microplastics, but these approaches may facilitate the initial examination of large samples and subsequent investigation by spectroscopic methods.[103]

4. Degradation pathways

Microplastics (MPs) can be cleaned using traditional cleaning techniques.[104] For instance, removing waste plastics from the beach, such as packaging, bags, and mess containers, can reduce the amount of plastic that enters rivers and the ocean, which helps to prevent the creation of SMPs. Green technologies to dispose of the gathered plastics are still lacking, though. The conventional approaches to treating plastic waste, such as landfilling or burning, are not the best ways to address the problem of MP contamination. The safe treatment of plastic garbage through incineration is quite effective, but it carries a danger of producing greenhouse gases such as carbon dioxide (CO_2), methane, and carbon monoxide (CO).[105,106] Today, several innovative strategies were proposed to lessen the pressing threat posed by MPs.

Since microplastics have a larger surface-to-volume ratio than macroplastic detritus, they degrade through the same mechanisms more quickly. Smaller counterparts of the original microplastic particles, known as nanoplastics, will eventually replace them.[107–111] Mechanical (abiotic), chemical (abiotic), and biological (biotic) degradation are the three basic categories that are taken into consideration, and in most cases, substantial particle degradation occurs when these processes are interconnected[112] (Fig. 8).

4.1 Mechanical degradation

MPs subjected to mechanical abrasion result in particles with low sharpness of particle edges, resembling the morphology of

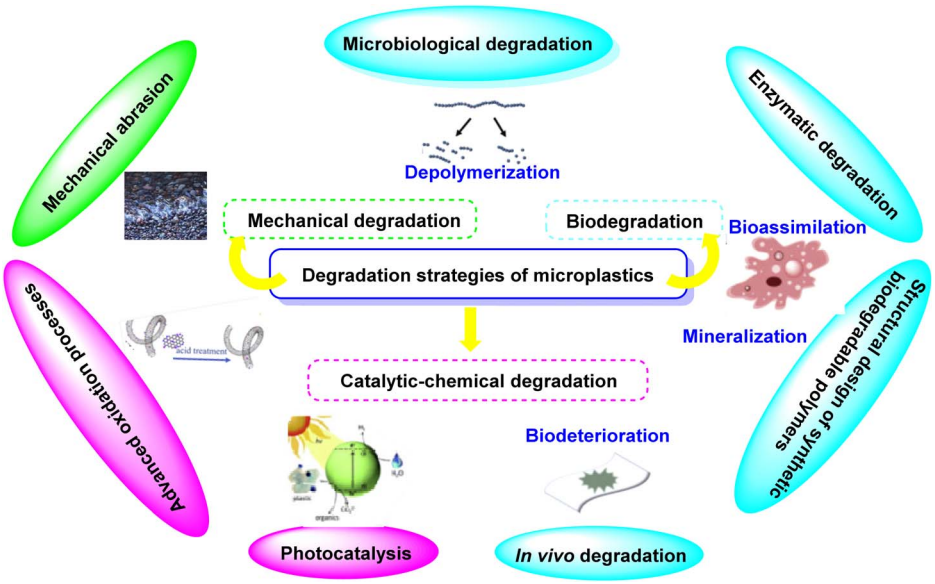

Fig. 8 Model diagram showing the pathways of MP degradation.

natural sediment grains subjected to repeated abrasion in high energy conditions or long transit lengths. Conchoidal fractures and grooves on surfaces have been proven to be indicators of mechanical weathering in studies using scanning electron microscopy (SEM).[113–118] As a result, beaches are the best places in nature for abrasion of microplastic debris to be present.[118] Under simulated beach and offshore circumstances, polyethylene (PE) films were experimentally investigated. According to Kalogerakis *et al.* (2017), exposure to sunlight and mechanical stress increased the rate of weathering. The latter involves filling bottles with sand and inserting plastic strips before rotating the bottles continuously for 24 hours. The plastic lost 14% of its weight, which was represented by tiny particles that couldn't be seen with the naked eye called microplastics. This experiment demonstrates that polymer deterioration can happen as a result of mechanical abrasion alone.[119]

In a study by Cooper and Corcoran (2010), plastic debris collected from the beaches of Kauai, Hawaii, exhibited surface features indicative of mechanical degradation, such as fractures, pits, and grooves. Scanning Electron Microscopy (SEM) analyses revealed that these physical alterations, resulting from wave action and sand abrasion, contributed to the embrittlement and subsequent fragmentation of polyethylene (PE) and polypropylene (PP) materials.[114]

Additional laboratory studies have measured the mechanical degradation rates under controlled conditions. As an example, in mesocosm experiments that mimic marine conditions, polyethylene films with mild mechanical stress following five months of weathering had a weight loss of around 13.9% to 16.7%, suggesting major fragmentation to the micro-sized particles.[119]

Recent research has also investigated the cumulative effects of photo-aging and mechanical stirring on plastic fragmentation. Haremaki *et al.* (2025) illustrated that photo-aged polypropylene (PP) samples, under water stirring, broke down into microplastics with sizes from 1 to 30 micrometers. The fragment size distribution shifted from exponential to power-law function as the stirring time increased, indicating an increasing fragmentation mechanism controlled by mechanical forces.[120]

Additionally, the synergistic action of ultraviolet (UV) radiation and mechanical abrasion has been demonstrated to enhance the degradation of different polymers. Under laboratory tests mimicking beach conditions, low-density polyethylene (LDPE), PP, and expanded polystyrene (EPS) pellets subjected to UV radiation followed by mechanical abrasion yielded considerably greater amounts of microplastic fragments than mechanical abrasion alone. For instance, PP pellets exposed to 12 months of UV and two months of mechanical abrasion produced around 6084 ± 1061 particles per pellet, while mechanical abrasion alone without initial UV exposure produced merely 10.7 ± 0.7 particles per pellet.[121]

These results highlight the significance of mechanical degradation as a dominant pathway for microplastic production in the environment. Quantifying the rates and mechanisms of mechanical fragmentation is essential in evaluating the environmental fate of plastic litter and designing efficient mitigation strategies.

4.2 Chemical degradation

The degree of chemical degradation of microplastics varies based on the kind of polymer, the presence of additives (UV stabilizers), as well as the depositional environment and medium.[122–124] For instance, it is anticipated that microplastics on beach surfaces may absorb more UV radiation than particles suspended in the water column or buried in benthic soil.[125–127]

A more brittle polymer that is susceptible to mechanical abrasion and/or biodegradation is produced as a result of the weight reduction. The hydrolysis of aromatic polyesters, like

PET, can result in shorter chains and the formation of terephthalic acid and ethylene glycol in environments where biodegradation, abrasion and photooxidation are not possible. These environments include landfills and the ocean floor.[112]

Both chemical and surface signs are present showing that chemical weathering activities have taken place. Microplastics' physical characteristics fluctuate with time, causing color changes, mechanical property loss that causes surface fissures and embrittlement, and molecular weight fluctuations.[128] Wider fractures produced by crazing result in a polymer that is more brittle and is linked to a reduction in tensile strength. Over-oxidation of the phenolic chemicals found in the polymer causes yellowing or discoloration.[129,130]

4.3 Degradation of MPs *via* advanced oxidation process

Chemical-catalytic degradation of MPs through advanced oxidation processes (AOPs) is a relatively new field of study, and in the past few years, there has been a notable interest in this area because of the environmental persistence of MPs.[131] AOPs are a collection of chemical treatments that employ reactive species, including hydroxyl radicals ($OH^{\bullet}$), to oxidize pollutants in wastewater and water. UV/H_2O_2, Fenton, and ozonation are some of the most common AOPs. These treatment processes are efficient in degrading various types of pollutants such as polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs), and polycyclic musk compounds (PCMs).[104,132]

Over the past few years, there has been a study of using AOPs to degrade MPs, specifically focusing on polyethylene (PE) and polypropylene (PP), which are the most frequently utilized polymers in consumer products. It has been found through studies that AOPs are able to degrade MPs effectively, with total mineralization being recorded in some instances. For instance, in a study by Li *et al.* (2018), UV/H_2O_2 was employed to degrade PE films and determined that complete mineralization was achieved, with the major products being CO_2 and H_2O.[133] Another study by Xiong *et al.* (2019) employed ozonation to degrade PP beads and determined that the process led to the production of carboxylic acids, which are degradation intermediates of PP.[134] Nonetheless, not all studies have established that AOPs are efficient in degrading MPs. For instance, Wang *et al.* (2019) reported that Fenton oxidation did not lead to complete PE film degradation, and that the process led to the generation of smaller particles instead of complete mineralization.[135,136]

Furthermore, AOPs can also generate by-products such as hydroxyl radicals, superoxide radicals, and hydrogen peroxide, which are toxic to aquatic life, and therefore the use of AOPs in the degradation of MPs should be judicious. AOPs, especially the Fenton reaction, have been utilized to oxidize many different MPs.[137]

In another study by Liu *et al.* (2024), ultrahigh-molecular-weight polyethylene (UHMWPE), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polystyrene (PS), polyvinyl chloride (PVC), polypropylene (PP), and polyethylene terephthalate (PET) MPs underwent a thermal Fenton reaction at 140 °C.[138] Treatment consisted of 4 mM $FeSO_4$ and 200 mM H_2O_2, where appreciable weight loss was observed for all the types of polymers, which is an indication of effective degradation. For example, UHMWPE MPs showed about a 30% weight loss following treatment.[137] AOPs employ reactive oxygen species (ROS) like hydroxyl radicals ($^{\bullet}OH$) to non-selectively oxidize organic pollutants. For example, a study proved that the treatment of polystyrene (PS) microplastics with a mixture of hydrogen peroxide (H_2O_2) and ultraviolet (UV) light led to a 95.9% weight loss in 16 hours, with a mineralization efficiency of 75.6% after 12 hours. Scanning Electron Microscopy (SEM) analyses revealed extensive surface erosion and fragmentation of the PS particles.[138]

In conclusion, chemical-catalytic degradation of MPs through AOPs is a promising study that can possibly degrade MPs efficiently. Nevertheless, more studies have to be carried out to develop the conditions in AOPs to fully mineralize MPs as well as avoid the formation of by-products harmful to aquatic animals.[139]

4.4 Degradation of MPs *via* photocatalysis

Chemical-catalytic degradation of microplastics (MPs) *via* photocatalysis is an emerging research area that has gained significant attention in recent years due to the persistence of MPs in the environment.[140] Photocatalysis is a technique whereby a semiconductor material, for example, titanium dioxide (TiO_2), serves as a catalyst to break down contaminants under the influence of light. The mechanism entails the absorption of light by the semiconductor, producing electron–hole pairs. The holes may subsequently react with oxygen or water to produce hydroxyl radicals ($OH^{\bullet}$), which are extremely reactive and can break down contaminants.[141]

One of the greatest challenges in photocatalytic degradation of MPs is the poor light absorption of MPs, leading to low photocatalysis efficiency. To address this, scientists have been investigating the use of various photocatalysts, including zinc oxide (ZnO), or the combination of MPs with other materials to enhance their light absorption. Besides, photocatalysis can also generate by-products like hydroxyl radicals, superoxide radicals, and hydrogen peroxide that are harmful to aquatic life. Therefore, the use of photocatalysis in MP degradation should be carried out with caution.[142]

Photocatalysis involves light-activated catalysts to produce reactive species that degrade polymer chains. TiO_2 nanoparticles are among the most investigated photocatalysts. Zandieh *et al.* (2024) reported that LDPE films coated with 10 wt% TiO_2 and exposed to UV light (36 W at 315 nm) for 360 hours achieved a weight loss of 78%.[143] Similarly, PS microspheres subjected to UV light (256 W at 254 nm) for 12 hours showed a 98% weight loss.[143]

Other nanomaterials, such as ZnO, MnO_2, and Cu_2O, have also demonstrated photocatalytic activity. For example, PE microplastics treated with a GO/TiO_2 composite under UV light (72 W at 350 nm) for 8 hours exhibited a 50% weight loss.[143]

Photocatalytic degradation employs semiconductors like titanium dioxide (TiO_2) activated by UV or visible light to generate ROS, facilitating polymer breakdown. In one study,

Table 2 Effect of catalyst on microplastics degradation (%) with corresponding irradiation source and degradation time

Photocatalysts used	Polymer	Degradation (%)	Time (h)	Irradiation source	Ref.
ZnO NRs (ZnO NRs)	Polypropylene	65	360	Visible light	145
Polypyrrole/TiO_2 (PPy/TiO_2)	Polyethylene	35.4	240	Sunlight	146
Ag/TiO_2/RGO	Polyethylene	76	4	UV light	147
ZnO NRs	Low density polyethylene	16–38	>100	UV-vis	148
TiO_2/ZnO	Polyamide microfibers	97	<100	UV	149
TiO_2	PE	86	300	UV	150
C,N–TiO_2/SiO_2	PET	16		UV-vis	151
Graphene oxide-based metal oxide	Polyethylene	35–50	20	Ultraviolet light	152
BiOI–Fe_3O_4	Polystyrene	64	8	Visible light	153

polyethylene (PE) microplastics exposed to TiO_2 under UV irradiation exhibited a degradation rate constant of 2.6×10^{-7} h^{-1} for particles sized between 10 and 150 nm. The degradation efficiency was influenced by factors such as particle size, light intensity, and catalyst concentration (Table 2).[144]

4.5 Biological degradation of MPs

Biodegradation is the process through which plastic waste is digested by microorganisms to produce smaller products, according to Pathak *et al.* (2017).[154] The following processes are used to carry out this process: colonization, bio-fragmentation, assimilation, and mineralization. When a microplastic particle's surface comes into touch with a body of ambient water, a conditioning film forms over the piece, which is necessary for biofilms to form.[155] According to Rummel *et al.* (2017), the chemical composition of the film has a major role in determining the kinds of organisms that sorb onto it.[156]

Exoenzymes are released by organisms once the microplastic surface has been colonized, and they cause the polymer to break down into oligomers, dimers, or monomers.[157] The term "plastisphere"[158] used to refer to the colonized surface area of microplastics is often used to refer to a microbial population forming in a biofilm.[158] A wide variety of microorganisms, including bacteria, algae, fungi, and bryozoa, can be found in the plastisphere.[158,159] *Zalerion maritimum* has been shown to degrade PE by Paço *et al.* (2017).[160] Assimilation can only begin once the original plastic particle has been broken up into pieces small enough for the molecules to pass the cell walls of microorganisms. The molecules can be employed as sources of energy and carbon once assimilation has occurred. This last stage, called mineralization, results in the production of CO_2, H_2, and CH_4. Additionally, this final stage completes the carbon biogeochemical cycle.[157] Carbon dioxide, H_2O, and CH_4 can be produced during aerobic or anaerobic biodegradation, respectively. In landfill environments, anaerobic conditions can occur naturally, and Zhang *et al.* (2022) have described the five stages of deterioration that take place there. The authors demonstrate through their analysis of published studies that the biodegradation rates of the most prevalent environmental polymers (polyolefins) are significantly lower in landfills than those of their biodegradable equivalents. Therefore, aerobic biodegradation is more productive.[161] Environmental factors, including the climate, salinity, amount of light, and atmospheric contaminants, may have an impact on biodegradation when aerobic conditions are present.[162]

The degradation of microplastic waste can be slowed down by colonization even though biological activity can help to break down microplastics in the environment. According to research by Long *et al.* (2015) and Rummel *et al.* (2017),[156] colonizing microbes can make microplastic particles denser, which causes them to sink through the water column or shift their vertical orientation.[163]

4.6 Pathway of microplastics biodegradation

A number of processes are involved in the microbial biodegradation of MPs, including: (1) initial degradation of polymers in smaller particles from large polymeric structures; (2) polymer degradation to oligomer, dimer, and monomer; and (3) mineralization of MPs by microbial biomass.[164] The complete mineralization of MPs into carbon dioxide is depicted in Fig. 9, along with the transformation of the intermediates that were created into a source of energy and biomass production. The hydrophilicity of plastic polymers is increased by microorganisms' extracellular enzymes, which include esterase, lipase, lignin peroxides, laccase, and manganese peroxides. Examples of hydrolases include lipases, esterases, poly(3-hydroxybutyrate) depolymerases, and cutinases (Fig. 9). These enzymes may attach certain sensitive bonds to the side chains of polymers or chemical groups to the polymer chain to facilitate chain cleavage during biodegradation. Due to their size, they are not likely to diffuse into the polymer structure; therefore, the degradation may take place on the surface, leading to cracks.[165]

4.6.1 *In vivo* biodegradation of microplastics. *In vivo* breakdown of MPs is a term used to describe the breakdown of microplastics in the body of an organism. Microplastic *in vivo* degradation is a multi-factorial process that depends on several factors, such as the type of polymer, particle size and shape, and the physiological properties of the organism. It has been demonstrated through studies that microplastics can be broken down by microorganisms in the gut of an animal, and enzymes within the body of an animal. For instance, Rochman *et al.* (2015) reported in their study that microplastics were broken down by gut microbe in the intestine of some species of fish.[166] Another study conducted by Li *et al.* (2017)[89] revealed that the enzymes in the gut of insects can break down microplastics.[167] But it must be remembered that microplastic *in vivo*

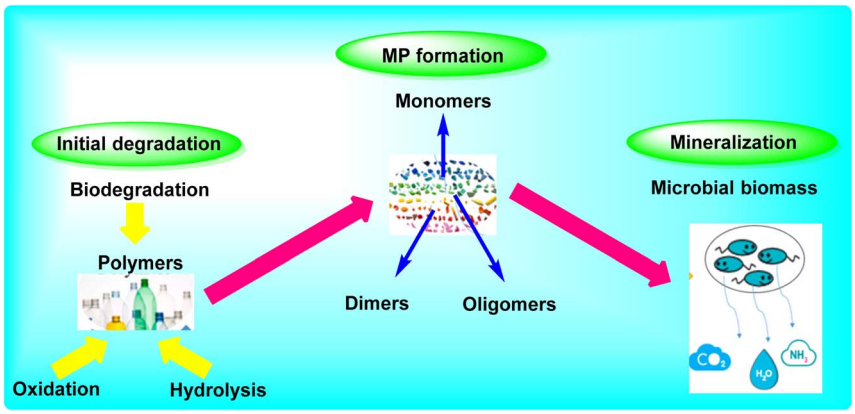

Fig. 9 Pathway of MPs biodegradation.

degradation is a very slow process taking months or years. Moreover, not all microplastics are as vulnerable to degradation by gut microbes or enzymes. For instance, certain research has indicated that high-density polyethylene (HDPE) is less vulnerable to degradation by gut microbes compared to low-density polyethylene (LDPE). Aside from degradation by enzymes and gut microbes, microplastics can also be broken down by physical processes within the body of the animal, including fragmentation and abrasion. These may lead to the creation of smaller particles, which can easily be expelled from the body or can find its way into the tissues and organs of the animal and lead to potential impacts on health. Hence, the *in vivo* degradation of microplastics must be dealt with carefully and more research has to be conducted to know the possible effects on aquatic life. Physical processes inside the body of the animal and possible toxic by-products of the degradation process also need to be taken into consideration while studying the *in vivo* degradation of microplastics.

4.6.2 Micro-biological degradation of MPs. Microbiological degradation of MPs is a research area which has gained considerable attention in recent years because of the persistence of MPs in the environment.[168] Microorganisms have been reported to degrade these polymers by enzymatic action, including the action of enzymes like hydrolases and esterases. These enzymes are capable of degrading the polymer into smaller molecules, which could then be metabolized by the microorganisms.

Studies have shown that a wide variety of microorganisms are capable of degrading MPs, including bacteria, fungi, and algae. For instance, Besseling *et al.* (2018) discovered that bacteria belonging to the genus *Pseudomonas* and *Sphingomonas* could degrade PE.[169] Chen *et al.* (2019) discovered that fungi belonging to the genus *Aspergillus* and *Penicillium* could degrade PP.[170] The conditions under which microorganisms degrade MPs also affect the efficiency of degradation. For instance, researchers have established that the availability of nutrients like nitrogen and phosphorus can promote degradation of MPs by microorganisms. Not all studies, however, have reported that microorganisms degrade MPs. For instance, Wang *et al.* (2019) conducted a study in which they detected that degradation of PE films by bacteria was extremely slow and that the process led to the generation of small particles and not total mineralization.[171] Moreover, micro-biological degradation of MPs can also generate by-products that are toxic to aquatic life. Therefore, use of micro-biological degradation of MPs should be carried out cautiously and with further studies to realize the possible effects on aquatic animals.[172]

In a typical process of biodegradation, polymers are subjected to the microbial community after initially permitting microorganisms to adhere to their surfaces. Subsequently, the polymer was subjected to extracellular enzymes, which resulted in the polymer interacting with them and starting to disintegrate into lower molecular-weight polymers.[173] In conclusion, micro-biological degradation of MPs is a promising area of research that can potentially degrade MPs effectively. Experiments have indicated that a broad range of microorganisms can degrade MPs, but the conditions under which microorganisms degrade MPs also influence the efficiency of degradation (Fig. 10). More research is required to determine the best conditions for micro-biological degradation of MPs and to reduce the formation of by-products that are toxic to aquatic life (Table 3).[174]

4.6.3 Enzymatic degradation of microplastics. Enzymatic degradation of microplastics (MPs) is a research area that has gained significant attention in recent years due to the persistence of MPs in the environment. Enzymes are known to degrade these polymers by hydrolyzing the ester or amide bonds that hold the polymer chains together.

The enzymes that are commonly used for the degradation of MPs include lipases, esterases, and cellulases. Studies have shown that a wide variety of enzymes are capable of degrading MPs. For example, Yang *et al.* (2018) found that a lipase from the fungus *Rhizopus oryzae* was able to degrade PE.[188] Another study by Li *et al.* (2017)[89] found that a cellulase from the bacterium *Bacillus subtilis* was able to degrade PP.[189] The conditions under which enzymes degrade MPs also have an impact on the efficiency of degradation. For example, studies have shown that the presence of surfactants can enhance the degradation of MPs by enzymes. Additionally, the pH and temperature of the reaction also play a role in the efficiency of

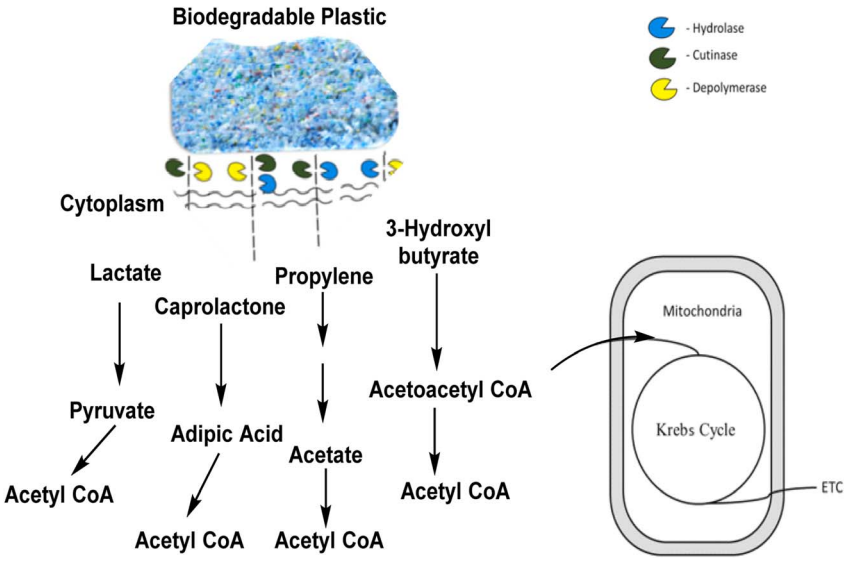

Fig. 10 Inhibition of MPs degradable in biological process.

Table 3 Degradation (%) of microplastics by various microorganisms

Microorganism	Polymer	Degradation (%)	Time (days)	Ref.
Aspergillus niger	Polyethylene (PE)	~40	90	157
Achatina fulica land snail	Polystyrene (PS)	31	28	175
Arthrobacter	PE	12	—	176
Pseudomonas	PE	15	—	176
Bacillus sp. and *Paenibacillus* sp.	PE	15	60	177
Bacillus cereus	PE	2	40	178
	PET	7		
	PS	7		
Bacillus gottheilii	PE	6	40	178
	PET	3		
	PP	4		
	PS	6		
Ideonella sakaiensis	PET	~75	60	179
Pseudomonas putida	PS	~30	56	180
Bacillus subtilis	Polyurethane (PU)	~50	60	181
Rhizopus arrhizus	Polyvinyl chloride (PVC)	~33	60	182
Penicillium simplicissimum	Low-density polyethylene (LDPE)	~25	90	183
Streptomyces sp.	Polycaprolactone (PCL)	~85	30	184
Phanerochaete chrysosporium	PE	~20	60	185
Thermobifida fusca	PET	~70	60	186
Alcaligenes faecalis	Polylactic acid (PLA)	~6	40	187

enzyme-mediated degradation of MPs. However, this method's PET conversion rate is still insufficient to keep up with the rate at which plastic trash is produced, and the enzymes are now too expensive (Fig. 11). Inspired by the LCC enzyme's strong potential for destroying long-lasting semi-aromatic polyesters like PET.[190]

Enzymatic degradation of MPs offers a sustainable and environmentally benign approach to mitigating plastic pollution. This process involves specific enzymes that catalyze the hydrolysis of polymer chains, leading to the breakdown of complex plastics into monomers or oligomers. Key enzymes in this context include hydrolases, esterases, lipases, and cutinases, each exhibiting distinct mechanisms of action and substrate specificities. Hydrolases (EC 3.1.1) encompass a broad class of enzymes that catalyze the cleavage of ester bonds through the addition of water molecules. In the context of polyethylene terephthalate (PET) degradation, hydrolases such as PETase and MHETase have been identified. PETase initiates the hydrolysis of PET into mono(2-hydroxyethyl) terephthalate (MHET), which is subsequently degraded by MHETase into terephthalic acid (TPA) and ethylene glycol (EG).[191] Cutinases (EC 3.1.1.74) are serine esterases that naturally degrade cutin, a structural component of plant cuticles. These enzymes possess an exposed active site, allowing them to interact with

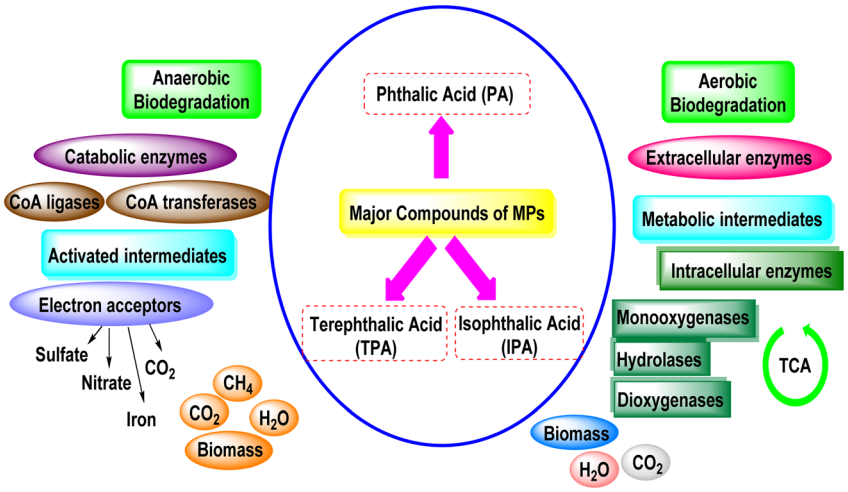

Fig. 11 Schematic aerobic and anaerobic pathways of enzymatic biodegradation of MPs.

a variety of hydrophobic substrates, including synthetic polyesters like PET. Cutinases catalyze the hydrolysis of ester bonds within the polymer backbone, leading to the formation of monomers such as TPA and EG. Notably, cutinases from *Fusarium solani* and *Humicola insolens* have demonstrated significant PET-degrading capabilities.[192–194] Esterases (EC 3.1.1.1) preferentially hydrolyze short-chain aliphatic esters and have been implicated in the degradation of various biodegradable plastics. For instance, esterases from *Comamonas acidovorans* have been shown to degrade low molecular weight polylactic acid (PLA), while those from *Aspergillus flavus* and *Aspergillus tubingensis* can degrade polybutylene succinate (PBS). The enzymatic action involves the cleavage of ester bonds, resulting in the formation of monomers or oligomers that can be further assimilated by microorganisms.[195,196] Lipases (EC 3.1.1.3) catalyze the hydrolysis of long-chain triglycerides and have been employed in the degradation of various synthetic polymers. Lipases from *Candida antarctica* (CALB) and *Rhizopus delemar* have demonstrated efficacy in degrading polymers such as PET and polycaprolactone (PCL). The mechanism involves the cleavage of ester bonds within the polymer matrix, leading to the release of monomeric units.[191] The enzymatic degradation process typically follows a surface erosion mechanism, where enzymes adsorb onto the polymer surface and catalyze the hydrolysis of accessible ester bonds. This results in the gradual breakdown of the polymer into smaller fragments, which can then be further degraded or assimilated by microorganisms.[197] Factors influencing the efficiency of enzymatic degradation include the crystallinity of the polymer, surface area, and the presence of additives or contaminants.[195] Combining different enzymes can enhance the degradation efficiency of complex polymers. For example, the sequential application of cutinase and lipase has been shown to result in a more complete depolymerization of PET, with cutinase initiating the breakdown of the polymer and lipase further degrading the resulting oligomers.[191]

The enzymatic degradation of microplastics has emerged as a highly promising and increasingly researched strategy within the broader framework of sustainable plastic remediation.[198] Enzymes, particularly those derived from microbial sources, offer a selective, efficient, and environmentally benign approach to breaking down synthetic polymers into simpler, non-toxic compounds. Among the most studied are PET-hydrolyzing enzymes such as PETase and MHETase, originally identified in *Ideonella sakaiensis*, which catalyze the depolymerization of polyethylene terephthalate (PET) into its monomeric constituents.[199]

Recent advances have extended to the engineering of mutant variants with enhanced thermal stability, catalytic efficiency, and substrate specificity, enabling faster degradation under environmentally relevant conditions. Moreover, enzymes like cutinases, lipases, laccases, and peroxidases have shown activity against a broader range of polymers, including polyethylene (PE), polypropylene (PP), and polyurethane (PU), although their mechanisms and degradation pathways remain under active investigation.[200]

Enzymatic strategies are also being integrated with pretreatment technologies, such as mechanical shredding, photooxidation, or chemical modification, to enhance polymer surface accessibility and increase enzymatic affinity. Immobilization techniques, such as the anchoring of enzymes onto solid supports or nanoparticles, further improve their reusability and operational stability, making them suitable for incorporation into wastewater treatment and remediation systems.[201]

However, challenges remain in scaling up enzymatic degradation for field applications, including enzyme production costs, environmental robustness, and reaction kinetics. As such, ongoing research is focused on metagenomic screening, synthetic biology, and directed evolution to discover and optimize novel enzymatic systems capable of degrading a wider spectrum of microplastic types under diverse environmental conditions.[202]

The growing body of literature underscores the transformative potential of enzyme-based technologies in microplastic mitigation. These biocatalytic approaches not only

support the degradation of existing pollutants but also provide insights into the design of next-generation biodegradable plastics and circular economy models.[203]

In summary, enzymatic degradation of MPs is a promising research area that has the potential to effectively degrade MPs. Studies have shown that a wide variety of enzymes are capable of degrading MPs, however, the conditions under which enzymes degrade MPs also have an impact on the efficiency of degradation. Further research is needed to understand the optimal conditions for enzymatic degradation of MPs and to minimize the production of by-products that can be toxic to aquatic organisms.

5. Current solutions for microplastic pollution

The solutions can be further grouped into three broad categories: source control, cleanup and treatment, and public awareness and education.[204] Source control measures try to prevent the amount of microplastics entering the environment in the very first place. This may include steps like the prohibition or the imposition of taxation on single-use plastics, encouragement of the usage of biodegradable alternatives, and regulations in order to govern the release of microplastics from industries such as textiles and personal care products.[204]

Treatment and cleanup methods target the elimination of microplastics from the environment after their release. Treatments involve physical extraction methods, such as beach cleaning and utilization of specialized boats or equipment to extract microplastics from the surface of the ocean. In addition, technologies that will extract microplastics from water are being designed, for example, membranes and filtration devices, and advanced oxidation processes (AOPs) are also under investigation to break down the plastics.[205] Education and public awareness solutions seek to make the issue of microplastic pollution more known and raise consciousness among people and institutions to act to minimize their use of plastics and disposed them in an appropriate manner. These measures comprise educational campaigns, public education campaigns, and the creation of environmentally friendly consumer products.

In general, three different categories-containment, mitigation, and separation of remedies have been put up to reduce microplastic pollution.[204] All of them aim to stop the spread of microplastics into the environment by taking action at crucial sources. Our current focus is on separation, which is a method of removing microplastics from wastewater during processing. Recycling and landfilling are the main methods of containment.[206] The majority of plastic items require physical segregation in a landfill for effective disposal at the end of their useful lives. In order to confine the secondary microplastics that break off plastic debris, well-maintained landfills are built to reduce leaching. However, new research indicates that landfill runoff is high in microplastics[206] and pollutes neighboring soil and natural water, spreading microplastic pollution. Furthermore, poor waste disposal and microplastic contamination are decreased by tougher littering legislation. In addition to these laws, several governments have supported educational initiatives to promote proper garbage disposal methods including recycling and using trash cans.[207,208]

Efforts to mitigate microplastic pollution encompass a wide range of strategies, including both conventional and emerging approaches. Traditional methods largely involve physical removal techniques such as filtration, sedimentation, and coagulation in wastewater treatment plants. While these approaches are effective to a degree, they often fail to capture the smallest microplastic particles, particularly those below 10 micrometers in size. Additionally, end-of-pipe solutions are limited in scope and do not address the upstream sources of microplastics.[205,209]

In response to these limitations, research has increasingly focused on innovative and multidisciplinary strategies. One promising avenue involves the development of advanced filtration materials, such as nanofiber membranes and bio-based filters, which exhibit enhanced selectivity and adsorption capacity for micro- and nanoplastics.[210] Magnetic separation techniques, using functionalized magnetic nanoparticles, are also under investigation for their potential to capture microplastics from aqueous media with high efficiency.[211]

Biotechnological approaches represent another frontier in this field. Certain strains of bacteria and fungi have shown potential in biodegrading synthetic polymers into less harmful or inert compounds. For instance, species like *Ideonella sakaiensis* produce enzymes such as PETase that can depolymerize polyethylene terephthalate (PET) into environmentally benign products.[179] Genetic engineering is being explored to enhance the efficiency and substrate specificity of these enzymatic systems.

Photocatalytic degradation, utilizing materials like titanium dioxide (TiO_2) and doped zinc oxide (ZnO), has emerged as a promising method for breaking down microplastics under light irradiation. These catalysts generate reactive oxygen species (ROS) capable of fragmenting plastic polymers. Such approaches are being tailored for application in wastewater treatment systems and environmental remediation technologies.[149,212]

Policy innovations and behavioral interventions are increasingly recognized as essential complements to technical solutions. Regulatory measures restricting the use of microbeads in cosmetics and controlling plastic waste discharge from industrial sources have demonstrated measurable benefits. Public awareness campaigns and citizen science initiatives further contribute to pollution reduction by promoting responsible consumer behavior and waste management practices.[213]

Furthermore, machine learning and artificial intelligence are being integrated into monitoring systems for real-time detection and quantification of microplastics in various environmental compartments. These digital tools facilitate data-driven decision-making and the optimization of mitigation strategies.[214]

In summary, while conventional technologies play a critical role in managing microplastic contamination, the

incorporation of advanced materials, biological degradation, catalytic processes, and digital innovation offers a more holistic and potentially transformative approach. Continued interdisciplinary research and international cooperation are pivotal to the successful deployment of these next-generation solutions in both developed and developing contexts.

6. Conclusions and future perspectives

In conclusion, MPs are a growing environmental concern due to their persistence in the environment and potential impacts on wildlife and human health. The degradation of MPs is a complex process that is influenced by a variety of factors, including the type of polymer, the size and shape of the particles, and the environmental conditions. The current research on the degradation of microplastics suggests that it can take hundreds to thousands of years for these particles to fully degrade and that they may persist in the environment for even longer. Future perspectives on the degradation of microplastics include the development of new technologies and methods for breaking down these particles more quickly and efficiently. This may include the use of enzymes, bacteria, or other microorganisms that can degrade plastics, as well as the development of new polymer materials that are more easily biodegradable. Additionally, there is a need for more research on the potential impacts of microplastics on human health, as well as the development of effective policy and management strategies to reduce the amount of microplastics entering the environment.

To fully realize the potential of these strategies, future research must adopt a multidisciplinary approach that bridges material science, molecular biology, toxicology, and environmental engineering. Special emphasis should be placed on elucidating the mechanistic pathways of bioaccumulation and oxidative stress, evaluating the long-term impacts on human and ecological health, and accelerating the development of scalable and economically viable remediation technologies.

Furthermore, integration of smart monitoring systems, supported by AI and machine learning, and the implementation of robust policy measures will be critical in reducing the influx of microplastics into the environment. By synthesizing scientific innovation with regulatory and behavioral change, a holistic and adaptive framework can be established to not only reduce existing pollution but also prevent future accumulation, guiding sustainable environmental stewardship for generations to come.

Data availability

All the data is provided in the manuscript file.

Author contributions

SY and MF designed the main idea and content of the article, including a write-up of different sections. MZ, NN, WZ, SF and ZA collected the data and wrote different portions of the article. NN, WZ and SF designed the graphical representation of data abstracted from different articles. SA critically reviewed the article. All the authors read and approved the final manuscript.

Conflicts of interest

The authors declare that they have no competing interests.

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