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On the degradation of (micro)plastics: Degradation methods, influencing factors, environmental impacts

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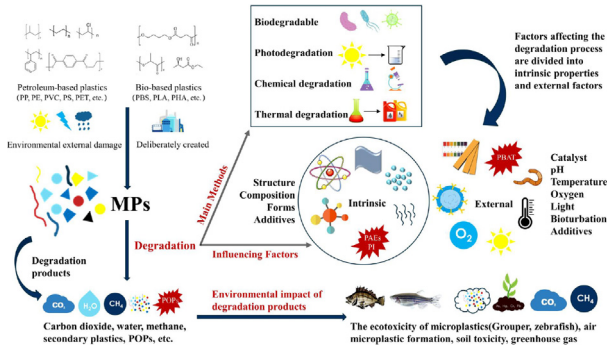
HIGHLIGHTS

- An overview of the degradation methods and influencing factors of (micro)plastics.
- The synergistic effect is the key to the degradation of (micro)plastics.
- The synergistic effect between degradation methods is not sufficiently studied.
- The synergistic effect between factors affecting degradation need more studied.
- The impact of microplastic degradation products has been poorly studied.

GRAPHICAL ABSTRACT



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ABSTRACT

Plastics and microplastics are difficult to degrade in the natural environment due to their hydrophobicity, the presence of stable covalent bonds and functional groups that are not susceptible to attack. In nature, microplastics are more likely to attract other substances due to their large specific surface area, which further prevents degradation from occurring. Some of these substances are toxic and harmful, and can be spread to various organisms through the food chain along with the microplastics to cause harm to them. Degradation is an effective way to eliminate plastic pollution, and a comprehensive understanding of the methods and mechanisms of plastic degradation is necessary, because it is the result of synergistic effects of several degradation methods, both in nature and in consideration of future engineering applications. The authors firstly summarize the degradation methods of (micro)plastics; secondly, review the influence of intrinsic properties and environmental factors during the degradation process; finally, discuss the environmental impact of the degradation products of (micro)plastics. It is evident that the degradation of (micro)plastics still has many challenges to overcome, and there are no mature and effective methods that can be applied in engineering practice or widely used in nature. Therefore, there is an urgent need for research on the degradation of (micro)plastics.

Contents

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1. Introduction

Microplastic (size <5 mm) are an important source of global environmental pollution, and they will continue to accumulate in the environment. It is reported that by 2060, the proportion of microplastic pollutants in the weight of global plastic pollutants will reach 13.2% (Sharma et al., 2020). Microplastic are widely present in the environment. There are a lot of microplastic in soil, ocean, atmosphere and fresh water, and microplastic are even found in human placenta (Sharma et al., 2020; Ragusa et al., 2021; Wang et al., 2021a). The widespread distribution of microplastic has aroused social attention.

There are two main aspects of the toxicity of plastics and microplastics to organisms: 1) Self-toxic effects: the intake of plastics will inhibit the growth of animals, destroy their intestinal tissues, and change the structure of their intestinal flora (Zhu et al., 2019; Rodriguez-Seijo et al., 2017; Wang et al., 2019); In addition, various additives (plasticizers, flame retardants, antioxidants, UV stabilizers, heat stabilizers, slip agents, curing agents, biocides, pigments and other substances) added in the production process of plastics are incorporated into the plastics. Under unstable environments, such as strong shear force (Lambert et al., 2014; Paluselli et al., 2018), continuous or strong UV light irradiation (Lambert et al., 2014; Wang et al., 2020b), weathering (Lambert et al., 2014), etc., it is easy to release these substances into the environment and cause damage to other organisms in the environment (Wang et al., 2020b; Paluselli et al., 2018); 2) Load-toxicity effect: Microplastics have small particle size and large specific surface area, so it has strong adsorption and is easy to adsorb various substances in the environment. Such as persistent organic pollutants (POPs) (Wang et al., 2020a) (polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), phthalic acid esters (PAEs), polybrominated diphenyl ethers (PBDE), dichlorodiphenyltrichloroethane (DDTs), hexachlorocyclohexane (HCHs), etc.), antibiotics (oxytetracycline (Zhang et al., 2017), amoxicillin, ciprofloxacin) and heavy metals (As, Cu, Zn), etc. These adsorbed substances will also indirectly affect biological produce toxic effects (Wang et al., 2021a).

Whether it is the plastic pollution caused by the accumulation of (micro)plastics or the indirect harm caused by its existence, we should seek one or more environmentally friendly and effective ways to remove (micro)plastics. It is necessary to develop an environmentally friendly and efficient environmental degradation method. At present, there have been certain studies on the degradation of (micro)plastics. The degradation of (micro)plastics is divided into degradation methods without biological intervention and degradation methods with biological intervention (Lambert et al., 2014). There are mainly the following

four degradation pathways: biodegradation, photodegradation, chemical degradation, and thermal degradation. The mechanism of biodegradation of plastics was more fully investigated by Ganesh, Ebmt et al. The biodegradation process is the mineralization of plastics by microorganisms (e.g. bacteria, fungi), the formation of biofilms on the surface of plastics, the destruction of their main skeletal structure and the depolymerization of side chains under the action of specific enzymes to produce oligomers, dimers and monomers. The results showed that the main influencing factors of the biodegradation process were enzyme specificity and temperature (Ganesh et al., 2019; Ebmt et al., 2021), and a biological consortium composed of multiple enzymes and microorganisms seemed to have better results compared to a single enzyme or a single microorganism for the degradation of plastics (Taniguchi et al., 2019; Singh and Wahid, 2015). In addition, the development of engineered enzymes is expected to overcome the limitation of enzyme specificity and to achieve better degradation results (Zurier and Goddard, 2020). Moreover, algal degradation and fungal degradation also have great potential (Wen et al., 2020; Ali et al., 2021b). Photodegradation and chemical degradation of microplastics have been less studied compared to biodegradation, and advanced oxidation processes (AOPs) are currently the most used processes for chemical degradation of microplastics (Du et al., 2021). Hakkarainen et al. showed that photodegradation processes and chemical degradation contributed to subsequent biodegradation, and that plastics were destroyed by UV light to produce products that could be further used by microorganisms utilized (Hakkarainen and Albertsson, 2004). Thermal degradation of plastics has various applications: 1) identification of plastics species in environmental samples by pyrolysis gas chromatography mass spectrometry (Pyr-GC/MS) (Toapanta et al., 2021); 2) similar to pyrolysis, thermal degradation of plastics can produce syngas (hydrogen, carbon monoxide, methane) or fuel oil under high temperature conditions (Arpia et al., 2021); 3) at low temperatures, thermal degradation can be used as a pretreatment technique for the degradation of plastics to facilitate their subsequent biodegradation, similar to oxidative degradation (Arpia et al., 2021; Zhang et al., 2020a). Each degradation method is not perfect. Biodegradation may be constrained by the carbon-carbon bond in plastics (Huang et al., 2017; Singh and Sharma, 2008); photodegradation may produce many toxic and harmful volatile compounds, and the collection of these gases increases the difficulty of plastics degradation (Lomonaco et al., 2020); advanced oxidation process provides a new idea for microplastics degradation, but its mechanism of action is not fully understood (Du et al., 2021; Duan et al., 2020; Liu et al., 2020; Wang et al., 2016); thermal degradation of plastics has the potential to convert them into biofuels, but there are many limitations of this approach. Although thermally degraded plastics have the potential to be converted into biofuels, there are many limitations in this approach (Peng et al., 2020; Butler et al., 2011). Better results may be achieved by combining multiple degradation methods to degrade mixed species of plastics, which can be pretreated with light and heat to break some chemical bonds in plastics that are difficult to be attacked biologically to form low molecular weight polymers, and then use the biodegradation process for the final degradation of these products. The intrinsic properties of plastics, such as structure, composition, form of existence and internal additives, have an influence on the degradation of plastics to different degrees; in addition, the influence of the external environment cannot be ignored, such as the selection of catalysts, the conditions under which the plastics are exposed (pH, temperature, oxygen and light, and bioturbation) and environmental additives (prothioconazole) seem to play a decisive role on the natural degradation of plastics role. These factors affecting the degradation of plastics often do not act alone, but in collaboration and in interaction with each other. Such as, Ariza-Tarazona et al. found that low temperature and low pH could effectively improve the photocatalytic degradation efficiency of polyethylene plastics (Ariza-Tarazona et al., 2020), but Edith et al. found that low pH slowed down the biodegradation of polyethylene plastics and that low temperature might counteract this effect (Ebmt et al., 2021). These studies indicate that the factors affecting plastic degradation are complex and may interact with each other, but the specific mechanism of action needs to be further investigated. It is recognized that plastic degradation products may place new burdens on the environment and the organisms within it. The environmental and biological effects of the photodegradation process of microplastics have also been partially studied, and Xiao Wang et al. showed that photodegraded PS inhibited growth and liver lipid deposition in Grouper (*Epinephelus moara*) (Wang et al., 2020b). However, Wei Zou et al. found that photooxidative degradation attenuated the inhibition of musculoskeletal development of Zebrafish Larvae by polyamide microplastics (Zou et al., 2020). Photodegradation of plastics in air leads to the production of atmospheric microplastics and nanoplastics, as well as the release of harmful substances such as aldehydes (Paluselli et al., 2018; Alimi et al., 2018; Crawford and Quinn, 2017; Chunzhao et al., 2019). These studies on the degradation of plastics in the environment and the generation of toxic and hazardous substances suggest that the degradation products deserve further investigation, as the generation of some potential degradation products and the interaction of known hazardous degradation products with the environment are not yet known. In addition, thermal degradation products can be used to identify microplastic species in the environment, for example, by Pyr-GC/MS to identify microplastics species in environmental samples, but the specific identification methods deserve further refinement (Dümichen et al., 2017). Up to now, the studied plastics and microplastic degradation methods are mainly used for experimental and environment-specific degradation, and an efficient and environmentally friendly degradation method that can be widely used in practical situations has not been studied yet. In addition, it is necessary to study the factors affecting the degradation of a plastics and microplastic in order to achieve a higher degradation efficiency in the corresponding environment (ocean, freshwater, soil, atmosphere, etc.). In addition, from the ecological point of view, the impact of plastic degradation methods on the environment is also very important, so that the degradation itself or the degradation products do not add more burden to the environment. For example, the toxic substances released from the photodegradation of microplastics in seawater may be toxic to fish, and may eventually affect humans as the food chain is enriched, so we should consider how to reduce this impact. The identification of degradation products for extraction deserves further study.

At present, there are relatively few researches on the degradation of microplastics. The paper mainly summarizes the following aspects: (1) The relationship between degradation of plastic and microplastics is explored; (2) The main degradation methods of (micro)plastics are summarized; (3) The intrinsic properties and environmental factors that affect the degradation of (micro)plastics; (4) The impact of the degradation products of (micro)plastics on the environment; (5) The problems existing in current research are summarized and prospected.

2. Types and properties of plastics

Due to the difference in composition and structure, the properties of microplastics are also very different, and the processing methods for different types of microplastics are also different. It is very necessary to understand the types and properties of the microplastics we are studying.

As shown in Table 1 and Table 2, plastics can be divided into different types according to different classification standards. Since microplastics are plastics with a smaller size that are broken down or made from plastics as the main raw material, some basic classification methods of microplastics are the same as those of plastics. For example, according to the different types of polymer materials, there are polyethylene, polypropylene, etc.; according to the different types of raw materials of synthetic plastics, they are divided into petroleum-based plastics and bio-based plastics; according to the difference in strength and toughness, they are divided into thermosets and thermoplastics (Alauddin et al., 1995), thermoplastics including polyethylene terephthalate (PET),

Table 1
Petroleum-based plastics and degradation methods.

Materials	Degradation methods	Experimental conditions	The result of degradation	References
PE MPs	Photocatalytic degradation	PE/N-TiO_2 film composite, aqueous media, visible irradiation	The mass loss was 6.40% after 18 h of visible irradiation, a kinetic rate constant of 38.2×10^{-4} h^{-1}	(Ariza-Tarazona et al., 2018)
		N-TiO_2-coated Batch reactor, aqueous media, visible irradiation	The mass loss was calculated as 2.86% after 8 h of visible irradiation, a kinetic rate constant of 27.4×10^{-4} h^{-1}	
	Biodegradation	Exposed to the fungus *Aspergillus flavus* strain PEDX3 for 28 days	The mass loss percentage (Δm/m0) was 3.9025 ± 1.18%, Mw was dropped by 132,202 Da, Mn was dropped by 29,069 Da	(Zhang et al., 2020b)
PP	Photo-oxidative degradation	PP in surface area for 60 days	Carbon content was decreased to 3.15%	(Khoironi et al., 2020)
		PP in 50 cm depth for 60 days	Carbon content was decreased to 6.67%	(Khoironi et al., 2020)
		PP in 170 cm depth for 60 days	Carbon content was decreased to 16.67%	(Khoironi et al., 2020)
PP MPs	Biodegradation	1 L glass bioreactor contained microalgae *Spirulina* sp. and PP microplastics with the size of 1 mm for 112 days.	The tensile strength decreased by 0.1977 MPa/day, the decreasing carbon in PP is 36.7%	(Khoironi et al., 2019)
PS	Biodegradation	PS fed *Achatina fulica* for 4 weeks	Mass loss of mean 30.7%, a significant increase in Mw and Mn of feces-residual PS, the formation of functional groups of oxidized intermediates	(Song et al., 2020)
		Incubated with *Acinetobacter* sp. AnTc-1 for 60 days	mass weight and molecular weight were significantly reduced.	(Wang et al., 2020c)
	Biodegradation	*Pseudomonas aeruginosa* strain DSM 50071 was cultured with a PS film in a solid LCFBM medium lacking an alternate carbon source	A chemical change from hydrophobicity to hydrophilicity, the formation of carbonyl groups (C═O), the gene expression level of serine hydrolase in *Pseudomonas* sp.	(Rae et al., 2020)
	Gasification	Supercritical water, under certain feedstock conditions, reacting for 20 min,	The carbon conversion efficiency of PS plastic reached 47.6% at 700 °C.	(Zhao et al., 2021)
PS MPs	Biodegradation	PS microplastics feed greater wax moth (Galleria mellonella) larvae for 24 h	Complete digestion/biodegradation	(Wang et al., 2021b)
PS NPs	Ozone and chlorine degradation	Nano-sized polystyrene plastics, ozonation, chlorination, etc.	Ozonation achieves 99.9% molecular weight (Mw) degradation and 42.7% mineralization of nano-sized polystyrene plastics in 240 min, while chlorination only attains 7.1% Mw degradation and 4.3% mineralization	(Li et al., 2022)
PET	Biodegradation	Microbial Consortium No. 46	Completely and assimilated the degradates into CO_2 and water	(Taniguchi et al., 2019)
		Ideonella sakaiensis 201-F6	Degrades and assimilates PET to produce CO_2 as the complete oxidation product	(Taniguchi et al., 2019)
		PETase and MHETase	PETase being responsible for hydrolytic conversion of PET into oligomers that include MHET as their main component and MHETase further hydrolyzing MHET into PET monomers, TPA, and EG.	(Taniguchi et al., 2019)
PET MPs	Photodegradation	The photodegradation of MPs mediated by five different types of soils, Harbin (S1), Huainan (S2), Jiangxi (S3), Shaanxi (S4) and Hainan (S5), 500 W xenon lamp, irradiation for 20 days	Degradation rate of MPs was S2 > S5 > S4 > S1 > S3, The degradation of MPs mediated by S2, with 28.9% weight loss	(Ling et al., 2021)
	Photocatalytic degradation	Photocatalysis MXene/ZnxCd1-xS photocatalysts, alkaline PET alkaline solution	The photocatalytic H2 evolution rate was 14.17 mmol•g^{-1}•h^{-1}, glycolate, acetate and methanol was generated	(Cao et al., 2022)
PET	Biodegradation	1 L glass bioreactor contained microalgae *Spirulina sp.* and PET microplastics with the size of 1 mm for 112 days	The tensile strength of micro plastic PET decreased by 0.9939 MPa/day the decreasing carbon in PET is 48.61%	(Khoironi et al., 2019)
PUR	Biodegradation	Exposure to compost environments for 12 weeks	Lost 30% mass, and 41% compression force	(Nrg et al., 2020)
	Biodegradation	Exposure to soil environments for 12 weeks	Lost 71% mass, and 71.5% compression force,	(Nrg et al., 2020)
PVC MPs	Biodegradation	PVC fed *Tenebrio molitor larvae* for 16 days at 25 °C.	A decrease in the Mw, Mn and Mz by 33.4%, 32.8%, and 36.4%; the formation of O═C and O═C functional groups	(Peng et al., 2020)

Note: MPs, microplastics; PE, polyethylene; PP, polypropylene; PS, polystyrene; PET, polyethylene terephthalate; PUR, polyurethane foams; PVC, polyvinylchloride; TPA, terephthalate; EG, ethylene glycol; Mw, weight-average molecular weight; Mn, number-average molecular weight; Mz, size-average molecular weight.

polyethylene (PE), polyvinylchloride (PVC), polypropylene (PP), polystyrene (PS), polylactic acid (PLA) etc. (Chamas et al., 2020), thermosetting plastics include epoxy resin, phenolic resin, etc.; according to their chemical composition, they are divided into biodegradable microplastics and non-biodegradable microplastics. According to the chain structure of its polymer materials, it is divided into aliphatic (linear main chain) and aliphatic/aromatic (contains ring in the main chain) polyester (Larraaga and Lizundia, 2019). For microplastics, there is also a special classification method. According to their sources, they are divided into primary microplastics and secondary microplastics. Primary microplastics are plastics with a size of micrometers deliberately manufactured, and secondary microplastics are produced by the fragmentation and cracking of the environment in which they are located through the action of external forces (Sharma et al., 2020).

2.1. Petroleum-based plastics

What people usually call plastic generally refers to synthetic petroleum-based plastics. The main raw materials for synthetic petroleum-based plastics come from petroleum products, and are polymer substances obtained by artificially adding or polycondensing different substances (Xu et al., 2019). Common ones are PE, PP, PS, PET, PUR, PVC and so on. Plastic products have superior performance, so they are widely used in production and life, which also leads to a steady stream of waste plastics entering the environment. Due to the high durability of plastics, the disposal of waste plastics has attracted widespread attention worldwide (Sánchez, 2019). Due to the high persistence of plastics, the disposal of waste plastics has attracted a lot of attention worldwide (Sánchez, 2019). Synthetic petroleum-based plastics are difficult to be used by microorganisms through biofilms because of their excessive

Table 2
Bio-based plastics and degradation methods.

Materials	Degradation methods	Experimental conditions	The result of degradation	References
(PLA)/algae biomass biocomposites	Abiotic degradation	1 M NaOH buffer solution, 5x5cm PLA/algae biomass biocomposites, 58 ± 2 °C	Molecular weight loss, acid accumulation, change in percentage crystallization	(Kalita et al., 2021)
	Biodegradation	700 g of compost for biodegradation 70 g PLA/algae biomass biocomposites, 58 ± 2 °C	Molecular weight loss, assimilation, acid accumulation, change in percentage crystallization, formation of co-enzyme and amides	(Gerngross and Slater, 2000)
PLA	Biodegradation	Standard procedures reported in ISO 17,556	After the biological processes, 15% TS of PLA degraded	(Mc et al., 2021) (ISO 17556, 2019)
SBSB	Biodegradation	Standard procedures reported in ISO 17,556	After the biological processes, 48.1% total solids (TS) of SBSB degraded	(Mc et al., 2021) (ISO 17556, 2019)
PHA MPs	Composting	0.5% PHA microplastics, the mixture of cow manure and sawdust	Composted for 60 days	(Sun et al., 2021)
PBS	Biodegradation	Microorganisms from Antarctic soil samples	The biodegradation rate was efficient at 14 °C	(Urbanek Aneta et al., 2021)
TPS	Fungal degradation	Soil burial under controlled laboratory conditions	84% mass loss after 18 weeks	(Neto et al., 2018)
		Home composting conditions	Weight loss was only 7–14%	(Adamcová et al., 2019)
TPS/Minerals Biocomposites	Biodegradation	Water bodies	Partial thermo-plasticization, surface roughness, lower contact angle values	(Silva et al., 2021)
CA	Biodegradation	Based on cotton linters	Weight loss of 33%	(Polman et al., 2020)
		Based on flaxfibre	Weight loss of 41%	
Lignin-based bioplastics	Biodegradation	Aqueous medium, standard conditions (DIN ISO 14851: 2004)	The bioplastic Arboform completely degraded in about 120 days	(Polman et al., 2020)

Note: MPs, microplastics; PLA, polylactic acid; PHA, polyhydroxyalkanoate; PBS, Polybutylene succinate; TPS, thermoplastic starch; CA, cellulose acetat; TS, total solids; SBSB, starch based shopping bags; Mw, weight-average molecular weight; Mn, number-average molecular weight; Mz, size-average molecular weight.

molecular weight and hydrophobicity; in addition, these synthetic plastics have covalent bonds such as carbon-carbon bonds that are difficult to be broken and unfavorable biodegradable groups such as the benzene carboxylic group (Xu et al., 2019; Huang et al., 2017), so these polymers that are continuously produced and continue to enter the environment are difficult to be degraded under natural conditions, bringing almost irreversible damage to nature.

It has been found that petroleum-based degradable plastics can be degraded by different pathways, including fungal degradation, enzymatic biodegradation, degradation by various bacteria against different substrates, and photocatalytic oxidative degradation. It has been reported that petroleum-based plastics can be degraded by fungi (Sánchez, 2019); enzymatic biodegradation has also been found to work well for petroleum-based plastics, and the half-life of plastics was significantly reduced from millions of years to weeks by introducing engineered enzymes for in situ degradation of microplastics in wastewater treatment unit operations (Zurier and Goddard, 2020); narrow-nutrient monas can secrete lipases that catalyze the breaking of ester bonds in the material and use the degradation products as a carbon source degradation of poly(adipic acid/butylene terephthalate) (PBAT) (Hao et al., 2021); synthetic polyesters such as polyesters and polyester polyurethanes have been shown to be susceptible to enzymatic degradation by microbial polyester hydrolases (Wei and Zimmermann, 2017); and photocatalytic degradation, $NiAl_2O_4$ spinel photocatalytic degradation (Venkataramana et al., 2020) and protein-based porous N-TiO_2 semiconductors for photocatalytic degradation of polyethylene (Ariza-Tarazona et al., 2018).

2.2. Bio-based plastics

GB/T 39514-2020 stipulates that in the research process we should pay attention to the distinction between bio-based plastics and biodegradable plastics. Bio-based plastics refer to plastics whose constituent units are wholly or partially derived from biomass sources. It is renewable and therefore very environmentally friendly. Research on it has been carried out in many countries. Common bio-based plastics include PLA, PHA and PBS (Kai and Sun, 2018). Biopolymers are not always biodegradable, for example, PBS, bio-polyethylene (bio-PE), etc. are difficult to biodegrade (Polman et al., 2020). Biodegradable plastics are generally considered as biodegradable petroleum-based plastics and biodegradable bio-based plastics.

What we usually call bio-based plastics is a kind of biopolymer (Polman et al., 2020). Biopolymers can be divided into unmodified biopolymers and modified biopolymers. Unmodified biopolymers such as starch, cellulose and lignin, which are naturally occurring unmodified biopolymers; their modified variants thermoplastic starch, cellulose acetate and lignin-based polymers, are modified biopolymers (Polman et al., 2020). Polylactic acid (PLA) is a polyester polymer obtained by polymerization of lactic acid as the main raw material. It can be produced by the fermentation of renewable plant resources and microorganisms (Tokiwa and Calabia, 2008). There is no natural biopolymer "precursor". Understanding the characteristics of unmodified biopolymers is necessary for the study of modified biopolymers.

2.3. Bioplastics

According to the provisions in GB/T 39514-2020, bioplastics are biosynthetic plastics derived from biomass, and plastics obtained from renewable materials as initial raw materials. Bioplastics are generally classified into three main categories (European Bioplastics, 2018): 1. bio-based but non-compostable plastics; 2. bio-based degradable plastics; and 3. biodegradable fossil resource plastics.

3. Relationship between degradation of plastic and microplastics

3.1. Similarities

First, by the usual definition of microplastics, microplastics are plastics less than 5 mm in diameter (Alimi et al., 2020). This indicates that the essence of microplastics is plastic, and the degradation of plastic in nature is the main source of microplastic production. There is an inseparable relationship between the degradation of microplastics and the degradation of plastics. Second, the ultimate goal of both plastic degradation and microplastic degradation is to degrade them into other degradation products such as water, carbon dioxide, and methane. The methods of degradation include biodegradation and abiotic technologies (Qin et al., 2021; Othman et al., 2021; Nabi et al., 2021). Generally, a combination of abiotic and biodegradation techniques can achieve better degradation results (Ali et al., 2021a). In nature, plastics are degraded by abiotic processes into small molecules, which are further degraded by natural organisms into carbon dioxide, water, methane, etc. Of course, it should not be neglected that the degradation process of plastics produces a large amount of microplastics and nanoplastics.

Under laboratory conditions, we can use some advanced oxidation processes and pyrolysis techniques to achieve the complete mineralization of plastics and microplastics (Dj et al., 2021 OM Rodríguez-Narvaez et al., 2021; Hu et al., 2021), but it is a great challenge whether these processes will produce many toxic and harmful intermediates, as well as the recovery and recycling of catalytic materials. Meanwhile, biodegradation is considered as an environmentally friendly process and is being studied by many scientists (Zhou et al., 2021; E Santacruz-Juárez et al., 2021; Taghavi et al., 2021; Sun et al., 2021), but some of the mechanisms involved in the biodegradation process have not been fully investigated.

3.2. Differences

Our research on the degradation of plastics includes macro-plastics and micro-plastics, and the macro-plastics can be considered as other plastics except microplastics and nanoplastics. Micro-plastics include nanoplastics and microplastics that are currently being studied. The study of degradation of microplastics is included in the study of degradation of plastics, but before the concept of microplastics was proposed, our study of degradation of plastics mainly focused on the degradation of plastics in macroscopic sense. Compared with the degradation of plastics, the degradation of microplastics has the following problems: 1) microplastics have small size, not easy to be removed in wastewater treatment plants, and then enter the environment without a good way to be collected centrally for degradation (Sarcletti et al., 2021; Rius-Ayra et al., 2021; Kundu et al., 2021), and in itself also in the environment in a large number of distribution is not easy to be collected; 2) microplastics have large specific surface area and strong adsorption, which leads to microplastics in the environment on the way to migrate will adsorb a large number of toxic harmful substances on their way to the environment, which increases the difficulty of degradation (Arpia et al., 2021; Guo and wang, 2020; Li et al., 2020a). Overall, the degradation of microplastics is not fundamentally different from the degradation of plastics, except that the degradation of microplastics poses more new challenges than the degradation of plastics.

4. Methods and mechanisms of degradation of (micro)plastics

As shown in Fig. 1, the degradation methods of (micro)plastics are divided into four major categories according to the different mechanisms of degradation: 1) biodegradation; 2) photodegradation; 3) chemical degradation; 4) thermal degradation.

4.1. Biodegradation

The biodegradation of plastics is the mineralization of plastics by microorganisms (e.g. bacteria, fungi), the formation of biofilms on the surface of plastics, the destruction of their main skeletal structure and side chains under the action of specific enzymes to undergo depolymerization to produce oligomers, dimers and monomers, such as carbon dioxide and water, and other depolymerization by-products, while this process is accompanied by the catabolism of microorganisms (Zhang et al., 2020a; Ganesh et al., 2019; Delacuvellerie et al., 2019; Polman et al., 2020). If mineralization is incomplete, biotransformation occurs, producing organic and inorganic metabolites or transformation products (Singh and Sharma, 2008). The end products of biodegraded plastics are carbon dioxide and water under aerobic conditions (Taniguchi et al., 2019); methane and carbon dioxide under anaerobic conditions (Giacomucci et al., 2020; Zhang et al., 2020c). Due to its eco-friendliness and environmental affordability, biodegradation of plastics has gained wide acceptance. The process of plastics biodegradation in the environment is the result of many factors, besides the influence of environmental factors, the type of microorganisms, the type of plastics, the structure of plastics, and the specificity of enzymes are all key factors affecting plastic biodegradation.

Biodegradation is currently studied and found to be bacterial degradation, fungal degradation, enzymatic biodegradation, and combined biological degradation. The types of biodegradation are different, and the corresponding mechanism of action is also somewhat different.

4.1.1. Bacterial degradation

Many researchers are experimenting with bacterial degradation of plastics and microplastics. Matjai et al. analyzed currently known

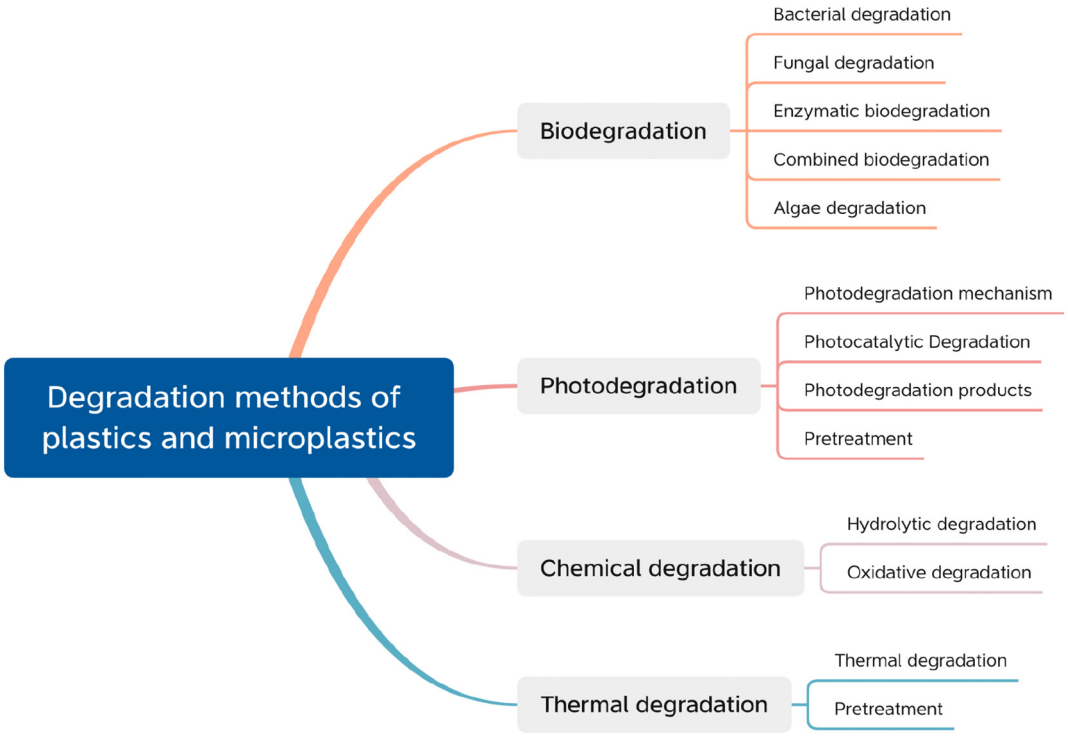

Fig. 1. Degradation methods of plastics and microplastics.

articles on biodegradable synthetic plastics using Scopus and the Web of Science online databases and concluded that most bacteria that degrade plastics are phyla Proteobacteria, Firmicutes and Actinobacteria isolated from landfills (Matjai et al., 2020). For example, *Pseudomonas aeruginosa* DSM 50071 isolated from the gut of a super worm has been shown to be effective in degrading polystyrene under experimental conditions (Rae et al., 2020). Auta et al. screened microplastic-degrading *Bacillus* strains from mangrove ecosystems in Peninsular Malaysia (Auta et al., 2018).

There are also some bacteria that degrade not directly through biodegradation, but through it has been proven to have a great relationship with the bacteria in the body. For example, polyvinylchloride can depolymerize and biodegrade in yellow mealworm larvae, and the inhibitory effect of the antibiotic gentamicin on intestinal microbes severely inhibits the depolymerization of polyvinylchloride, indicating that the depolymerization and biodegradation of polyvinylchloride depends on intestinal microbes (Peng et al., 2020), expanded polystyrene and low-density polyethylene foam can be biodegraded in the *Tenebrio molitor larvae* (Li et al., 2020b); Land snails *Achatina fulica* underwent significant changes in the gut microbial community after polystyrene ingestion, with a significant increase in a fraction of the flora, suggesting that polystyrene degradation is associated with gut microbes (Song et al., 2020). An *acinetobacter bacterium* isolated from the larvae of *Tribolium castaneum* could effectively degrade polystyrene (Wang et al., 2020c). Endosymbiotic bacteria in the citrus mealybug can degrade polyethylene (Ibrahim et al., 2021).

A single bacterium alone tends to degrade only one or few plastics and microplastics and is not as efficient as a mixture of bacteria for plastics and microplastic degradation. For microplastic mixtures their degradation performance is not very high. Because microplastics are inherently complex in composition, and because they have been damaged by the environment, it is even more difficult to clearly understand their composition. Therefore, the degradation by bacteria alone has great limitations.

4.1.2. Fungal degradation

Under experimental conditions, the marine fungus *Zalerion maritimum* was able to use polyethylene as a growth substrate, leading to a reduction in the mass and size of polyethylene particles (Ana et al., 2017). The filamentous fungi tips *Fusarium oxysporum* and *Fusarium solani* can grow on top of mineral media of polyester yarn (Taniguchi et al., 2019). Studies of macroscopic and microscopic plastic biodegradation by fungi have shown that fungi are able to use polymers as the sole source of carbon and energy for their own growth (Sánchez, 2019). Fungi have the ability to detoxify pollutants and invade substrates using enzymes that are not substrate specific. Fungi produce hydrophobic proteins that can attach mycelium to hydrophobic substrates, and mycelium has the ability to penetrate three-dimensional substrates. A polyethylene-degrading fungal strain of *Aspergillus flavus* PEDX3 was isolated from the intestinal contents of the wax borer to degrade high-density polyethylene to low-molecular-weight high-density polyethylene (Zhang et al., 2020b).

Fungi have a greater advantage over bacteria that can only degrade specific microplastics due to the specificity of a single enzyme secreted by bacteria that can act on non-specific substrates, overcoming the limitations that exist for bacterial degradation alone. There is a great potential for using fungi to degrade plastics and microplastics.

4.1.3. Enzymatic biodegradation

Enzymatic biodegradation is one of the main principles of biodegradable plastics. Almost all polymer degradation in nature requires enzymatic biodegradation (Zurier and Goddard, 2020). Plastic degrading organisms have been found in the insect digestive tract, in terrestrial environments, and in aquatic environments, but they are very specific and have very different degradation efficiencies (Yuan et al., 2020; Danso et al., 2019). Although enzymatic biodegradation relies on well-defined enzyme species, well-defined catalytic reactions and has a long incubation period, it is still a good way to degrade plastics and microplastics, especially nowadays the research on engineered enzymes increases the superiority of this degradation method (Zurier and Goddard, 2020).

Both bacterial and fungal degradation of plastics and microplastics is largely associated with microbial enzymes, but there are limitations to relying only on naturally occurring enzymes to degrade microplastics, as the purity of naturally occurring enzymes is not high and the variety of enzyme systems is not freely combinable as we would like. Therefore, there are studies to synthesize enzymes to improve the efficiency of enzyme degradation.

4.1.4. Combined biodegradation

Numerous studies have shown that the biodegradation of polymers by a single bacterium is unsatisfactory and manifests itself as an inhibition of microbial growth, due to the fact that the degradation of polymers by a single bacterium produces toxic end products (Dobretsov et al., 2013). To overcome this drawback, we considered the use of multiple bacteria to form stable microbial communities to degrade microplastics, and stable biological communities have the following advantages (Yuan et al., 2020; Singh and Wahid, 2015; Giacomucci et al., 2020; Evdokia et al., 2019): (1) elimination of metabolic toxicity, because often the products of polymer degradation by one type of bacteria be used as a substrate for the growth of another microorganism (Singh and Wahid, 2015); (2) an abundant and stable biological community can overcome the single microbial community specificity and can degrade multiple microplastics; (3) bacteria in a stable abundant and stable microbial community can harmoniously symbiotically and synergistically degrade microplastics efficiently with each other, and, at the same time, can enhance bacterial activity and tolerance. At present, many researches have successfully developed a biodegradation system composed of a variety of microorganisms. Ikuo Taniguchi and others have developed three systems that can degrade PET (Taniguchi et al., 2019): (1) Microbial Consortium No. 46; (2) *Ideonella sakaiensis* 201-F6, and (3) PETase and MHETase. Seon Yeong Park et al. isolated a mixed bacterial culture mainly consisting of Bacillus sp. and *Paenibacillus* sp. from the landfill accelerate the degradation of polyethylene microplastics (Park and Kim, 2019).

Combined biological degradation overcomes the limitations of single bacterial degradation to a large extent. However, the degradation and utilization of plastics and microplastics by bacterial communities is a very complex process due to the interaction of multiple microorganisms and multiple enzymes, and we are not well able to control the occurrence of degradation at the present research stage. Therefore, it is necessary to conduct more in-depth studies on the relevant influencing factors and mechanisms in the future.

4.1.5. Algae degradation

Algae have been shown to synthesize biodegradable plastic materials on their own, as well as degrade polymers using polymers as a carbon source, and algal degradation has very high potential for future research (Wen et al., 2020; Ali et al., 2021b). Algal synthetic microplastics overcome the poor water resistance and mechanical properties of traditional bio-based degradable plastics, which are lightweight, waterproof and robust (Machmud et al., 2013; Wen et al., 2020). Moreover, algae are easy to grow and have a short harvest time, which is very time and land cost efficient (Chew et al., 2017; Tang et al., 2020). Although currently limited to the laboratory stage, algal synthetic plastics still hold great promise for application.

Up to now, only a few algal species have the ability to degrade plastic articles products. Algae have been shown to colonize plastic surfaces (Moog et al., 2020; Ali et al., 2021b; Sarmah and Rout, 2018) and to produce extracellular polysaccharides and lignin on the surface to degrade plastic waste (Sarmah and Rout, 2018), and plastic degradation has been observed on plastic surfaces with algae (green alga *Scenedesmus*

dimorphus, the diatom *Navicula pupula*, and the blue-green alga *Anabaena spiroides*) settled on plastic surfaces were observed to degrade plastic (Ramachandran et al., 2017; Khoironi et al., 2019). Furthermore, Khoironi et al. found a higher degradation rate of PET plastics than PE, suggesting that the rate of microplastic degradation by algae may be related to the type of microplastic (Khoironi et al., 2019). In addition, some bacterial and fungal species capable of degrading plastic waste are not well adapted to the marine environment where most plastic waste accumulates (Tanasupawat et al., 2016), but some non-toxic and harmless algae overcome this drawback by forming algal biofilms in various contaminated water bodies that can and do effectively degrade plastic waste (Sharma et al., 2014; Khoironi et al., 2019). In addition to the direct degradation of plastic waste, algae can also be used as microbial factories to produce engineered PETase (Moog et al., 2020; Kim et al., 2020). Synthetic biology is a promising tool to develop an environmentally friendly solution to degrade biological PET using microalgae (Ali et al., 2021b). However, the mechanism and algal efficiency as plastic degraders need more research and investigation.

4.2. Photodegradation

4.2.1. Photodegradation mechanism

UV irradiation causes molecular breakage of polymers and cross-linking reactions to form new non-polymer structures, oxidized polymers, hydrocarbon polymers, and a range of low molecular weight substances and oxidation products such as gases (Ranby and Lucki, 1980; Gewert et al., 2015; Nakamura et al., 2006). Some of these products can be used by microorganisms (Hakkarainen and Albertsson, 2004).

In the natural environment, photodegradation is a major degradation mode that destroys plastics (Lucas et al., 2008; Klemchuk, 1990), and the main processes involved are chain-breaking and cross-linking reactions (Al-Salem, 2009). The process of photodegradation is often accompanied by oxidative decomposition, since most plastics activate their electrons after absorbing high radiant energy in order to obtain higher reactivity (Shah et al., 2008). Different UV wavelengths have different destructive capacities for different materials, depending on the chemical bonds present in the corresponding materials (Singh and Wahid, 2015). Polymers under UV radiation produce changes in mechanical properties as well as a decrease in average molecular weight (Singh and Wahid, 2015; Nagai et al., 1999). The photooxidation of polypropylene leads to the formation of carbonyl products such as ketones, esters, carboxylic acids and hydroxyl groups through an autocatalytic process (Carlsson and Wiles, 1969). Luo et al. found that the hydroxyl content and specific surface area of colored MPs increased after xenon light aging treatment, and fragmentation and crack generation occurred, which promoted the entry of photosynthetic oxygen into the inner layer for further oxidation of MPs (Luo et al., 2020). Toapanta et al. identified six photooxidation products, carbon dioxide, acetone, acetic acid, 2,4-dimethyl-furan, 2,4-pentanedione, and 3,5-dimethyl-5-isobutyl-2, 5dihydrofuran-2-one, can be used as markers of photo-oxidative degradation of microplastics, further improving the accuracy of Pyr-GC/MS studies to quantify environmental microplastic contamination (Toapanta et al., 2021). Significant morphological changes in irradiated samples were also shown by Ainali et al. using Scanning Electron Microscopy (SEM), and the deterioration of mechanical properties was shown to be significant evidence of UV irradiation leading to reduced plastic properties and its progressive brittleness, potentially leading to the formation of microplastics (Ainali et al., 2021).

4.2.2. Photocatalytic degradation

Photocatalytic degradation is an environmentally friendly technology that can degrade organic pollution into water, carbon dioxide and inorganic acids (Ariza-Tarazona et al., 2020). Photocatalytic degradation of microplastics is mainly based on semiconductor materials, and photocatalytic degradation based on semiconductors (e.g., TiO2, ZnO) can effectively degrade microplastics (Nabi et al., 2020; Uheida et al., 2020; Ariza-Tarazona et al., 2018; Tofa et al., 2019). Initially, it was shown that when the absorbed photon energy (E) is higher than the band gap energy (Eg) of the semiconductor (E ≥ Eg), electrons (E) in the valence band (VB) will be transferred to the conduction band (CB), resulting in the creation of positive holes (h+) in the VB (Nakata and Fujishima, 2012), leading to the separation of electron-hole pairs (Hou et al., 2020). Both substances (e and h+) react with OH, O2 or H2O adsorbed on the surface of the microplastic to produce highly reactive oxygen species (Nakata and Fujishima, 2012), which directly triggers the degradation process of the microplastic (Tofa et al., 2019). The generation of reactive oxygen species leads to chain breakage, branching, cross-linking and eventually complete mineralization to H_2O and CO_2 (Jiang et al., 2020; Tofa et al., 2019).

4.2.3. Photodegradation products

Most current research on microplastics is concerned with the detection and identification of the polymers that make up the plastic particles, often with much less attention paid to the complex degradation processes that plastic fragments undergo in the environment, leading to the fragmentation of these plastic fragments, resulting in the formation of nanoparticles and polymer fragments, and the release of various volatile degradation products into the environment with environmental impacts. (Biale et al., 2021; Wang et al., 2020b). The photodegradation products of polyolefins included a wide range of alcohols, aldehydes, ketones, carboxylic acids, and hydroxy acids, which are non-oligomer, oxides, the polymer hydrocarbons (Biale et al., 2021; Zhu et al., 2019).

4.3. Chemical degradation

Chemical degradation includes hydrolytic degradation and oxidative degradation.

4.3.1. Hydrolytic degradation

Hydrolysis is a way in which plastics undergo chemical degradation. The ability of a plastic to be decomposed by water depends on whether the plastic contains hydrolyzable covalent bonds such as ester, ether, anhydride, amide, carbamide, or ester amide groups, etc. Water activity, temperature, pH, and time are the key factors that affect the efficiency of hydrolysis (Lucas et al., 2008). Plastics with hydrolysable covalent bonds (e.g., PET) can absorb water, thus promoting the hydrolytic degradation of the polymer (Krzan et al., 2006). Hydrogen ions in acidic or alkaline media attack the ester bonds and the polyester undergoes hydrolytic degradation (Magued et al., 2001). In addition to chain breakage, hydrolytic degradation in alkaline media also leads to surface corrosion of polyesters (Magued et al., 2001).

4.3.2. Oxidative degradation

Oxidative degradation is another important way in which chemical degradation occurs. The introduction of oxygen leads to the formation of hydroxyl and carbon monoxide functional groups in polymers, which contribute to subsequent biodegradation (Lambert et al., 2014). The oxidation process can be induced by light or heat, and for non-hydrolyzable materials, it is particularly important that thermal and light-induced oxidative degradation occurs (Rutkowska et al., 2002).

Within the factors that cause degradation of substances, oxygen is the strongest factor, atmospheric oxygen can attack the covalent bonds in plastics, causing them to generate free radicals, the structure of the polymer largely affects oxidative degradation, and the peroxy radicals generated by oxidative degradation can lead to cross-linking reactions and/or chain breakage (Lambert et al., 2014; Duval, 2004). Even low concentrations of ozone in the atmosphere accelerate the aging process of plastics to promote further degradation (Lucas et al., 2008).

Advanced oxidation processes based on persulfate have also attracted a lot of attention because of their low-cost efficiency, complete degradation of pollutants by sulfate with a high degree of mineralization, and

the ability to degrade arbitrarily difficult polymers by overcoming the specificity of biological enzymatic degradation (Zhang et al., 2016; Dong et al., 2017; Dan et al., 2018). Advanced oxidation processes (AOPs) are an effective chemical degradation technology characterized by the formation of a variety of reactive oxygen species (ROS) with strong oxidative capacity to effectively degrade persistent pollutants in complex aqueous environments (Duan et al., 2020; Liu et al., 2020; Wang et al., 2016). Advanced oxidation processes are also effective in degrading microplastics, and advanced oxidation processes include photochemical oxidation, photocatalytic oxidation, and electrochemical oxidation (Du et al., 2021). The sulfate based AOPs (SR-AOPs) technique was reported to be effective in degrading microplastics in cosmetics by catalytic activation of peroxynitrite by magnetic nanohybrids to generate reactive radicals under hydrothermal conditions, and this robust carbon hybrid was able to effectively degrade microplastics in cosmetics (Jian et al., 2019). The degradation process of microplastics was directly induced by ROS, a product of AOPs, leading to chain breaking, formation of products and even complete mineralization of microplastics (Du et al., 2021).

4.4. Thermal degradation

Thermal degradation here is to be distinguished from what is commonly referred to as pyrolysis, thermal degradation and pyrolysis are not exactly the same. Pyrolysis is generally a process in which long-chain microplastics are converted to small molecular weight substances by thermal degradation in an inert gas environment at a certain temperature (usually 300 to 900 °C) (Chen et al., 2014). Pyrolysis is mainly applicable to the treatment of polymers composed mainly of hydrocarbons (e.g.: mix plastic waste) to produce various valuable products, such as gasoline (Wong et al., 2015; Butler et al., 2011). Thermal degradation leads to the breakage of the polymeric backbone, causing molecular deterioration of the polymer as well as changes in properties, such as destruction of tensile strength, alteration of crystallinity, reduction of durability, cracks and color changes (Lambert et al., 2014; Arkatkar et al., 2009). Thermal degradation can be used as a pretreatment to improve the degradation efficiency of subsequent biodegradation. Thermal pretreatment can also enhance the biodegradability of polymers, and the heat released during thermal degradation can also provide energy for the oxidation of carbon in the polymer backbone (Liu et al., 2021b; Arkatkar et al., 2009; Krzan et al., 2006).

There are three main application scenarios of thermal degradation techniques for the degradation of microplastics: 1) identification of microplastics species in environmental samples by pyrolysis gas chromatography mass spectrometry (Pyr-GC/MS) (Toapanta et al., 2021); 2) similar to pyrolysis under high temperature conditions, thermal degradation of microplastics can produce syngas (hydrogen, carbon monoxide, methane) or fuel oil (Arpia et al., 2021). Supercritical water gasification technology overcomes the low heat transfer and low flow diffusion capacities inhibitors of conventional thermal degradation and can effectively convert microplastics into fuel products (Arpia et al., 2021; Bai et al., 2019), Bai et al. showed that the factors affecting the gasification efficiency were temperature and time, which were not much related to the reaction pressure, and achieved 98 wt% carbon conversion after 10 min of thermal degradation at 800 °C, and the metal salts contained in seawater facilitated this reaction process, indicating that the seawater environment is a suitable environment for syngas production from microplastics (Bai et al., 2019); 3) Thermal degradation can be used as a pretreatment technique for microplastic degradation at low temperatures to facilitate subsequent biodegradation of microplastics with a mechanism similar to oxidative degradation (Arpia et al., 2020; Zhang et al., 2020a). Arkatkar et al. showed that the surface of polypropylene formed carbonyl, carboxyl, and ester functional groups and reduced the hydrophobicity of polypropylene (Arkatkar et al., 2009).

5. Factors affecting the degradation process

As shown in Fig. 2, the factors affecting the degradation process are divided into its intrinsic properties affecting its degradation behavior and external environmental conditions affecting its degradation behavior. Its intrinsic properties are mainly: the composition, material, structure and existence form of (micro)plastics. External environmental conditions include temperature, pH, humidity, microorganisms, kinetic factors (shear stress), hydrolysis, catalysts, enzymes, etc.

5.1. Intrinsic properties

The intrinsic properties of the plastics polymer play an important role in the degradation rate of the plastics polymer (Lambert et al., 2014). The composition and structure of plastics affect the degradability of plastics. In addition, the different forms of plastics presence also affect the degradability; a larger specific surface area will have a faster degradation rate, as most plastics degradation will degrade the plastics surface first (Gewert et al., 2015). However, a larger specific surface area results in greater adsorption, which affects degradation by adsorbing more other substances. In addition, the different molecular composition

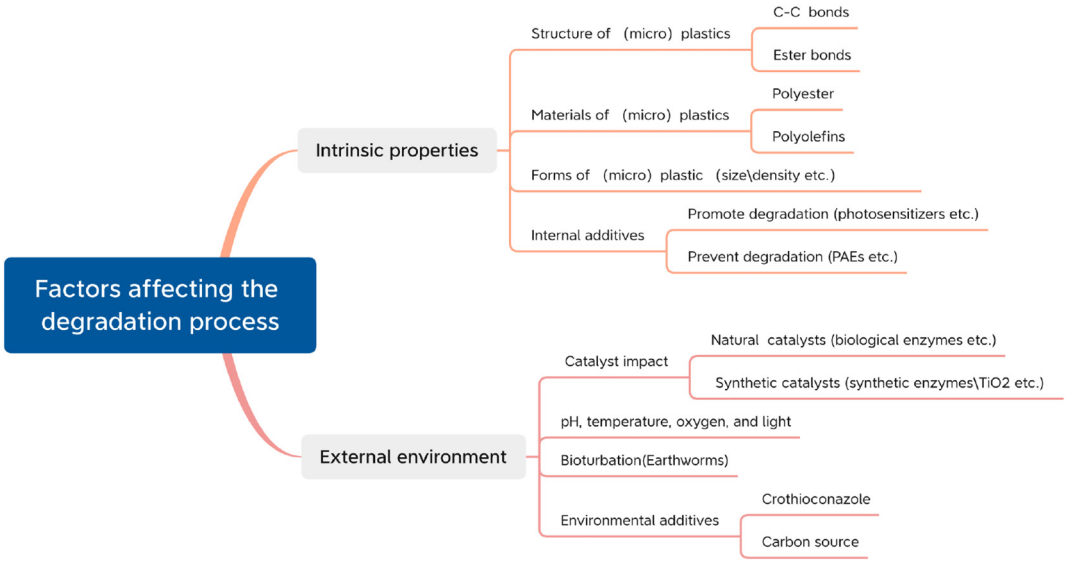

Fig. 2. Factors affecting the degradation process.

of plastics can lead to differences in the hydrophobicity of the plastics, which in turn affects the adsorption of the plastics (Artham and Doble, 2010).

It has been reported in related studies that those plastics polymers containing ester bonds (e.g., polyester polyurethanes) are more biodegradable than those without ester bonds (Albertsson and Karlsson, 1993; Barlow et al., 2020). The specific structure and the complexity of the microplastic composition can influence the degradation efficiency of microplastics by affecting enzyme accessibility and photosensitivity, etc. Plastics polymers with short and regular repeating units with high symmetry and strong interchain hydrogen bonds (e.g., polyethylene, polypropylene, and polyethylene terephthalate) usually limit enzyme accessibility and are not easily degraded (Artham and Doble, 2010; Kumar et al., 2006; Kaczmarek et al., 2007). In addition, the color of microplastics may also affect the photodegradation of microplastics, probably because dark colors, especially black, have stronger light absorption and provide better photodegradation than light-colored microplastics (Jiang et al., 2020).

5.1.1. Structure

The presence of chemical bonds and functional groups that are not easily attacked in microplastics, such as carbon-carbon and ester bonds, can largely affect the degradation of microplastics. Some other important factors, such as the minimally reactive functional groups in the backbone, chain mobility and crystallinity, also affect the degradation process (Webb et al., 2012; Tokiwa and Calabia, 2008; Shah et al., 2008). In addition, the different molecular composition of plastics also affects the degradation process, because the different molecular composition of plastics affects the surface hydrophobicity of polymers, which in turn affects the adsorption of plastics, and the strength of adsorption determines the ease of attachment of the plastics itself to microorganisms (Artham and Doble, 2010). The presence of ester bonds in some plastics, such as polyesters, polyurethanes, and polyethylene terephthalate, makes them then relatively susceptible to biodegradation (Albertsson and Karlsson, 1993; Barlow et al., 2020; Liu et al., 2021a). Common plastics such as PE, PP, PVC, and PS have very low biodegradability in the natural environment (Tokiwa and Calabia, 2008; Chandra, 2015) because the presence of highly stable carbon-carbon bonds in their backbone as well as their high molecular weight and hydrophobicity result in their chemical biological inertness, and no enzymes have been identified that can effectively cleave their carbon-carbon bonds (Taniguchi et al., 2019; Chamas et al., 2020), in addition, they do not have functional groups that are susceptible to erosion by biological enzymes, light, or water (Chamas et al., 2020). Although current studies suggest that these plastics may be attacked by some mixed microbial communities and pure fungi or bacteria from the environment, the degradation efficiency under actual natural conditions is very low (Noura et al., 2019). Therefore, the degradation of these polyolefins in nature needs to rely on other abiotic factors, such as ultraviolet (UV) irradiation and polymer oxidation, where the formation of carbonyl groups under UV irradiation and during oxidation as well as the triggering of polymer carbon-carbon backbone chain breaks to form smaller polymer fragments to aid subsequent biological reactions (Wei and Zimmermann, 2017; Gewert et al., 2015).

5.1.2. Materials

Due to the different materials of plastics, there are some differences in the degradation methods and bacterial species involved. The main difference is the degradation of two major classes of plastics, polyesters and polyolefins. Polyester can be effectively degraded by biodegradation methods due to the presence of ester bonds that are easily attacked by polyester hydrolases, polyester hydrolases is a type of enzyme that can degrade polyester (such as PET, PUR), this type of enzyme is mainly composed of cutinase (Wei and Zimmermann, 2017; Taniguchi et al., 2019). Polyolefins cannot rely on biodegradation alone because they contain carbon-carbon bonds, and usually polyolefin degradation requires a pretreatment of photo-oxidation catalysis combined with subsequent biological treatment.

There have been a certain number of successful cases for the biodegradation of PET. Three biological systems for the degradation of PET were developed by Ikuo Taniguchi et al. (1) Microbial Consortium No. 46; (2) *Ideonella sakaiensis* 201-F6, and (3) PETase and MHETase (Taniguchi et al., 2019). Because of the high percentage of aromatic terephthalate units contained in PET, this leads to a low chain mobility of PET, which is not easily hydrolyzed (Wei and Zimmermann, 2017; Tokiwa and Calabia, 2008). The degradability of PET relies heavily on its non-crystalline regions, as enzymes usually attack the non-crystalline regions (Tokiwa and Calabia, 2008; Marten et al., 2003; Marten et al., 2005). The enzymes capable of degrading PET consist mainly of keratoses, which are capable of hydrolyzing keratin, an insoluble aliphatic polyester secreted from plant epidermis (Taniguchi et al., 2019).

Polyethylene can achieve better results mainly by photocatalytic degradation, such as green photocatalysis by porous N-TiO2 semiconductor based on protein, CO_2 was found as the main end product (Ariza-Tarazona et al., 2018; Nabi et al., 2020). However, fungal strains capable of degrading it have also been found, such as the fungal *Aspergillus flavus* strain PEDX3, a polyethylene degrader isolated from the intestinal contents of the wax borer (Zhang et al., 2020b). But the several redox enzymes that have been identified to aid in the degradation of polyethylene do not seem to be able to bring about the complete biocatalytic degradation of plastics with carbon-carbon backbones (Wei and Zimmermann, 2017). The biodegradation process of polyethylene is preceded by the formation of a thick biofilm on its surface (Delacuvellerie et al., 2019).

Due to its hydrophobicity, high molecular weight and high surface roughness, polypropylene hardly degrades in the aquatic environment. Polypropylene relies mainly on photo-oxidative degradation, which produces polar carbonyl groups, esters, ketones, and acids in the presence of UV light and oxygen, thus improving hydrophilic properties (Khoironi et al., 2020). Maldovan et al. found that the degradation of microplastics was more related to the location where they were located, at the surface of seawater, polypropylene microplastics mainly underwent photo-oxidative degradation, at deeper depths of seawater polypropylene was predominantly biodegraded and most of the degraded structures were not completely mineralized, but further produced filamentous and fibrous microplastics (Khoironi et al., 2020).

PS can be degraded to some extent by some microorganisms or by some physicochemical pretreatment to achieve better biodegradation. Ozonation pretreatment can enhance the subsequent biodegradation of polystyrene by fungi (Tian et al., 2016). Some bacteria isolated from the bodies of the yellow fly, the larvae of the red anthropomorphic cereal steal and land snails can degrade polystyrene (Song et al., 2020; Wang et al., 2020c; Peng et al., 2020).

PVC can depolymerize and biodegrade in yellow meal larvae, but like polyethylene and polystyrene, there is very limited mineralization of polyvinyl chloride microplastics in the presence of biodegradation (Peng et al., 2020).

Algae-based polyurethane foams degraded after only 12 weeks of incubation in compost and soil with significant loss of structural integrity (Nrg et al., 2020). Natasha R. Gunawan selected bacteria capable of utilizing polyurethane as the sole carbon source and demonstrated that in a vitro environment, cholesterol esterase from *Pseudomonas* spp. depolymerized 38% of polyurethane back to monomer and in a 24-hour enzyme treatment oligomers, this study demonstrates the possibility of creating commercially viable biodegradable polyurethane products and shows the potential of using recombinant enzymes to depolymerize and recycle polyurethane products (Nrg et al., 2020).

5.1.3. Forms

Plastics exist in the form of fragments, pellets, films, and fibers. The size of the molecules in plastics affects its mechanical, thermal, and biological degradation. Ideally, the degree of these degradations increases

with decreasing molecular size (Gowariker et al., 2000). Under laboratory conditions, smaller or coarser microplastic particles are more susceptible to degradation because the larger specific surface area can adsorb more catalyst to increase the contact area with the catalyst to aid in microplastic degradation (Jiang et al., 2020). In practice, however, the situation is more complex, as microplastics are small and have a large specific surface area to adsorb large amounts of contaminants thus increasing the difficulty of degradation (Chen et al., 2019b). These contaminants may hinder the photodegradation of microplastics as they block the UV radiation. In addition, the antibiotics and POPs in these contaminants may be toxic to the biofilm on the surface of microplastics and thus hinder the biodegradation process of microplastics (Zhang et al., 2020a).

Many plastics float on the water surface due to their density being less than that of seawater, resulting in many plastics which can reach more sunlight and oxygen and thus undergo degradation under aerobic conditions. The rest of the plastics that sink to the seafloor will undergo anaerobic biodegradation into small molecules such as methane and water because they are mainly under anaerobic conditions (Ryan et al., 2009; Stephanie et al., 2013). For plastics with carbon backbone in the main chain, such as polyolefins and polystyrene, anaerobic biodegradation is mainly through the following processes (Vazquez et al., 2020): 1) formation of free radicals triggered by light or heat; 2) random breakage of polymer chains; 3) production of methane and hydrogen gas by anaerobic microorganisms. For plastics without carbon backbone in the main chain, such as PCL and PLA, anaerobic biodegradation starts with the formation of small molecule polymers by hydrolysis, which are further degraded by anaerobic microorganisms (Gorrasi and Pantani, 2017). Therefore, we should understand the distribution of different types of plastics with density when considering the natural degradation.

5.1.4. Internal additives

Along with the addition of plasticizers and some other additives that may increase the difficulty of degradation, various antioxidants and stabilizers used to extend the working life of plastics further prevent the degradation of plastics in the environment (Chamas et al., 2020), in addition, the addition of pigments used for coloring also brings new difficulties to the degradation of plastics. However, if additives such as photosensitizers are added, it is possible to help plastics to undergo better photodegradation. Whether it prevents or promotes the degradation of plastics depends on the type of additive. However, from the point of view of commercial production and people's use, they all want more durable and beautiful plastic products, which makes it difficult for most plastics present in the natural environment to degrade by natural environment. Therefore, further research is necessary to investigate the degradation of additives in plastics and the mechanisms by which the presence of additives affects degradation. The plasticizer phthalate has been found to be chemically degraded by iron-cerium oxide-catalyzed persulfate (Dong et al., 2019).

5.2. External environment

The main influencing factors of the external environment are catalysts, acidity, temperature, light and oxygen, dynamic factors (shear stress), and the presence of microorganisms in the environment.

5.2.1. Catalyst

Catalyst is a substance in a chemical reaction that changes the rate (increases or decreases) of the chemical reaction of the reactants without changing the chemical equilibrium, and whose own quality and chemical properties remain unchanged before and after the chemical reaction. Catalysts used for plastic degradation include both natural and synthetic catalysts. Enzymes are a common catalyst used for plastic degradation. Enzymes are classified into natural biological enzymes and synthetic enzymes, with biological enzymes being the most common type of natural catalysts, produced by secretion from living organisms. Enzymes present in nature are often difficult to purify and expensive to produce, so there is an increasing amount of research on synthetic enzymes. There are other types of catalysts, such as iron-cerium bimetallic catalysts catalyzing the degradation of phthalates in marine sediments by peroxynitrite (Dong et al., 2019), and elements aluminum and iron found in plastic samples excavated from landfills act as catalysts during the pyrolysis of plastic waste (Canopoli et al., 2020). In addition to some metallic elements that can act as catalysts, some metal oxides have been found to be good catalysts for the degradation of microplastics, for example, semiconductor catalysts (e.g., TiO_2, ZnO) in the presence of a light source of suitable energy generate reactive substances (e.g., O_2- and OH-) that react with the polymer, causing its chemical oxidative decomposition (Sharma et al., 2020; Ariza-Tarazona et al., 2018).

The specificity of enzymes for plastic, the regulation of enzyme gene expression, the requirement of multiple enzymes for polymer decomposition, and the nutritional deficiency of enzyme synthesis all affect the degradation of plastics. Contact of microorganisms and specific enzymes with plastics can significantly disrupt their main backbone structure and side chains (Ganesh et al., 2020); the plastics component is responsible for the most susceptibility of polyurethanes to microbial degradation, usually due to the activity of secreted hydrolases (Barlow et al., 2020).

In nature, enzymes usually function in a synergistic manner, using their respective specific functions to perform an efficient continuous catalytic process for the degradation of organic pollutants (E Santacruz-Juárez et al., 2021). This also gives an idea to synthesize enzymes artificially. However, enzymes present in nature are usually not pure enough and difficult to extract and have low activity, so there are two solutions: (1) developing whole-cell biocatalysts to improve their degradation efficiency through biocatalysts (Chen et al., 2019a; Wei and Zimmermann, 2017); (2) introducing the concept of engineered enzymes to investigate the engineering of efficient, high-purity and high-activity engineered enzymes needed to degrade polymers (Zurier and Goddard, 2020; Wei and Zimmermann, 2017).

The catalytic degradation of microplastics by specific materials is an emerging research idea. Zinc oxide nanorods on glass fiber substrates can effectively photocatalytically degrade suspended microplastic particles under visible light irradiation, and the degradation by-products are non-toxic and non-hazardous (Uheida et al., 2020). It has also been shown that a novel ultra-thin hydroxyl-rich BiOCl (BiOCl-X) can efficiently degrade microplastics 24 times more efficiently than nanosheet BiOCls, based on the principle that the surface hydroxyl group of the BiOCl can effectively enhance the production of hydroxyl radicals, leading to a decrease in the performance of microplastics (Jiang et al., 2020). In addition, there are magnetic spring-like carbon nanotubes on microplastics can get effective integration of carbon catalytic oxidation and hydrothermal hydrolysis by catalytic activation of peroxynitrite to generate active radicals, and this robust carbon hybrid exhibits excellent degradation performance of microplastics, and the helical structure and high graphitization ensure excellent stability of carbon catalysts in high temperature environment, and organic intermediates of degraded microplastics are environmentally friendly and can provide a carbon source for aquatic microorganisms and aquatic products (Jian et al., 2019).

Jiang et al. conducted photocatalytic degradation experiments on microplastic particles with BiOCl-X. The microplastic particles were mixed and treated with the catalyst under 250 W Xe lamp and then the photocatalytic activity was evaluated experimentally using a circulating water system. The experimental results showed that this new hydroxyl-rich BiOCl could effectively degrade microplastics with 24 times higher efficiency than nanosheet BiOCl, based on the principle that the surface hydroxyl group of BiOCl-X could effectively enhance the production of hydroxyl radicals, leading to the degradation of microplastics (Jiang et al., 2020). The larger specific surface area, more active sites and faster charge separation and transfer rates are the main reasons for the improved performance of BiOCl-X (Jiang et al., 2020).

In addition, Jian et al. performed catalytic oxidation and hydrothermal hydrolysis of microplastics in an autoclave using a deionized aqueous solution containing a certain amount of (Mn@NCNTs), and this robust carbon hybrid exhibited excellent degradation properties for microplastics. The helical structure and high graphitization ensured the excellent stability of the carbon catalysts in high temperature environment, overcoming the drawback of previous nanocarbon materials which were unstable in oxidizing environment. And the toxicity experiments on microalgae showed that the organic intermediates of the degradation process are environmentally friendly and can provide a carbon source for aquatic microorganisms and aquatic products (Jian et al., 2019). However, the authors did not provide a clear account about the recycling of this carbon nanocatalyst. Moreover, since this is the first report on (Mn@NCNTs), the structural control of (Mn@NCNTs) also needs to be further optimized in future studies (Jian et al., 2019).

In addition to the treatment stage where carbon nanotubes can be used to catalyze the degradation of microplastics in water, studies have also attempted to incorporate carbon nanotubes into plastic products during the production stage to accelerate the degradation rate of plastics in the environment. Poly (lactic acid) (PLA)/poly (ethylene oxide) (PEO)/carbon nanotubes (CNTs) nanocomposites are an example. Zare et al. investigated the hydrolytic degradation behavior of this composite in PBS solution and showed that carbon nanotubes play a catalytic role in the degradation of this composite (Zare et al., 2019).

5.2.2. pH, temperature, oxygen, and light

Low pH and low temperature have a combined effect on the degradation of microplastics; low pH introduces hydrogen ions into the system, which favors plastic degradation and better interaction of colloidal nanoparticles with microplastics; low temperature leads to fragmentation of microplastics and increases their surface area and carbon and nitrogen-titanium dioxide interactions (Ariza-Tarazona et al., 2020). While high pH and the presence of hyaluronic acid (humic acid) inhibited the UV/biosulfate degradation of di(2-ethylhexyl) phthalate in aqueous solutions (Huang et al., 2017). Under alkaline environment, the catalyst and microplastic particles are negatively charged on the surface, generating coulombic repulsive forces that weaken the adsorption capacity between them and ultimately lead to a decrease in catalytic performance (Jiang et al., 2020). The pH mainly affects the electrostatic interactions between plastics and contaminants to modify the adsorption behavior (Xiong et al., 2020). The acidic pH of the environment slows down the biodegradation of polyethylene plastics by the bacterium *Pseudomonas aeruginosa*, but this effect may be counteracted if the environment is at a low temperature (Ebmt et al., 2021).

When considering the environmental degradation of plastics, we should consider the availability of oxygen in the area, temperature, and light to determine the degradation method. Most of the current research on plastic degradation is focused on aerobic biodegradation, and relatively little research has been done on anaerobic biodegradation of microplastics. Biodegradable plastics are materials that are completely converted (for a limited time) by aerobic microorganisms to carbon dioxide, water, minerals, and biomass, or in the case of anaerobic biodegradation, to carbon dioxide, methane, and humic substances (Matjai et al., 2020). The retention of beach-deposited plastics is mainly controlled by the composition and degradation rate of plastic particles, and the degradation of microplastics in beach sediments is much faster than in the ocean because beach sediments are exposed to more UV radiation during the daytime, thus accelerating the process of photocatalytic degradation (Narmatha et al., 2019; Arthur et al., 2009; Rochman et al., 2015). UV radiation from the sun can break down plastics into microplastics smaller than five millimeters in size or even nanoplastics (Gall and Thompson, 2015), which is a cause of secondary plastic production. Visible light irradiation can also promote the degradation of microplastics (Wang et al., 2020b).

Changes in pH can influence the electrostatic interactions between plastics and contaminants to modify the sorption behavior. Usually, high pH (alkaline) environments exhibit inhibited adsorption behavior of plastics, while acidic environments or neutral favor promoting adsorption behavior of plastics; elevated temperature can accelerate the oxidative degradation of plastics; the main effect of oxygen can determine which degradation method plastics will adopt in that environment.

5.2.3. Bioturbation

The main application scenario for bioturbation is the degradation of biodegradable plastic agricultural films. Earthworms can be used as a carrier for plastic biodegradation. Bioturbation can reduce the accumulation time of microplastics in the soil and reduce the impact of film mulching on soil fertility (Sanchez-Hernandez et al., 2020). Bioturbation has many benefits for soil degradation: (1) enhancing bioturbation through the introduction of earthworms, which enhances the degradation of soil microplastics, can reduce the bioaccumulation time of polymers in the soil; and (2) vermicomposting of waste agricultural films with solid waste can produce environmentally friendly value-added products (biofertilizers) (Sanchez-Hernandez et al., 2020).

5.2.4. Environmental additives

It has been shown that prothioconazole, a fungicide widely used in agriculture and gardens, promotes the degradation of polyethylene and biodegradable polybutylene adipate-ethylene terephthalate (PBAT) plastic films (Li et al., 2020a). Furthermore, the biodegradation of microplastics was enhanced by the addition of an additional carbon source, and the addition of glucose enhanced the biodegradation of microplastics after 60 days compared to natural biofilms alone, but the addition of peptones, glucose and peptones together was inhibitory (Sadaf et al., 2020). This difference in the appearance of biodegradation may be due to the altered nutrient structure resulting in a change in the biotic community.

6. Environmental impacts of degradation products

An important criterion for evaluating a degradation method is whether it is environmentally friendly. While we focus on more efficient ways to degrade microplastics, we cannot ignore the other impacts of such degradation on the environment and the organisms in it.

6.1. Environmental impacts of photodegradation products

6.1.1. Photodegradation increases or decreases biotoxicity

Due to the presence of nanotoxicity, endocrine disruption and carcinogenic toxicity, the ensuing production of photodegradation products may exacerbate the potential hazards of microplastics, such as nanoparticles, chemical additives, polymer fragments, etc., making it necessary to pay attention to the ecological effects of microplastic degradation in the relevant environment. It has been found that the photodegradation of polystyrene microplastics inhibits growth and liver lipid deposition in juvenile grouper (*Epinephelus moara*), mainly due to the accumulation of microplastics in their bodies and leaching of endogenous contaminants (Wang et al., 2020b). However, another study found that photooxidative degradation of polyamide microplastics attenuated the inhibition of musculoskeletal development of Zebrafish Larvae, the mechanism being that degradation of microplastics modulates macrophage-triggered pro-inflammatory responses and attenuates damage to antioxidant systems and apoptosis (Zou et al., 2020).

The large differences that exist for the ecotoxicity of microplastics may be explained by 1) the different forms of microplastics present in the studied microplastics, e.g., primitive plastic microbeads and irregular microplastics aged in nature (Wang et al., 2020b); 2) the different environments in which the degradation of microplastics is simulated, e.g., specific experimental environments and simulated natural environments. 3) the

size of microplastic particles, the strength of binding to organic toxic pollutants, and aquatic animal species can also affect the ecotoxicity of microplastics (Cai et al., 2017).

6.1.2. Photodegradation to produce volatile organic compounds

The number of studies related to the organic compounds and types released during photodegradation of microplastics is small, but the study of these released organic compounds can help to better evaluate the degradation of microplastics (Lomonaco et al., 2020). The release of organic compounds from the degradation of microplastics has been confirmed by Yamashita, Royer et al. who determined the release of volatile organic compounds during the degradation of plastics in specific environments (Yamashita et al., 2009; Sarah-Jeanne et al., 2018), but experimental studies under natural conditions are lacking. Biale et al. confirmed that photodegradation of polyolefins (polyolefins) volatilizes long chain alcohols, aldehydes, ketones, carboxylic acids, and hydroxy acids, long chain alcohols, aldehydes, ketones, carboxylic acids, and hydroxy acids by EGA-MS, Py-GC–MS, and SEC analyses, ketones, carboxylic acids, and hydroxy acids, alcohols, aldehydes, ketones, carboxylic acids, and hydroxy acids. In addition, other studies have reported a positive correlation between the rate of VOCs production and specific surface area, which suggests that organic compounds can be continuously released into the environment throughout the degradation of plastics and that the degree of aging of plastic debris determines the production of VOCs due to the occurrence of oxidative photodegradation (Lomonaco et al., 2020). Among these are toxic and harmful compounds (e.g. acrolein, benzene, propanal, methyl vinyl ketone, and methyl propenyl ketone), and the burden of these toxic and harmful compounds on the environment deserves further attention (Lomonaco et al., 2020).

6.1.3. Photodegradation as a source of airborne microplastics

Polymer degradation tends to release volatile organic compounds (Rabek, 1995; Ray, 2018), and the degradation of polyolefins produces volatile organic compounds belonging to the lactone, ester, ketone, and carboxylic acid groups, thus lowering their molecular weight, and making them more likely to float in the air (Gardette et al., 2013). Most of the released volatile compounds participate in complex photochemical reactions that affect the atmospheric photochemical processes in various ways (Koppmann, 2007). Aldehydes are susceptible to photodegradation in the atmosphere, which leads to the formation of microplastic particles in the air (Atkinson, 2000).

6.2. Interaction of biodegradation products with soil

The impact of microplastics on soil mainly affects soil microbial structure and activity, enhances nutrient uptake by plants, and changes soil physicochemical properties (Sintim et al., 2021; Hou et al., 2021). The use of polyethylene film, one of the most widely used agricultural films, will continuously increase the amount of microplastics in the soil and increase the burden of soil plastic degradation, thus causing different degrees of impact on the soil and the organisms living in it. Further degradation of microplastics will bring more nanoplastics to the soil, and the addition of nanoplastics may have a greater impact on the organisms in the soil. Since nanoplastics have a smaller size than microplastics as well as a larger specific surface area, its small size makes it easier for it to enter organisms and crops, and thus the human body. Because of its larger specific surface area, nanoplastic is also more likely to adsorb more other substances from the environment, which can also enter the food chain cycle along with the nanoplastic and thus affect the entire ecosystem.

Encapsulation of fungicides and/or insecticides in a seed film coating to protect seeds from disease and pests has been widely used. However, this treatment technique introduces more plastic debris into the soil. Therefore, it is necessary to investigate whether these plastic fragments are well degraded in the soil and whether these plastic fragments bring new impacts on the soil environment (Cesare et al., 2019). Studies have shown that the degradation of plastic coatings in soil varies and that the factors affecting their degradation are the type of plastic in the plastic film layer and plastic additives, and that the addition of spores of the plant growth-promoting *Bacillus subtilis* to the biodegradable plastic film coating increases the degradation efficiency of the plastic film coating, and if the addition of the corresponding biodegradable strains would achieve better results (Cesare et al., 2019).

6.3. Microplastic degradation releases harmful substances

The degradation of microplastics is accompanied by the release of harmful or potentially hazardous substances such as plasticizers, additives, organic contaminants, and copolymers (Chunzhao et al., 2019; Paluselli et al., 2018; Alimi et al., 2018; Crawford and Quinn, 2017). The rate of leaching of these substances may be related to the polymer material, and studies have shown that both PVC cables and polyethylene bags leach specific phthalates into the surrounding seawater, with the latter having a higher release rate (Paluselli et al., 2018).

7. Summary and outlook

The article provides a detailed review of degradation methods, influencing factors and interactions with the environment for plastics that can degrade, including petroleum-based degradable plastics and bio-based degradable plastics. Also, the relationship between degradation of plastic and microplastics is illustrated. However, for those non-degradable plastics, they may also become degradable plastics with further research. Some of the degradable plastics mentioned in this paper are degradable, but there are no examples of successful commercial use. And many degradation reactions of degradable plastics nowadays occur under aerobic conditions, and there is a great lack of research on degradation under anaerobic conditions. In addition, when considering degradation products we should consider not only the environmental friendliness, but also the ability to produce products of greater value, such as methane production from anaerobic biodegradation of plastics. It is worth noting that algae also have a great potential to degrade plastics, and it is better adapted to the environment of plastic waste accumulation than bacteria and fungi to degrade plastics; in addition, from the perspective of synthetic biology, algae can also be used as a biological factory to produce engineered PET enzymes, but the current research on algae degradation of plastics and synthetic biology is very limited, and more research is needed on algae degradation mechanism and degradation efficiency. More research is needed on algal degradation mechanisms and degradation efficiency.

Most of the studies on microplastic degradation are still focused on single treatment for single microplastic degradation, but in fact the composition of microplastics is quite complex. Therefore, we should build on these studies to further investigate the synergistic effects of different degradation methods to degrade microplastics with complex composition, which is crucial for the practical application of microplastic degradation. In addition, some studies have shown that various factors affecting microplastic degradation are not acting individually, but synergistically and interactively, but the mechanism of interaction between these factors needs to be further studied.

The misuse of bio-based plastics in the market has also caused a great burden to the environment. The market for fully bio-based biodegradable plastics has not been well developed due to the high price and some drawbacks compared to petroleum-based plastics, and people usually add some petroleum-based plastics to bio-based plastic products to reduce the cost and enhance the durability. With the addition of petroleum-based plastics, the biodegradable plastic part is better degraded during the degradation process of this hybrid product, but this may cause the petroleum-based plastic part to break into smaller microplastics or even nano-plastics into the environment, causing a greater burden to the environment. And biodegradable polymers

(BPs) have now been found to be causing new pollution problems. In addition, there are many studies on the ecological risk of microplastics, but there are few studies on the environmental impact of microplastic degradation products, and the methods and processes of extraction and identification of degradation products also need to be further optimized. In the future, we can simulate the degradation reaction, mechanism, and degradation effect of microplastics in the actual environment, to better guide the practice of microplastic degradation. At the same time, we can also carry out research on the impact of microplastic degradation products on the ecological environment, to provide theoretical support for the scientific selection of environmentally friendly microplastic degradation methods in the future.

CRediT authorship contribution statement

Lingchen Liu: Writing, Original Draft preparation, Methodology. **Mingjie Xu**: Methodology, Software. **Yuheng Ye**: Methodology, Software. **Bin Zhang**: Conceptualization, Supervision, Writing -Review & Editing, Funding acquisition.

Declaration of competing interest

There is no conflict of interest with respect to our manuscript.

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